Department of Defense

The Militarily Critical Technologies List

Part II:

WEAPONS OF MASS DESTRUCTION TECHNOLOGIES

February 1998

Office of the Under Secretary of Defense for Acquisition and Technology
Washington, D.C.

THIS DOCUMENT WAS PREPARED BY THE OFFICE OF THE UNDER SECRETARY OF DEFENSE FOR ACQUISITION AND TECHNOLOGY

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(The order number for this document at DTIC and NTIS is: ADA 330102)

PREFACE

A. THE MCTL

The Militarily Critical Technologies List (MCTL) is a detailed and structured compendium of the technologies DoD assesses as critical to maintaining superior U.S. military capabilities. DoD develops the MCTL with participation of other agencies of the United States Government, U.S. industry, and academia and updates it on an ongoing basis. In the past, the MCTL was published in one document. The MCTL is being published in three documents. Three parts of the MCTL will cover weapons system technologies, technologies associated with weapons of mass destruction, and developing technologies. These three documents provide the opportunity to highlight different technologies and technology levels.

B. USES OF THE MCTL

The action plan accompanying the 23 January 1995 Deputy Secretary of Defense Tasking Memorandum stated that the MCTL is used as a:

- Technical foundation for U.S. proposals for export control in the New Forum,* Missile Technology Control Regime, Nuclear Suppliers Groups, Australia Group, and other nonproliferation regimes.
- Technical reference for licensing and export control by Customs Officials, DoD, DOS, DOC, and DOE.
- Technical reference for contracts and scientific papers by government, industry, and academia.
- Technical reference and guide for intelligence collection.

In addition, the MCTL:

- Provides background and support for international cooperative activities.
- Supports development of technology transfer policy, technology release guidelines, and specific proposals or controls to be implemented by multinational organizations.

The MCTL is not an export control list.

- There may be items in the MCTL that are not on an export control list.
- There may be items on an export control list that are not in the MCTL.

The MCTL is to be used as a reference for evaluating potential technology transfers and technical reports and scientific papers for public release. The information must be applied using technical judgment. It should be used to determine if the proposed transaction would result in transfer that would permit potential adversaries access to technologies, not whether a transfer should or should not be approved.

C. ORGANIZATION OF THE MCTL

The three parts of the MCTL are the following:

Part I, "Weapons Systems Technologies," (published in June 1996) details those critical technologies with performance parameters that are at or above the minimum level necessary to ensure continuing superior performance of U.S military systems.

Part II, "Weapons of Mass Destruction Technologies," (this document) addresses those technologies required for development, integration, or employment of biological, chemical, or nuclear weapons and their means of delivery. This document is not oriented to U.S. capabilities. Rather, it addresses technologies that proliferators might use to develop WMD. It provides technical information to assist various entities of the DoD to develop, support, and execute counterproliferation initiatives.

Part III, "Developing Critical Technologies," (to be published in 1998) will contain a list of technologies which, when fully developed and incorporated in a military system, will produce increasingly superior performance or maintain a superior capability more affordably.

The format of Parts II and III, insofar as possible, is consistent with the MCTL, Part I.

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* Note: The Wassenaar Arrangement (initially called the New Forum) is the successor organization to COCOM, and is named for the city in The Netherlands where the arrangement was formalized.

D. THE MCTL PROCESS

The MCTL process is a continuous analytical and information-gathering process which updates the MCTL by adding information and refining existing documents to provide thorough and complete technical information. In addition, the Technology Working Groups (TWGs), which are part of the MCTL process, provide a reservoir of technical experts in many disciplines that can be called upon to assist in time-sensitive and quick-response tasks.

The TWGs comprise about 500 technical experts from both government and the private sector. In general, TWG members are drawn from the military services, DoD and other federal agencies, industry, and academia. A balance is maintained between public officials and private sector representatives. TWGs maintain a core of intellectual knowledge and reference information on an array of technologies. The data is used as a resource for many projects and other assignments, and TWG members are available to the national security community as technical experts. Working within an informal structure, TWG members strive to produce precise and objective analyses across dissimilar and often disparate areas. Currently the TWGs are organized to address 20 basic technology areas:

Aeronautics Systems
Armament and Energetic Materials
Biological Systems
Chemical Systems
Directed and Kinetic Energy Systems
Electronics
Ground Systems
Information Systems
Information Warfare
Manufacturing and Fabrication
Marine Systems
Materials
Medical Systems
Navigation Systems
Nuclear Systems
Power Systems
Sensors and Lasers
Signature Control
Space Systems
Weapons Effects and Countermeasures

E. MCTL PART II METHODOLOGY

For each part of the MCTL, sets of task-organized experts are supplemented with other experts when required. Their efforts are focused on technology areas according to the particular task assignments. For Part II, “Weapons of Mass Destruction Technologies,” there were six task-organized TWGs corresponding to the six sections of the document: Means of Delivery, Information Systems, Biological Weapons, Chemical Weapons, Nuclear Weapons, and Nuclear Weapons Effects.

The TWGs applied the following guidance in selecting technologies for inclusion in this document—identify and assess technologies required for the development, integration, or employment of biological, chemical, or nuclear weapons and their means of delivery. The technologies detailed in Part II are those selected by the TWGs after technical analyses and application of professional judgment. Fundamentally, Part II views technologies from the perspective of a foreign proliferator. It describes technologies that may provide alternative means to achieve a military capability. Emphasis is placed on technologies that a proliferant country might use. It is recognized that a proliferator might obtain key items surreptitiously or through illegal acquisition. The TWGs recognize that small numbers of WMD can be obtained by theft or be provided by another country. The TWG did not focus on these possibilities because they involve transfer of weapons, and not transfer of technologies to build weapons.

F. LEGAL BASIS FOR THE MCTL

The Export Administration Act (EAA) of 1979 assigned responsibilities for export controls to protect technologies and weapons systems. It established the requirement for an MCTL. The EAA and its provisions, as amended, were extended by Executive Order 12924 (19 August 1994), which was continued on 15 August 1995, 14 August 1996, and 13 August 1997.

The legislation and execution directive are amplified and implemented by DoD Directives 2040.2 and 5105.51 and by the Deputy Secretary of Defense letter dated 23 January 1995.

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INTRODUCTION TO MCTL PART II

A. CONTEXT AND BACKGROUND

Before the demise of the Soviet Union, the proliferation of nuclear, biological, and chemical weapons was considered in the context of superpower relations. The breakup of the Soviet Union and the subsequent events have had many consequences. Regional conflicts, once constrained, are now increasingly likely to result in the use of weapons of mass destruction. Opportunities to acquire key technologies and components have expanded through the dual stimuli of underutilized technical expertise and difficult economic circumstances. Simultaneously, development and availability of applicable technologies have expanded.

Responsible states have endeavored to stem proliferation of WMD through international agreements and export controls. Such tools, while imperfect, remain the basis for increasingly comprehensive steps to address the broad WMD threat. United Nations' inspectors in Iraq discovered that Saddam Hussein, in spite of international treaties, had efforts underway to develop nuclear, biological, and chemical weapons and the means to deliver them. North Korea developed the infrastructure to produce nuclear weapons even though it was a party to the Nuclear Nonproliferation Treaty. South Africa produced six nuclear devices while under the constraints of an international trade embargo. The Aum Shinrikyo cult killed and injured people in Japan by placing containers of the nerve agent sarin in crowded Tokyo subway trains. The same group had a very capable laboratory including fermentors, dryers, and sizing equipment and had produced the biological pathogen anthrax.

Concern about the proliferation of nuclear, biological, and chemical weapons and their means of delivery has reached exceptional levels. On November 14, 1994, the President of the United States found that "...the proliferation of nuclear, biological, and chemical weapons ('weapons of mass destruction') and of the means of delivering such weapons, constitutes an unusual and extraordinary threat to the national security, foreign policy, and economy of the United States...." He declared a national emergency to deal with the threat. This executive order (12938) was extended on November 8, 1995; November 12, 1996; and again on November 12, 1997.

B. OBJECTIVE

This document identifies technologies and technology levels required for the development, integration, or employment of nuclear (including radiological), biological, and chemical weapons and their means of delivery. Technologies describing the effects of the employment of these weapons and technologies for information systems required for many employment options for WMD are also included. Emphasis is placed on a proliferant country's ability to threaten the United States and its allies; however, subnational activities are also considered. Of greatest interest are technological capabilities "sufficient" to produce WMD of a given type and the ability to deliver them. Commercial-off-the-shelf (COTS) technologies can be used in many cases to obtain capability without extensive, development programs. Other technologies of concern are those that are built on the grid of existing technologies such as commercial networking of communications.

The above criteria differ from those used in MCTL, Part I, "Weapons Systems Technologies," where the performance levels of interest were those that ensure the superiority of U.S. military systems. In Part II WMD, operational technology capabilities are stressed without making any assumptions regarding an adversary's strategy or tactics, intentions, objectives, methods of employment, or target selection.

Items of proliferation concern that are on export control lists as well as those that do not appear on export control lists are included to provide indicators of possible capabilities for WMD development and to inform U.S. export control decision makers. Foreign Technology Assessments are provided to assist in understanding the capabilities of selected foreign countries in WMD-related technologies.

While every effort was made to prepare a comprehensive listing of technologies of proliferation concern, the absence of a technology should not be construed to mean that the technology could not make a contribution to proliferation.

C. OVERVIEW

This document identifies and discusses the technologies required for the development, integration, or employment of nuclear, chemical, and biological weapons and their means of delivery. Since the United States has forsworn the use of biological and chemical weapons, the underlying technologies include those usable by another country to develop an offensive capability and those needed to defend against their use. The parameters listed indicate those levels agreed to in the MCTL Technology Working Group process. They provide a description of technologies which are appropriate for possible actions by those assigned responsibility to constrain proliferation.

The technologies treated in this volume differ greatly. The development of nuclear weapons generally requires significant infrastructure, including a large capital investment required for the production of special nuclear material. By contrast, pathogenic biological agents can be made in small commercial facilities which are difficult to distinguish from legitimate pharmaceutical or related production activities. Technologies required to produce toxic chemicals are widely available, and much of the equipment is embedded in legitimate chemical industry. The infrastructure complexity and expense associated with different means of delivery vary widely. Proliferant states which have been prominent in world affairs have opted for extended investment in means of delivery, command and control, and their associated infrastructures. While not all proliferants follow such a path, there are very real reasons for doing so when the world is viewed through the eyes of the individual proliferants.

Nuclear technologies receive wide publicity. Technical information is available in the public sector at an increasingly fine level of detail. Technologies for the production and operation of means of delivery are also well known. Examples of items include the widely distributed cruise missile systems and use of the U.S.-deployed Global Positioning System, which offers users precise time and location worldwide. Biotechnologies which can be applied to biological weaponry are predominantly dual use, growing rapidly and requiring relatively small amounts of capital investment.

Heightened interest in the proliferation of WMD and their means of delivery has been accompanied by a significant amount of misinformation. Factual and carefully considered technical information is needed to address constraints effectively through nonproliferation and counterproliferation initiatives. This report provides technical data on WMD. In addition, it distills, from a technological viewpoint, reality from the myths of nuclear, biological, and chemical weapons and their means of delivery. It is helpful to retain an ongoing awareness that the problem is complex and the challenge is often driven by unique cultural considerations.

WMD warfare involves a myriad of factors: types of weapons; delivery systems; conflict arena size and WMD launch-to-target distance; attack size, timing, tactics, frequency, and duration; military or political, counterforce or countervalue attack objectives; weapon stockpile sizes; and custody and release policies and procedures.

In summary, development, integration, and employment of Weapons of Mass Destruction and their means of delivery is grounded in a huge number of choices which will be driven overwhelmingly by the political aims, culture, and resources of the proliferator. Other drivers include economics, a trained workforce, and available technical knowledge.

1. Means of Delivery

The Means of Delivery (MOD) treated here are exceptionally diverse. Included are manned and unmanned aerial vehicles of various levels of cost and sophistication. Artillery systems and multiple launch rocket systems make up the ground-based elements of MOD. These last two are traditional weapons of war, widely available and relatively inexpensive. By contrast, intercontinental ballistic missiles are complex, difficult to develop, and very expensive to maintain in operational status. Of particular interest in this section is the compatibility of the MOD with the actual payload. Physical parameters of speed, heat, shock, and delivery angle tend to drive the survivability, dispersion, and efficiency of chemical or biological payloads. In each MOD system, application of all of the technologies known to or used by the United States is not required. A proliferator has the latitude to select among often disparate, but equally satisfactory choices of means of delivery. MOD usually requires some information systems, however simple, to control assets and complete missions.

2. Information Systems

Each proliferator will use information systems to some degree throughout processes appropriate to acquire and employ WMD. Technologies treated here are commonly found within the commercial information technologies available throughout the world. Selection of information systems suites is driven by the particular combination of weapons selected, cost of information systems, and culture of the individual proliferator. The impact in various kinds of employment is addressed in detail.

3. Biological Weapons

Biological organisms are easier and less expensive to produce than special nuclear material or many chemical warfare agents. The required technology is widely available, with dual-use applications in the commercial fermentation and biotechnology industries. Because data on producing biological organisms is so widely available in open literature, it is difficult for industrialized nations to withhold relevant information from potential proliferants. Most equipment needed for large-scale production of biological warfare agents is also dual use and widely available in world markets.

Biological agents must retain their potency during storage, delivery, and dissemination. When weaponized for missile, bomb, or cluster bomblet delivery, agents are weakened by the environmental stresses of heat, oxidation, and desiccation. While it is relatively difficult to develop munitions with predictable effects, it is less difficult to spread biological agents indiscriminately to cause large numbers of casualties. Standard biological agents for covert sabotage or attacks against broad-area targets are easy to produce and easy to disseminate using commercially available agricultural sprayers.

Because biological agents reproduce, a small amount can multiply into a significant threat. When disseminated, they are slow acting; microbial pathogens require incubation periods of days to weeks between infection and the appearance of symptoms.

Toxin agents are poisonous substances made from living systems or produced from synthetic analogs of naturally occurring poisons. They are covered under biological weapons technologies in this document even though they act as chemical agents.

4. Chemical Weapons

Technologies to produce chemical weapons are difficult to distinguish unambiguously from those used to manufacture commercial chemical compounds. Many technologies that benefit chemical weapon production are dual use and widely available. Legitimate commercial chemical facilities can produce chemical warfare agents. Multiple-purpose chemical plants which manufacture organo-phosphorous pesticides or flame retardants could be converted to produce nerve agents. Open literature and standard principles of chemical engineering enable proliferants to learn how to produce chemical weapons. Although some chemical agents, such as mustard gas, are simple to produce, others are produced by more complex processes involving corrosive or reactive material.

More than 100 countries have the capability to produce simple chemical weapons such as phosgene, hydrogen cyanide, and sulfur mustard. Somewhat fewer countries are able to produce nerve agents such as sarin, soman, tabun, and VX. Commercial equipment that could be used to produce chemical warfare agents is generally available.

An operational capability to use chemical weapons involves design and development of effective munitions, filling them before use, and integrating them with a delivery system. Dispersion of chemical agents is hindered by atmospheric turbulence, which increases vertical dilution and thereby reduces casualties. Dispersion is also affected by air temperature and temperature gradient.

5. Nuclear Weapons

The basic concepts of nuclear weapons are widely known. Nuclear bomb-related physics is available in unclassified publications, and experienced foreign nuclear designers could be hired to expedite a proliferant country's nuclear weapon program, which requires a large, specialized, and costly scientific-industrial base. For most countries, the biggest obstacle to developing nuclear weapons is procuring plutonium or highly enriched uranium. Because production of these nuclear materials is the most difficult and costly part of a nuclear weapon program, leakage of weapon-grade material from nuclear-capable countries is a very serious concern.

Despite wide availability of the basic design concepts, a proliferant country must have technical expertise to produce a single nuclear weapon. First-generation nuclear weapons developed by most proliferant countries would likely be designed for delivery by short-range ballistic missile (like a SCUD) or tactical aircraft. High-performance computers would not be needed to design first-generation fission weapons.

Nuclear weapons are so destructive that delivery accuracy would seldom be a problem. Nuclear weapon effects are blast, thermal, and radiation. Against human beings, blast and thermal effects are immediate; nuclear radiation effects can be immediate or delayed.

6. Nuclear Weapons Effects

Nuclear weapons effects simulation and hardening technologies have been widely employed in the United States. Other nuclear states have employed these technologies to a lesser degree. Employment of simulation technology by a proliferator is an effective means of ensuring that the desired results will be achieved while avoiding the adverse public reaction to an actual nuclear test. Although these technologies are less widely understood than the technologies for WMD, they are included to provide key elements of insight into nuclear weapons phenomena. They are presented independently because they are a highly specialized set of technologies which have been the subject of significant research and development.

D. ORGANIZATION OF PART II

Weapons of Mass Destruction include nuclear, chemical, and biological weapons; means of delivery; information systems that enable a proliferant to command, control, and manage resources required for a WMD program; and certain nuclear weapons effects technologies that provide insight into nuclear weapons, their applications, and constructing defenses appropriate to these effects.

Each of the six sections contains the following parts:

- **Scope** identifies the technology groups covered in the section; each group is covered by a separate subsection.
- **Background** provides historical perspective and/or complementary information about the section's technologies.
- **Overview** discusses the technology groups identified under "Scope."
- **Rationale** indicates why the technology groups are important.
- **Foreign Technology Assessment (FTA),** with accompanying figure, provides summary estimates of foreign capabilities; these estimates are expert judgment by the TWGs and are discussed in Section E below.

There is a subsection for each technology group identified under scope. Each subsection contains these parts:

- **Overview** identifies and discusses technologies listed in tables that follow.
- **Rationale** indicates why listed technologies are important to proliferators.
- **Foreign Technology Assessment (FTA)** provides comments on a more detailed technology level than in the section FTA above.
- **Tables,** which are the heart of the MCTL, present data elements related to the development, production, or employment of WMD. The principal data element is **"Sufficient Technology Level,"** which is the level of technology required for a proliferant to produce entry-level WMD, delivery systems, or other hardware, and software that are useful in WMD development,

integration, or use. The **"Export Control Reference"** column provides general reference to assist in identifying potential national and international control guidelines. This column is provided for general reference and should not be construed as a definitive determination of U.S. export control policy for these technologies. Jurisdictional determination of a specific technology and/or commodity must be made in accordance with the procedures in the ITAR and EAR. (Note: For a brief description, see Appendix F, "International Regimes.") The following references are used:

- USML: United States Munitions List
- CCL*: Commerce Control List
- NRC: Nuclear Regulatory Commission
- WA: Wassenaar Arrangement
  - Cat: category designation—CCL and WA Dual Use list
  - ML: Munitions List
- NTL: Nuclear Trigger List (Nuclear Suppliers Group)
- NDUL: Nuclear Dual Use List (Nuclear Suppliers Group)
- MTCR: Missile Technology Control Regime
- AG List: Australia Group List
- BWC: Biological Weapons Convention
- CWC: Chemical Weapons Convention

Other data are defined in Appendix B, "Explanation of Table Elements."

E. FOREIGN TECHNOLOGY ASSESSMENT

The MCTL includes estimates, called Foreign Technology Assessments (FTA), of foreign capabilities in each of the MCTL technology areas. These FTA estimates are the scientific and technological consensus of the TWG members from industry, government, and academia. Collaboration with the Intelligence Community is an essential part of the FTA determination, and selected members of the Intelligence Community are TWG members who participate regularly in the MCTL process. These MCTL FTAs are foreign capability assessments and do not constitute *findings* of foreign availability, which are the responsibility of the Department of Commerce under the Export Administration Act.

Tables containing summaries of general foreign capabilities appear in each of the six MCTL Part II sections. The technological capability level is represented by diamond icons. ♦♦♦♦ indicates capability in the technology area that exceeds the sufficient level. It does not mean that the country has capability in all of the technologies associated with that technology area. It implies a range of technologies, e.g., ♦♦♦♦ for ICBM indicates that the technological capability of a country exceeds the sufficient level of technology to develop an ICBM; it does not necessarily mean that the country has the technological sophistication of the United States in ICBMs. In a corresponding manner, ♦♦♦ indicates sufficient technology capability; ♦♦ shows some technological sophistication but less than a sufficient level; and ♦ means limited capability. (*Note: This is NOT the same as MCTL Part I, where the number of blocks was related to technologies listed in the accompanying tables "at or above the minimum level necessary to ensure continuing superior performance of U.S. military systems."*) If two or more countries have the same number of diamonds, it does not necessarily mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability.

The diamonds indicate indigenous capability to produce or the ability to legally acquire and use those technologies. A country could obtain key items surreptitiously or through illegal acquisition, catapulting the possessed WMD capability past the lower levels of expected evolutionary development.

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* CCL EAR 99: Items that are subject to the Export Administration Regulations (EAR) that are not elsewhere specified in any CCL category are designated by EAR 99.

SECTION I

MEANS OF DELIVERY TECHNOLOGY

SECTION 1—MEANS OF DELIVERY TECHNOLOGY

Scope

BACKGROUND

The means that a nation uses to deliver a weapon of mass destruction (WMD) depends in part on the availability of a vehicle, the survivability of the delivery system, the characteristics of its intended target, and the nation's military objective (even if the target is civilian in nature). These factors are not mutually exclusive considerations. Many proliferants have demonstrated clever methods to adapt one delivery vehicle, which it can easily acquire, to other applications much different from the original purpose of the vehicle. Similarly, some nations have launched effective attacks against targets that U.S. analysts might initially overlook because of a different perception of the importance of these targets.

When a proliferant has invested both the expense and talent to develop a WMD arsenal and the means to deliver it, it does so to be capable of launching a sufficiently effective attack. Consequently, the means of WMD delivery a proliferant selects usually reflects some planning and coordination of its objectives. No strategist can completely rule out an irrational or desperate WMD attack from a proliferant. However, such attacks, *because* of their very irrationality, will generally not inflict the damage necessary to change the course of a conflict. Nor is the threat of an ineffective and irrational attack likely to serve the goal of deterrence or further the change that a proliferant might pursue.

With these restrictions in mind, a nation will select a means of delivery that furthers its goals. This does not mean that the proliferant must seek ways to *optimize* the effectiveness of a WMD attack, as nations with modernized militaries do. Proliferants might conduct an attack merely to demonstrate an intention or a capability. Certain characteristics of delivery systems and the types of WMD they carry are naturally associated with these goals.

Highlights

- Several means are available to deliver WMD: ballistic missiles, cruise missiles, aircraft, and artillery.
- The delivery means a nation uses depends on the availability of the vehicle, the survivability of the delivery system, the nature of the target, and the objective.
- Optimum effectiveness might not be the driving factor when selecting a means of delivery.
- Aircraft generally carry more payload weight than ballistic or cruise missiles.
- Ballistic missiles which are mobile are less vulnerable than fixed sites to U.S. offensive operations.
- Modern cruise missiles are generally more accurate and less expensive than ballistic missiles.

Delivery Systems Considerations for Chemical or Biological Payloads

To be truly effective, chemical or biological agents must be spread in a diffuse cloud over a large area. Certainly, any chemical or biological cloud may find some victims, but highly concentrated clouds spread over very small areas or pools of agent puddled on the ground have limited effectiveness because they come into contact with only a small portion of the targeted population or equipment.

Meteorological conditions affect the size and concentration of a windborne agent cloud and its durability. Hence, the interaction of the delivery vehicle and the local meteorology is an important consideration when a proliferant contemplates a chemical or biological attack. Some of these conditions even affect the probability that the cloud will reach its target after it has been released from a delivery vehicle. The United States' experience in testing windborne agents has shown that a cloud must be released below an atmospheric shear layer or it will disperse before reaching the ground. Most shear layers occur at around 500 feet above ground level (AGL).

Shifting wind conditions, local topography and micro-meteorology, and the presence of manmade structures also affect the distribution of the agent within the cloud and its dissemination from a delivery vehicle. Biological agents, in particular, decay rapidly in the presence of strong sunlight and quickly become ineffective. Some chemical agents also suffer from degradation in sunlight and from interaction with water vapor and other constituents of the atmosphere. Winds channeled by tall buildings and geographic features may deposit some of the cloud in unexpected locations. Delivery vehicles themselves create a disturbance in the wind field because of the aerodynamic and propulsive effects generated by the vehicle. Since some of these conditions change over the course of hours, an attack that is launched at a particularly propitious time under the local meteorological conditions at the target may not be effective by the time the WMD arrives. With sufficient warning of a chemical and biological weapon attack, a population can take protective measures that may be quite effective.

To be effective, a delivery vehicle employed to spread chemical or biological agents must distribute the material in a fine cloud below a certain altitude and above the surface. It should be capable of all-weather operations and should not betray its presence to air defense assets. These traits are considerations that will determine the overall effectiveness of a chemical or biological attack. Proliferants with limited military budgets must also consider the cost of acquiring and maintaining a WMD delivery system arsenal as well as the warheads. This may limit a proliferant to developing or purchasing only one or two types of delivery systems rather than simultaneously pursuing multiple systems.

Delivery systems vary in their flight profile, speed of delivery, mission flexibility, autonomy, and detectability. Each of these considerations is important when planning a chemical or biological attack.

Ballistic missiles have a prescribed course that cannot be altered after the missile has burned its fuel, unless a warhead maneuvers independently of the missile or some form of terminal guidance is provided. A pure ballistic trajectory limits the effectiveness of a chemical or biological attack because, generally, the reentry speed is so high that it is difficult to distribute the agent in a diffuse cloud or with sufficient precision to ensure a release under the shear layer of the atmosphere. In addition, thermal heating upon reentry, or during release, may degrade the quality of the chemical or biological agent. U.S. experience has shown that often less than 5 percent of a chemical or biological agent remains potent after flight and release from a ballistic missile without appropriate heat shielding.

A ballistic missile also closely follows a pre-established azimuth from launch point to target. The high speed of the ballistic missile makes it difficult to deviate too far from this azimuth, even when submunitions or other dispensed bomblets are ejected from the missile during reentry. Consequently, if the target footprint axis is not roughly aligned with the flight azimuth, only a small portion of the target is effectively covered.

A ballistic missile has a relatively short flight time, and defenses against a ballistic missile attack are still less than completely effective, as proved in the Allied experience during the Gulf War. However, with sufficient warning, civil defense measures can be implemented in time to protect civil populations against chemical or biological attack. People in Tel Aviv and Riyadh received enough warning of SCUD missile attacks to don gas masks and seek shelter indoors before the missiles arrived. Even with these limitations on ballistic missile delivery of airborne agents, Iraq had built chemical warheads for its SCUDs, according to United Nations' inspection reports.

Cruise missiles, in contrast, can be guided and follow almost any course over the ground that a mission requires. The speed of a cruise missile is compatible with an effective dissemination of both chemical and biological agents, although designers generally must plan to release these agents outside of the aerodynamically disturbed flow field around the vehicle. If the cruise missile is outfitted with a sensor platform, it may determine the local meteorological conditions and alter its flight profile appropriately before it releases the agent. Unmanned air vehicles (UAVs) are naturally more difficult to detect because of their small size and ability to fly below radar horizons. On the other hand, their slow speed increases their vulnerability to defenses.

Most nations that manufacture chemical and biological agents produce these agents in large quantities. The delivery system costs can become the ultimate limiting factor. Since cruise missiles are much less expensive than either manned aircraft or ballistic missiles, a proliferant can overcome the liabilities of delivery cost efficiency by selecting suitable cruise missile systems.

Manned tactical aircraft and bombers have several of the advantages of cruise missiles, but some additional liabilities. Manned aircraft are expensive to maintain. They also require routine flight operations for crew training, expensive upkeep programs, hangars for housing, and large air bases for basing. If an airplane is lost or shot down, the loss of the pilot complicates subsequent attack planning. Unless a nation has acquired highly capable aircraft or retrofitted its existing aircraft with advanced technology, there may be limitations to all-weather or night operations. Since biological attacks are most effective at night when there is no sunlight to decay the agent and the atmosphere is settling towards the ground as it cools, a limitation on night operations characteristically limits the effectiveness of some biological attacks. The flexibility of flight planning and attack strategy, however, weighs in favor of manned aircraft. A pilot is able to change targets if the battle situation dictates.

Delivery System Considerations for Nuclear Payloads

Nuclear weapons differ markedly from chemical, biological, or conventional warheads. The principal difference is the size, shape, and inertial properties of the warhead. Generally, nuclear weapons have a lower limit on their weight and diameter, which determines characteristics of the delivery system, such as its fuselage girth. Though these limits may be small, geometric considerations often influence the selection of a delivery system. Chemical and biological weapons, which are usually fluids or dry powders, can be packed into almost any available volume. Nuclear weapons cannot be retrofitted to fit the available space; however, they can be designed to fit into a variety of munitions (e.g., artillery shells).

Nuclear weapons also have a different distribution of weight within the volume they occupy. Fissile material, the core of a nuclear weapon, weighs more per unit of volume than most other materials. This high specific gravity tends to concentrate weight at certain points in the flight vehicle. Since virtually all WMD delivery systems must fly through the atmosphere during a portion of their trip to a target, a designer has to consider the aerodynamic balance of the vehicle and the required size of control system to maintain a stable flight profile while carrying these concentrations of weight. Chemical, biological, and conventional weapons all have specific gravities near 1.0 gram/cc, so these materials may be placed further from the center of gravity of the vehicle without providing large compensating control forces and moments. In some special applications, such as ballistic missile reentry vehicles and artillery shells, the designer needs to include ballasting material—essentially useless weight—to balance the inertial forces and moments of the nuclear payload.

Because nuclear weapons have a large kill radius against soft and unhardened targets, accuracy is a minor consideration in the delivery system selection as long as the targeting strategy calls for countervalue attacks. Nuclear weapons destroy people and the infrastructure they occupy. They only require that the delivery system places the warhead with an accuracy of approximately 3 kilometers of a target if the weapon has a yield of 20 kilotons and to an even larger radius as the yield grows. Most unmanned delivery systems with a range of less than 500 kilometers easily meet these criteria. Often, as is the case with ballistic missiles, the quality of the control system beyond a certain performance does not materially change the accuracy of a nuclear warhead, because a large fraction of the error arises after the powered phase of the flight as the vehicle reenters the atmosphere. While this is true of chemical and biological warheads as well, with a nuclear warhead, there is less need to compensate for this error with such technologies as terminal guidance or homing reentry vehicles.

A proliferant most likely would not manufacture or obtain nuclear weapons in the same quantities as chemical, biological, or conventional weapons. This may cause a proliferant to place more emphasis on the reliability of the vehicle and the targeting methods it selects to deliver nuclear weapons. Reliability may refer to the delivery system or its ability to penetrate defenses to deliver a weapons load.

Many factors contribute to the ability to penetrate defenses, including the proximity of approach before detection, the velocity of the delivery system, and the time to target after detection. Cruise missiles approach much closer to a target before being detected, but their slow speed also means that the defense has time and capabilities to intercept them in a realistic manner once they are detected. Ballistic missiles can be detected upon launch, but their high reentry speed still makes them difficult targets to acquire and intercept before they reach the target. A proliferant nation must weigh these considerations along with the availability of technologies for building certain delivery systems when it develops a targeting strategy for its nuclear weapons. If a defending country can alert its population of an impending attack, a ballistic missile launch detection system provides about 8 minutes of warning for a missile with a 500-km range. Alternatively, the population has 5 seconds of warning for every mile from the target that a transonic cruise missile can be detected. If the defending nation can detect the cruise missile 100 miles from the intended target, it has about 8 minutes to intercept the missile.

From the standpoint of defense, stealthy cruise missiles pose the greatest threat as a delivery system, regardless of the WMD type. Manned aircraft, while a serious threat, have other limitations, such as their unrefueled range, their capability or lack of capability to operate in all weather conditions and at day or night, their visibility to defense detectors, and their high acquisition, maintenance, and training costs.

OVERVIEW

Proliferants that are acquiring WMD have an array of vehicles available to deliver their payloads. The “Means of Delivery” section covers the primary *military* methods of delivering WMD. The section focuses on unique aspects of these delivery systems and simple modifications to them that enhance the ability of a proliferant to conduct a WMD attack. Excluded from this topic are adaptations of civilian vehicles, such as automobiles or small boats, which usually accompany terrorist acts. Furthermore, the discussion generally considers only the primary delivery means to carry a weapon to its final target. Except for aircraft carrying WMD bombs or glide devices that steer or fly toward a target after being dropped, the discussion does not treat secondary vehicles that move WMD closer to a target before launch. These vehicles, which include submarines and surface ships carrying ballistic or cruise missiles on board, have such broad military applications that their acquisition cannot be uniquely associated with WMD.

This section will first list the conditions for effective delivery of a payload and then its associated influences on the choice of a delivery system. Each of the subsections that follow emphasizes and elaborates upon certain technologies that a proliferant might use to make its delivery system more effective.

RATIONALE

The ability to produce any of the three types of WMD does not give a proliferant operational capability in that type of weapon. The weapon must be integrated with a delivery system to get the weapon to the intended target. Military systems have been included in this section because they are of most concern. Civilian vehicles (e.g., boats, aircraft, trucks) are not covered because they are so common throughout the world. Yet, they could also be used to deliver a WMD or other significant weapons to a particular location, as was demonstrated in the Saudi Arabia bombing in which a commercial truck was used.

Some ballistic missiles have been purchased (and possibly modified for longer range), and others have been developed indigenously. Although intercontinental ballistic missiles (ICBMs) are not widespread, proliferants might obtain the technology to produce them. Cruise missiles provide WMD delivery capability with relatively low technology and ease of acquisition. Most militaries have combat aircraft or the means to purchase them. As long as a nuclear, biological, or chemical weapon can be developed to be carried on an aircraft and successfully released, it is a threat that needs to be considered.

Artillery is common in the world's armies and can also be used to deliver a WMD. There are many kinds of artillery with varying capability. Nuclear, chemical, and biological munitions that are usable by many existing artillery systems have been produced. The technology has been available for many years and is quite well understood. Also included in the Artillery subsection is the Multiple Launch Rocket System (MLRS).

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.0-1)

Over two-thirds of the countries that cause concern have programs to acquire ballistic missiles. Even though short-range anti-ship cruise missiles are widely available, only a few countries possess long-range land-attack cruise missiles. With the success of long-range cruise missiles in Desert Storm and its aftermath, indigenous development programs can be expected among proliferants. Combat aircraft are already available in every country that has or is suspected of acquiring WMD, and many are being modernized. All armies have artillery that could be adapted to deliver WMD.

Country	Sec 1.1 Theater Ballistic Missiles	Sec 1.2 ICBMs	Sec 1.3 Cruise Missiles	Sec 1.4 Combat Fixed-Wing Aircraft	Sec 1.5 Artillery
Argentina	♦♦	♦♦	♦♦	♦♦	♦♦♦
Brazil	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
Canada	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Chile	♦	♦	♦	♦	♦♦♦
China	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
India	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦
Iran	♦♦	♦	♦♦	♦♦	♦♦♦
Iraq	♦♦	♦	♦♦	♦♦	♦♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Japan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦	♦	♦	♦	♦♦♦
North Korea	♦♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦
Pakistan	♦♦	♦♦	♦♦	♦♦	♦♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
South Korea	♦♦	♦♦	♦♦	♦♦	♦♦♦♦
Sweden	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Syria	♦♦	♦	♦	♦	♦♦♦
Taiwan	♦♦♦	♦♦	♦♦♦	♦♦	♦♦♦♦
Ukraine	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Notes: Each delivery system column reflects the technologies listed in greater detail in the section describing that delivery system.

The technology columns listed in the Foreign Technology Sections on the individual delivery systems refer to technologies that one or more of the listed countries may need. Lack of capability in one technology does not indicate a country has limited capability. It may indicate the country is pursuing a different technology solution.

Figure 1.0-1. Means of Delivery Foreign Technology Assessment Summary

SECTION 1.1—THEATER BALLISTIC MISSILES (TBMs)

OVERVIEW

The Theater Ballistic Missiles (TBMs) subsection describes the technologies that a nation can employ to build a TBM and the associated means by which they can use it. The U.S. Government defines a TBM as a ballistic missile with a range of less than 3,500 km. Except where noted, this document will use that definition. This subsection emphasizes those technologies that improve accuracy, reduce intercept at boost, increase lethality, and assist a country in extending the range of its missiles, transporting and launching the missiles clandestinely, and building them in sufficient numbers to achieve its objectives. The tables tabulate technologies or their adaptation to entire missiles and their subsystems. They are ordered as follows: *airframe; propulsion; guidance, control, and navigation*; and *weapons integration*.

When a proliferant seeks a range extension from an existing airframe, it may need to strengthen the airframe if the original missile had a low factor of safety. This is necessary so the missile can withstand higher aerodynamic loads; change the *propulsion* subsystem by altering either the burning rate or the duration of propellant flow or by selecting a high-energy propellant; adapt the *guidance* system to accommodate the new acceleration loads and the higher cutoff velocities; and *weaponize* the warhead by including thermal protection on the nosetip or modifying the reentry strategy of the missile to withstand the higher aerodynamic heating on reentry.

Proliferants can modify or manufacture longer range ballistic missile airframes in several ways. Iraq extended its missile range by reducing the payload and lengthening existing airframes to hold more fuel and oxidizer. Iraq also introduced the concept of “strap-ons” to extend a missile’s range when it launched the “al Abid” in December 1990. To manufacture the “al Abid” missile, Iraq strapped five SCUDs together to form a single large missile, theoretically capable of a 2,200-km range.

Proliferants can also stage missiles in parallel or serial. The United States used a concept known as “parallel staging” to extend the range of its Atlas missile. Parallel staging fires several component engines simultaneously at launch. Then, as the missile accelerates, it drops these extra engines. When a nation possesses the technical capability to support extra range, the most efficient way to achieve it is through conventional “serial” staging, in which a missile’s stages fire one at a time in sequence. Some Chinese TBMs, such as the M-11, which may have originally been designed as a multiple-stage missile (and, therefore, has sufficient thrust-to-weight ratio), can be converted to two-stage missiles with minor modifications and modest assistance from technical experts if they are aware of certain design limitations.

Highlights

- Chemical and biological weapons are difficult to dispense efficiently from TBMs.
- Proliferants with just a few nuclear weapons may consider TBM reliability before using this means of delivery.
- Separating warheads increase the probability of defense penetration.
- Attitude control modules and post-boost vehicles increase TBM warhead accuracy.

But some constraints, such as avoiding maximum dynamic pressure at staging and timing the staging event precisely enough to maintain control over the missile, are solved when multi-stage missiles are built derived from components which originally came from a multi-stage missile.

To extend the range of liquid-fueled and solid-fueled missiles, these missiles require different adaptations to the *propulsion* subsystem. Liquid-fueled missiles supply fuel to the thrust chamber by turbopumps. To increase the range of an existing liquid-fueled missile, the proliferant must either increase the flow rate of the propellant and oxidizer or allow the missile to burn for a longer period of time. This can be accomplished by adding more propellant, which usually requires a modification to the airframe, and consideration of other factors such as structural integrity, stability, and thermal integrity. If a longer burn time is chosen, many surfaces that are exposed to the combustion process, such as jet vanes in the exhaust flow or components of the thrust chamber, may need to be modified to protect them from the increased thermal exposure. Alternatively, if the missile thrust is to be increased, the combustion chamber must be designed or modified to withstand the increased pressures, or the nozzle must be redesigned with a larger throat area to accommodate the increased mass flow rates. In addition, structural modifications may be required to compensate for the higher aerodynamic loads and torques and for the different flight profile that will be required to place the warhead on the proper ballistic phase trajectory. Usually a country will design a completely new missile if new turbopumps are available. A proliferant that wishes to increase its liquid-fueled missile’s range may need to consider upgrading all the valving and associated fluidic lines to support higher flow rates. The proliferant will seek lightweight valves and gauges that operate with sub-millisecond time cycles and have a reliable and reproducible operation time. These valves must also accept electrical signals from standard computer interfaces and require little if any ancillary electrical equipment. A country may use higher energy propellant combinations in existing missile designs with relatively minor structural, material, and turbopump modifications. Technology requirements would focus on thermal protection for the thrust chamber and improved injector design.

A solid-propellant missile differs in overall operation because it simply burns propellant from an integral motor chamber. A proliferant seeking to make longer range solid missiles generally has to stage the missile (either in parallel or serial); strap on additional whole motors or motor segments; improve the stage fraction; or improve the propellant. When a nation chooses to stage an existing missile, it may be able to procure the first stage of a serially staged design, which is larger and more difficult to manufacture, and simply add an indigenous smaller upper stage of its own. A key determinant of a missile's utility as a first stage is the performance specification of thrust-to-weight ratio. Whole missile systems used as a first stage must produce a thrust-to-weight ratio greater than one for the entire assembled multi-stage missile. Missiles that may fall below the Missile Technology Control Regime (MTCR) guidelines are still of interest because they might be used by proliferants as upper stages of serial staged missiles or as strap-ons.

Once a country can indigenously produce a solid rocket motor, few, if any, components do not automatically scale from more basic designs. If a proliferant desires a more advanced solid rocket fleet, it may choose to build the missile case from carbon graphite or more advanced organic matrix materials. To support this, it will need to import either filament winding machines, an equivalent manufacturing process, or the finished motor cases. A proliferant might import the finished filament wound cases without propellant if it chooses to use a manufacturing technique pioneered in the former Soviet Union known as "cartridge loading." Cartridge loading allows the propellant to be inserted into the case after it is manufactured. The competing manufacturing procedure, known as "case bonding," usually requires the case, propellant, and insulating liner to be assembled in close proximity at the same site, though it is still possible to import empty cases for case bonding. Designs employing propellants with higher burning temperatures require many supporting components, including better insulating material to line the inside of the rocket case and stronger or larger thrust vector control actuators to direct the increased thrust.

The three separate flight functions performed by the *guidance, control, and navigation* subsystem generally require separate technical considerations. Guidance refers to the process of determining a course to a target and maintaining that course by measuring position and attitude as the missile flies (while, at the same time, steering the missile along the course). Control generally encompasses the hardware and software used during the missile's burn phase to change the missile's attitude and course in response to guidance inputs and to maintain the missile in a stable attitude. Navigation concerns locating a target and launch point and the path that connects them in three-dimensional space. An effective design requires that all three functions operate in concert before and during flight for the missile to reach its target. Some of the hardware and software in each feature overlaps functions.

The aerodynamic and inertial properties of the missile and the nature of the atmospheric conditions through which it flies determine the speed with which guidance commands need to be sent to the control system. First generation TBMs, such as the SCUD and the Redstone, have fins to damp out in-flight perturbations. The rudimentary guidance systems used in these missiles do not support rapid calculations of position changes. When a missile's thrust vector control system becomes responsive enough to overcome these perturbations without aerodynamic control surfaces, these fins are usually removed from the design because their added weight and aerodynamic drag diminish the missile's range.

Most TBM designs have a resonance around 10 Hz (cycle time of 100 milliseconds). Calculations to correct disturbances must occur within this cycle time. Guidance and control engineers generally add a factor of safety of two to their cycle time or, in other words, half the cycle time. When thrust vectoring is the exclusive control standard of a missile, the system must respond or have a major cycle time of 50 milliseconds or less. When fins are used, the control cycle time for a missile may be much longer than a second.

As the guidance and control subsystems work together to keep a missile stable and flying on its trajectory, all the components of these subsystems must operate within the major cycle time. Guidance computers, for instance, have to accept acceleration, angular position, and position rate measurements; determine if these positions are proper for the missile's course; and correct any deviations that have occurred in the flight profile. Computers of the i8086 class, and later, are capable of making these calculations in the times required. In addition to the calculation procedures, all the control hardware must reliably and repeatedly accept the control signals generated by the flight computer and effect the commands within the cycle time. Since some of these operations must occur in a specific sequence, the sum of all operational times in the sequence must be much shorter than the major cycle time. Therefore, valves, electric motors, and other actuators must produce steering forces within 50 milliseconds to support an unfinned ballistic missile control system. When the missile has fins, the allowable response times increase, permitting the hardware operational specifications to be greatly reduced.

In addition to the cycle time, the control subsystem must also hold the missile within acceptable physical deviations from specified attitude and velocity during its short burning period. Missiles with autonomous control systems generally rely on acceleration measurements rather than position measurements to determine attitude and position rates. However, positional indications can be substituted if the positional variables can be determined quickly and accurately enough. Position measurements reduce the control system cycle time by generally reducing the computer integration of accelerations that are required to determine position. Positional measurements also do not suffer the degradation in performance that occurs with time, acceleration force, and vibrations on measurement instrumentation that supports acceleration measurements.

Multi-source radio signals that allow a triangulation of position offer an alternative to acceleration measurements. Advanced missile powers dropped radio guidance in the 1960's and switched to autonomous inertial measuring units, which are carried onboard the missile. The United States considered radio guidance again in the late 1980's for mobile missiles but dropped the idea in favor of a Global Positioning System (GPS). Nonetheless, if a proliferant chose to build a radio guidance system, it could transmit signals from the launch site, or it may build an accurate transmitter array near the launch site to create the signals. Guidance engineers often refer to this latter technique as using pseudolites. However, radio command and control schemes, because of the immediate presence of a radio signal when the system is turned on, alert defenses that a missile launch is about to occur. However, performance for these systems degrades because of the rocket plume and radio noise. Also, these systems are very much subject to the effects of jamming or false signals.

On the other hand, GPS and the Global Navigation Satellite System (GLONASS) are unlikely ever to be used in the control function of a ballistic missile. The best military grade GPS receivers produce positions with an uncertainty of tens of centimeters. If a missile has two of these receivers in its airframe spaced 10 meters apart, the best angular resolution is roughly in the centi-radian range. TBMs require milliradian range angular accuracy to maintain control. However, GPS has significant application for an TBM outfitted with a post-boost vehicle (bus) or attitude control module that navigates a reentry vehicle to a more accurate trajectory.

Older, less-sophisticated guidance systems perform less navigation than modern TBMs. In the older TBMs, a launch crew sets the azimuth to the target at a mobile site and the control computer determines when the missile is traveling at the proper velocity and velocity attitude angle to achieve the desired range. These three properties, in addition to random winds at the target and errors that accrue in the guidance instruments, uniquely determine where the missiles land. Any technologies that allow a proliferant to position and target its missiles in the field quickly reduces the time defending forces have to target and destroy the missile. GPS allows a mobile launch crew to operate more quickly in the field when not launching the missile from a presurveyed launch site.

When no in-flight update of position is given, a crew must set a reasonably accurate azimuth before the missile is launched. To be consistent with the overall accuracy of an older missile, such as the SCUD, which has a non-separating warhead, the crew must strike an azimuth line within 1 milliradian of the actual azimuth to maintain a satisfactory cross range accuracy. With military grade GPS receivers of 1–3 meter accuracy, the launch crew must survey no further than 1 km from the actual launch point to support a 1-milliradian azimuth. Pseudolites or differential GPS will either reduce survey distance required or increase accuracy—whether using military or civilian GPS signals.

Any technologies that allow for the separation of a reentry vehicle after the boost phase assist the proliferator in two ways. First, a separating warhead is often more accurate than a warhead that reenters while still attached to the main missile body. Secondly, the separated warhead produces a much smaller radar cross section (RCS), thus making the warhead harder to locate.

Technologies that assist a country in separating its warheads and producing a clean aerodynamic shape for reentry include computer aerodynamic prediction routines, nosetip materials that can withstand higher aerodynamic heating, and space-qualified small missile motors that can steer out accumulated error. Hardware that assists in separating a warhead from a booster includes timing circuits, squibs, and other cutting charges, and if accuracy is an issue, an alignment mechanism. This mechanism might be as simple as aerodynamic fins that unfold upon reentry.

RATIONALE

TBMs can carry a conflict outside of the immediate theater of fighting and can usually penetrate to their targets. Iraq's limited capability missiles made an impact by tying up allied air assets on seek-and-destroy missions against mobile launchers and in the other steps taken to calm Israeli and Saudi populations. Extant whole *missile systems,* such as the SCUD and SS-21, can satisfy the targeting needs for many proliferators.

A proliferator's potential ability to upgrade existing, outmoded missiles (e.g., short-range SCUDs) is quite real. Much of the hardware and technology to support many of the modifications described in the Overview are readily available or can be produced indigenously. However**,** some of the hardware and technology (those requiring more advanced technology, special materials, and/or precise manufacturing) are not readily available and may require special design and production efforts by more advanced countries. A proliferator can achieve an understanding of the most efficient and cost-effective methods to extend the range of a missile by using finite element structural and fluid dynamic computer routines and automated codes to predict missile performance and aerodynamic properties. A proliferator can also test and validate the computer routines in wind tunnels and structural laboratories. Since these computer routines reduce the number of engineers needed to modify missiles, they are particularly key to reducing both the unit and system costs. Automated engineering computer routines are ranked at the same level of importance in the technology tables as hardware items.

The type of propulsion system selected also affects *launch strategy*, the second important proliferant capability. Liquid-propellant missiles generally create less of a military threat than solid-propellant missiles. Solid-propellant missiles are stable and storable and do not require fueling before launch, a time when the missile is particularly vulnerable because of its exposure. In addition, solid-fueled missiles have a shorter launch support train than liquid-fueled missiles. Fewer vehicles and less activity associated with the vehicles limits exploitation of acoustic, seismic, and other signatures.

The enormous progress made in guidance and navigation with the GPS, particularly in automated design with computer routines such as finite element codes and in materials science with the introduction of composite materials, has further reduced the design burden on proliferants seeking TBMs. Transferred to proliferant nations, these advances streamline the manufacturing processes, which accelerate and expand the potential for a missile arsenal.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.1-1)

Several countries purchased SCUDs up to the end of the Cold War, and many of these countries still have arsenals of varying size and threat. These countries include Afghanistan, Egypt, Iraq, Iran, Libya, Syria, and Yemen. The Soviets also sold Syria, Yemen, and possibly Libya, the shorter range SS-21 missile. Egypt, Iraq, Iran, and North Korea all display the manufacturing base and technical prowess to make range extension modifications similar to those that Iraq accomplished before the Gulf War.

In addition to these countries, several nations have built or attempted to build their own TBMs. An inherent capability to produce unique and totally indigenous missiles exists in these countries: Argentina, Brazil, India, Iran, Iraq, Israel, North Korea, Pakistan, South Africa, and Taiwan, and nearing production in Syria. Iran and Iraq must import the guidance and control systems of these missiles; however, beyond those constraints imposed on Iraq by UN sanctions, it has no limitations on its ability to produce 600-km range TBMs.

Systems

Both China and North Korea continue to sell missile technology and missile systems. Also, North Korea continues to sell missiles abroad. North Korea has offered the 1,000-km-range No Dong missile, and the Chinese sold between 30 and 50 CSS-2's, a 2,200-km-range missile, to Saudi Arabia in the late 1980's. Apparently, the Israeli government acted as an intermediary for shipping Lance missiles to the Taiwanese. Lances are a short-range nuclear delivery system that the United States based in Europe. They can be reverse engineered to serve as strap-ons for existing missiles.

Each TBM may cost as little as $1.5 million dollars, so a proliferator with even modest resources can afford to build a sizable missile force. If a country seeks autonomy from the world market and wishes to build its missile indigenously, it can purchase a manufacturing plant from the North Koreans or Chinese for about $200 million and purchase critical parts, such as guidance systems, elsewhere. To develop complete autonomy requires a capital investment of about $1 billion dollars.

Technical Assistance

Besides whole systems, many corporations and nations have offered technical assistance during the last 10 years to some emerging missile powers. German firms reportedly assisted the missile programs of Argentina, Brazil, Egypt, India, Iraq, and Libya. Italians have offered assistance to Argentina, Egypt, and India, and the French have participated in missile programs in Iraq and Pakistan.

Most European countries can lend technical assistance to emerging missile powers. The French have a long history of developing missiles not only to support the Ariane space launch capability but to launch the *force de frappe* nuclear arsenal. The Italians have participated in the European Union space program that helped design and prototype the *Hermes* missile. While the British relied on American missile programs to supply their TBM needs in the 1960's, a technical exchange program between Britain and the United States has trained and educated a sizable pool of missile talent from the British Isles. Many Western European nations and Russia are in the process of downsizing their defense industries. As many as 2 million physicists and engineers may become available over the course of the next decade.

As of 1997, the U.S. Government lists at least 11 countries outside of the Former Soviet Union (FSU) and China with programs for producing an indigenous missile. Most of these programs are technologically sophisticated enough to produce a militarily threatening system in a relatively short time. Guidance systems are the principal impediment to most countries in developing their own missile, followed by propellant manufacturing and warhead mating to prevent failure caused by the heat of reentry and vibration during boost.

Country	Airframe		Propulsion			Guidance and Control			Weapons Integration		
	Airframe Extension to Liquid-Fueled Missiles	Post-Boost Vehicles	High Energy Solid-Fuel Motors	Storable Liquid Propellant Engines	Strap-on Boosters	Floated Inertial Measure-ment Units	Digital Navigation and Control	Post-Boost Position Realign-ment and Spin	Bomblets or Submun-itions	TEL Manufac-turing	Separating Warheads
Argentina	◆◆◆	◆	◆◆◆	◆◆	◆◆◆	◆◆	◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆
Brazil	◆◆◆◆	◆◆	◆◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆
Canada	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
Chile	◆◆	◆	◆◆	◆◆	◆◆	◆	◆	◆	◆	◆◆◆	◆◆
China	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
Egypt	◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆	◆◆◆	◆◆	◆◆	◆◆◆◆	◆◆◆
France	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
Germany	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
India	◆◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆	◆◆◆◆
Iran	◆◆◆	◆	◆◆	◆◆◆	◆◆	◆	◆◆	◆	◆	◆◆	◆◆
Iraq	◆◆◆◆	◆	◆◆◆	◆◆◆	◆◆◆	◆	◆◆	◆	◆	◆◆◆	◆◆
Israel	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆
Italy	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆	◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
Japan	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
Libya	◆◆	◆	◆	◆	◆	◆	◆	◆	◆	◆◆	◆
North Korea	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆	◆◆◆	◆◆	◆◆	◆◆◆	◆◆◆◆	◆◆◆
Pakistan	◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆	◆	◆◆	◆	◆◆	◆◆	◆◆
Russia	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
South Africa	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆	◆◆	◆◆◆	◆◆◆	◆◆◆
South Korea	◆◆	◆◆	◆◆◆	◆◆	◆◆	◆◆	◆◆	◆◆◆	◆◆	◆◆◆	◆◆◆
Sweden	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆◆	◆◆◆◆	◆◆	◆◆◆◆	◆◆◆	◆◆◆◆
Syria	◆◆	◆◆	◆◆	◆◆	◆	◆	◆	◆	◆	◆◆◆	◆
Taiwan	◆◆◆	◆◆	◆◆◆	◆◆	◆◆	◆◆	◆◆	◆◆◆◆	◆◆	◆◆	◆◆◆◆
Ukraine	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
United Kingdom	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆
United States	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆	◆◆◆◆

Legend: Sufficient Technologies Capabilities: ◆◆◆◆ exceeds sufficient level ◆◆◆ sufficient level ◆◆ some ◆ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 1.1-1. Theater Ballistic Missiles Foreign Technology Assessment Summary

Table 1.1-1. Theater Ballistic Missiles Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
AIRFRAME					
Complete missile systems (Propellants having >86% total solids)	Capable of delivering >500 kg to >300 km	WA ML 4; MTCR 1; USML IV	None identified	None identified	Automatic-guidance/ target-loading software
NC turning machines or NC turning/milling machines	Rotary tables >1.0 m	WA Cat. 2B; CCL Cat. 2B; NDUL 1	None identified	Optical alignment and surface finish measuring equipment; roller and thrust bearings capable of maintaining tolerances to within 0.001 in.	Machine tool control software
Acid etch metal removal	Masking and etching facilities to remove <0.001 in. layers of metal from complex shapes	CCL EAR 99	None identified	Acid baths and handling equipment	None identified
Spin, flow, and shear forming machines	Capability to manufacture curvilinear or cylindrical cross-section parts of 0.1 in. thickness or less	WA Cat. 2B; CCL 2B MTCR 3; NDUL 1	None identified	Thermal and viscosity constant flow controls	None identified
Automated welding equipment	Capable of producing longitudinal welds up to 10 m and circumferential welds on 0.8-m diameter or larger cylinders	CCL EAR 99	None identified	Jigs and frames to maintain shapes and rotate large cylinders	None identified
Composite filament winding equipment	Two or more axis control of filament placement	WA Cat. 1B; MTCR 6; CCL 1B	Aramid fiber	None identified	Helical winding logic
Composite tape laying equipment	Two axis or more control of tape placement	WA Cat. 1B; MTCR 6; CCL 1B	None identified	None identified	Tape supply and tension numerical controls
Composite weaving or interlacing equipment	Two-dimensional or more automated broad goods production of carbon carbon and woven fabric	WA Cat. 1B; MTCR 6; CCL 1B	Aramid fiber	None identified	Numerical control of the weaving process

(cont'd)

Table 1.1-1. Theater Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Hot melt prepregs for composite materials	Filament tensile strength >100,000 psi. and a melting or sublimation point >1,649 °C	WA Cat. 1C; CCL Cat. 1C; MTCR 8	Prepreg material produced from phenolic or epoxy resins	Hot melt prepreg machine	None identified
Adaptive aerodynamic control surfaces and actuators	Capable of producing a vehicle pitch rate of 1 deg/sec and control response to <10 Hz perturbations	WA ML 4, 10; USML IV; MTCR 10	None identified	None identified	Digital transducer reduction and position measurement (unless analog controlled)
Mach 0.9 and greater wind tunnels	None identified	WA Cat. 9B; MTCR 15; CCL 9B	None identified	Schlieren photography or other flow field phenomena recording instruments	Automatic data reduction software that predicts aerodynamic coefficients from subscale model force and moment measurements
Blow-down tunnels	Blow-down piping and valves to create 1.6 million Re on models of <= 2 in. length	WA Cat. 9B; MTCR 15; CCL Cat. 9B	High-pressure storage vessels; blow-down piping	Short response time instrumentation	Software for sequencing of instructions
Digital control, closed-loop vibration test equipment	Vibration spectrum between 20 and 5,000 Hz at 10 g's rms	WA Cat. 9B; MTCR 15; CCL Cat. 9B	Low impedance feedback transducers and spectral calibration equipment	Calibration equipment	Data reduction software employing advanced signal processing techniques such as Fast Fourier transform and "chirp" calculations

(cont'd)

Table 1.1-1. Theater Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
PROPULSION					
Solid propellant motors	Total impulse of >1,000,000 lb f-sec	WA Cat. 9A; MTCR 2, 20; CCL Cat. 9A; USML IV	Liners, insulation, adhesives, and case materials to withstand high pressures (2,500 psi or greater) and temperatures (2,400 °F or greater)	High-energy x-ray machines; rocket test stands; CT machines	None identified
Liquid propellant engines	Total impulse of >1,000,000 lb f-sec	WA Cat 9A; MTCR 2, 20; CCL Cat. 9A; USML IV	Valves and piping with flow-control deviation no greater than 0.5% and duty cycle timing deviation <20 msec	Rocket test stands; valves and piping with flow control deviation no greater than 0.5% and duty cycle timing deviation <20 msec	None identified
Solid propellants	Solid composite propellant that produces a theoretical sea-level Isp of 255 sec	MTCR 4; CCL Cat. 1C; USML V	Appropriately sized, sufficiently pure and uncontaminated oxidizer, fuel, and additives	"T cell" propellant burners and equipment instrumented to detect flow oscillations in segmented solid rocket grains	Programs that calculate thrust time traces for given internal grain cutouts
Ultrafine ammonium perchlorate (UFAP) size filtration and size gauges	The principal energetic ingredient within a solid-propellant formulation providing oxygen or oxidizing species to react with fuel	WA ML 8; USML V; MTCR 4; CCL Cat. 1C	Uniformly fine (5–50 μm) ammonium perchlorate or energetic oxidizers such as RDX, ADN, CL-20, HNF, and HAN	Electrolytic cells, crystallizer and separator to produce uniform particles of pure AP. Other energetic oxidizers now being considered for ballistic missile application require unique production equipment not yet identified	None identified
Solid propellant additives	Additives used to modify propellant burning rate, viscosity, curing rate, bonding, moisture resistance, chemical deterioration, and aging	WA ML 8; USML V; MTCR 4; CCL Cat. 1C	MAPO, TEPAN, Catocene, Butacene	None identified	None identified
Turbopumps	Shaft speeds >8,000 RPM or discharge pressures >7,000 KPa	MTCR 3; USML IV	None identified	Large torsion shaft dynamometers	None identified

(cont'd)

Table 1.1-1. Theater Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Rocket motor/engine test stands	Test stands capable of withstanding a thrust of >20,000 lb.	MTCR 15; CCL Cat. 9B; USML IV	None identified	High frame rate cameras that are shock, vibration and thermal hardened; Thrust measurement hardware	None identified
Thrust vector control (for strap-on or multiple body missiles)	Steering guidance for multiple-body missiles that produces in excess of 1 deg/ sec pitch rate and control for <10 Hz oscillations	MTCR 2; USML IV	High atomic weight injection fluid for steering and pitch control; carbon carbon or other heat and flame tolerant material for jet vanes	Thrust stand with torsional force and moment measurement capability to determine pitch and roll forces and moments	Adaptive software to calculate theoretical positional change with measured position change in flight and compensate for the difference
Telemetry or encrypted telemetry data transmission hardware	Transmission rates of 20 kbit/s or analog equivalent and operation in a high vibration environment	CCL Cat.5A-P1; USML X; WA Cat. 5A-P1; WA ML 11; MTCR 12	None identified	Calibration equipment with 100 kbit/s sample and hold capability	Encryption algorithms of DES standard 40 bit and higher
Fluid energy mills for grinding and mixing highly energetic materials	Explosion-resistant equipment designed to handle energetic materials	WA ML 18; MTCR 5; USML XXI	None identified	None identified	None identified
GUIDANCE, CONTROL, AND NAVIGATION					
Inertial measurement units	Boost cut off command signals within 0.25 deg of programmed injection angle, 2% of burnout altitude, and 1% of burnout velocity	WA ML 11; MTCR 9; WA Cat. 7A; CCL Cat. 7A; USML XV	None identified	Vibration environmental test facilities sometimes combined with centrifuges	Efficient software algorithms that support major cycle time of <50 msec.
Radio command guidance	Boost cut off command signals within 0.25 deg of programmed injection angle, 2% of burnout altitude, and 1% of burnout velocity.	CCL Cat.5A-P1; USML XV	None identified	None identified	Efficient software algorithms that support major cycle time of 50 msec

(cont'd)

Table 1.1-1. Theater Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Ground-based "GPS" systems	Position accuracy of 1 m	CCL Cat. 7A; WA Cat. 7A; MTCR 11; USML XV	None identified	Calibration test articles that can be placed in and move through the measurement field; time clocks with signal accuracy <1 micro-second	Nonlinear multiple equation solving algorithms based on matrix mathematics and Doppler corrections
Propulsion/airframe/ flight control system integration	Provide optimum system performance within confines of airframe/propulsion system architecture to meet mission requirements	WA ML 11; MTCR 10; USML XV	None identified	Six degrees of freedom computer model	Source code for CAD/CAE
Thrust vector control technologies	Missile pitch rate of 2 deg/sec	MTCR 2; USML IV	None identified	None identified	Efficient software algorithms that support major cycle time of <50 msec
High-frequency piezoelectric instrumentation	Pressure gauges with 25 khz response and 0.1% linearity; Force transducers with <50 Hz response and 0.1% linearity	CCL EAR 99	None identified	Calibration equipment	None identified
Servo valves	Flow rates >24 liters per minute, at absolute pressures of >7,000 KPa (1,000 psi) and have actuator response time to support control of <50 msec.	MTCR 3; USML IV	None identified	Hysteresis loop measurement equipment	None identified
WEAPONS INTEGRATION					
Weapons Separation Technology	Warhead separation with no greater than 0.5 m/sec velocity change or 1 deg injection angle change	MTCR 3; USML XV	None identified	Separation firing circuits and exploding bridge wire charges with 20 msec. or less deviance	Timing circuit and sequencing logic
Ablative heat shields or whole RVs with ablative heat shields	Ablation rates of less than 3 mm/sec at 2 km/sec or greater reentry velocity	MTCR 2; USML IV	Carbon carbon or other materials with heat capacities >11 MJ/kg (5,000 BTU/lb)	Arcjets	None identified

(cont'd)

Table 1.1-1. Theater Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Heat sink or whole RVs with heat sink	Material capable of sustaining 1,000 BTU/lb.	MTCR 2; USML IV	None identified	Test ranges	None identified
Transporter/Erector Launchers (TELs) for surface to surface missile systems	Launchers capable of leveling to within 0.001 deg of Earth-centered ellipsoidal axis and with firing tables capable of 0.02-deg launch azimuth	WA ML 4; USML IV; MTCR 12	None identified	Theodolites automatic load levelers and high precision surveying equipment or GPS-based surveying equipment (or equivalent)	Automatic targeting software including geographic algorithms that calculate trajectory corrections for difference in launch and target point elevations
Safing, arming, and fuzing for chemical and biological weapons	Multi-step arming devices that arm and fuze based on telemetered radar signals, measurements of g's, barometric pressure, flight time, altitude, or other physical variable with <50 msec response time	WA ML 4; MTCR 2; USML IV	None identified	High energy density batteries and fast rise time firing circuits	None identified
Submunitions separation or dispensing mechanisms	Designed to meet individual system mission performance requirements under worldwide environmental conditions	WA ML 4; USML IV	None identified	Aerodynamic braking hardware, parachutes, split flap control hardware	None identified

Table 1.1-2. Theater Ballistic Missiles Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
AIRFRAME			
Complete missile systems (Propellants having >86% total solids)	Longer range missiles can be constructed from existing airframes by clustering engines, booster strap-ons, and stretched tanks	Ranges above 1,000 km allow proliferants to reach targets of United States interest	Cruise missiles, manned bombers and tactical aircraft
NC turning machines or NC turning/ milling machines	Bell-shaped missile nozzles are difficult to make without numerical control	All TBM systems	Non-NC turning/milling machines
Acid etch metal removal	Control and removal of material	Additional payload may replace removed structural and excess structural material mass	Machining of complex contours
Spin, flow, and shear forming machines	Designing and forming complex shapes that are required for aerodynamic or structural efficiency	Increases either range or payload capability	Sheet metal brakes and stamping equipment
Automated welding equipment	Air frames are structurally stronger and aerodynamically smoother with advanced welding techniques	Reduces unpredictable flight characteristics improves accuracy	Conventional welding
Composite filament-winding equipment	Higher strength-to-weight ratio materials allow use of high Isp solid propellants	High Isp solid-fueled rockets yield significant range increases and are easier to fire and maintain	Steel cases
Composite tape-laying equipment	Higher strength-to-weight ratio materials allow use of high Isp solid propellants	High Isp solid-fueled rockets yield significant range increases and are easier to fire and maintain	Steel cases
Composite weaving or interlacing equipment	Higher temperature performing materials	All TBM systems	Metal or ceramic nozzle throat sections and heat sink re-entry vehicle nose tips
Hot melt prepregs for composite materials	Reduces use of more costly and difficult methods to create uniform resin/filament composite	May be used to manufacture solid-propellant rocket cases for higher range and payload performance	None identified
Adaptive aerodynamic control surfaces and actuators	Solving the guidance equations in a closed loop(s) to create adaptive changes in near real time	More accurate boost-phase guidance produces lower CEPs	Open loop guidance with error corrections performed by a post-boost vehicle or Attitude Control Module (ACM)
Wind tunnels capable of Mach 0.9 or greater	Studies of high ballistic coefficient reentry vehicles requires speeds >Mach 0.9	More accurate reentry vehicles for better CEP and maintaining better control by retaining more of the reentry velocity	Flight testing

(cont'd)

Table 1.1-2. Theater Ballistic Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Blow down tunnels	Provision of pressurized gas supply and instrumentation capable of simulating flight conditions beyond those provided by continuous flow wind tunnels	Indigenous research in aerodynamic variables leading to better flight predictions and lower CEPs	Extrapolations from lower Reynolds number subscale models
Digital control, closed-loop vibration test equipment	Prediction of vibration modes	Structural efficiency increases range and/or payload capability	Analog computers or finite element codes without experimental validation
PROPULSION			
Solid propellant motors	Casting and curing either case-bonded or cartridge-loaded propellant without cracking or delaminations	Indigenous production of second stages for existing missiles allows a proliferant to extend range	Liquid propellant engines
Liquid propellant engines	Increasing the propellant flow rate and combustion chamber pressure/ temperature, by using such processes as regenerative cooling, without damaging the engine	Engines in existing missiles can be replaced with higher performance engines for extended range or payload	Solid propellant motors
Solid propellants	Increasing the Isp of the propellant	Solid propellant missiles are difficult to locate and target because of their simplicity, storability, and smaller support train	Liquid propellants
Solid propellant oxidizers	Increasing the oxidizer efficiency and supporting faster burn rates by the reduction in particle size	Better oxidizers provide a more efficient, longer range missile	None identified
Solid propellant additives	Achieving the desired propellant properties (e.g., burn rate, deflagration control, flow stability) with unconventional materials	Propellant signature modification disguises a launch for cueing satellites, which direct missile defense batteries	None identified
Turbopumps	Increasing propellant and oxidizer flow to the thrust chamber	Modern, higher performance turbopumps make liquid propellant missiles more reliable	Ullage tanks

(cont'd)

Table 1.1-2. Theater Ballistic Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Rocket motor/engine test stands	Accurately measuring the force and torsional response of the stand to generate an accurate thrust time profile	Thrust time profiles allow proliferants fly on unusual trajectories (e.g., depressed or lofted)	None identified
Thrust vector control (For strap-on or multiple body missiles)	Predicting the proper mixture ratios and flow rates under dynamic conditions to precisely control the flight	Compensate for misfired cluster engines and control the flight path of the missile	Aerodynamic surfaces
Telemetry or encrypted telemetry data transmission hardware	Real time encryption and transmission of data from a moving vehicle	Prevents observers from understanding the intention of the missile flight and static test programs	Open channel communication
Fluid energy mills for grinding and mixing highly energetic materials	Safety of personnel and facilities	Manufacture of high Isp propellants and oxidizers	Older, more dangerous facilities
GUIDANCE, CONTROL, AND NAVIGATION			
Inertial measurement units	Low drift rate and g insensitive response in accelerometers and gyros	Reduced CEP to support military targeting	Radio command guidance; Ground-based GPS
Radio command guidance	Line-of-sight command guidance	Highly accurate guidance for reduced CEP that does not require extensive improvement in gyros or accelerometers	Ground-based GPS; IMUs
Ground-based "GPS"systems	Signal timing and transmission	Jam-free, highly accurate, boost-phase guidance for reduced CEP	IMUs; Radio command guidance
Propulsion/airframe/flight control system integration	Aligning guidance and control system inertial space reference with geometric reference of airframe	Reduced CEP and higher azimuth accuracy	Post boost vehicles and ACMs which steer out boost inaccuracy
Thrust vector control technologies	Making adaptive corrections for a variety of flight profiles	Supports real time targeting by allowing variable flight profiles to be used as military situation changes	Aerodynamic control surfaces such as fins
High-frequency piezoelectric instrumentation	Reducing or transmitting data and evaluating the data from flight tests, static tests or actual launches	All military air vehicles	Low frequency analog transducers

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Table 1.1-2. Theater Ballistic Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Servo valves	Making control loop time constant consistent with flight requirements	Lower time constant servo valves increase the range of the missile by allowing the removal of fins or other aerodynamic controls surfaces or increase the accuracy on finned missiles	None identified
WEAPONS INTEGRATION			
Weapons Separation Technology	Incorporating separating warheads into the flight profile	Separating warheads reduce the CEP error contribution during the reentry phase of flight; complicates defense	Non-separation of warheads
Ablative heat shields or whole RVs with ablative heat shields	Reducing ablation rate of the nose tip	Ablative heat shields permit the design of high ballistic coefficient re-entry vehicles which have better penetration of missile defenses	Low-ballistic coefficient re-entry with blunt-nosed re-entry vehicles
Heat sink or whole RVs with heat sink	Building heat sinks into a warhead without decreasing the packing fraction to unacceptable levels for high ballistic coefficient vehicles	Heat sinks may be used with biological warheads when the packing fraction is not as important as lowering the exposure temperature of a live agent	Low-ballistic coefficients reentry with blunt-nosed re-entry vehicles
Transporter/Erector Launchers (TELs) for surface to surface missile systems	Reducing the setup and strike down time for launch operations and remote location azimuth of mobile launches	Reduced operation times lower the possibility of counter battery fire to destroy the TELs which are high-value components of a missile force	Fixed launch sites
Safing, arming, and fuzing for chemical and biological weapons	Reducing the compound probability of failures of multiple step arming, safing, fuzing, and firing operations	Allows for more accurate and effective delivery of chemical and biological warheads	Single-stage timing devices, g sensors or altimeters
Submunitions separation or dispensing mechanisms	Separating submunitions without inducing additional velocity or injection angle error and maintaining the viability of warhead	Allows for more accurate and effective delivery of chemical and biological warheads	Maneuvering re-entry vehicles

SECTION 1.2—INTERCONTINENTAL BALLISTIC MISSILES (ICBMs)

OVERVIEW

The Intercontinental Ballistic Missiles (ICBMs) subsection continues the description of missile technology that was begun in the TBM section and extends it to the additional technologies that a nation needs to increase the range of its missiles to intercontinental distances (>5,500 km). ICBMs are particularly troubling to the world community because they have few, if any, distinguishing characteristics from space launch vehicles. Many nations can build an ICBM capability while claiming to be building a space launch fleet. Few would question, for instance, India's assertion about the benefits of a communication satellite to link remote regions in its country or a meteorological satellite to predict the path of monsoons. If a country chooses to further assert that national sovereignty compels it to build its own launch vehicle, the world community has few legitimate reasons to argue.

In the last 20 years, several countries have built, or sought to build, missiles with an intercontinental reach, usually under the auspices of a space launch capability. France led the way with the introduction of the S-2 launch vehicle in the late 1960's. Derivatives and motor technology from their S-2 missile assisted France in developing its Ariane space launch vehicle, which competes directly with the American Delta class space vehicles. Israel demonstrated the technical capacity to put a satellite in orbit in 1991, indicating to the world that it could deliver WMD to any spot on the globe.

Space launch programs came out of South Africa and India in the late 1980's. The South Africans constructed an especially credible prototype for a three-stage launch vehicle that had immediate use as an ICBM. Finally, Iraq showed that a long-range missile did not necessarily have to be built from the ground up. With the help of foreign consultants, Iraq test fired the al Abid Space Launch Vehicle in December 1990. The al Abid consisted of five SCUD missiles strapped together to form a lower stage, which was designed to boost two upper stages, together with a payload, into orbit. The al Abid did not work as predicted, and, if it had, it would have put only a few kilograms of useful payload into orbit. As an ICBM, though, it established the possibility of building a long-range rocket from dated technology. The various technologies will be addressed as complete *systems* and as *subsystems.*

Systems

Iraq built its al Abid capability with the direct assistance of foreign scientists and engineers and by attempting to purchase technology, such as carbon-carbon materials, for rocket nozzle throats and nosetips directly from foreign companies. The multiple uses for aerospace materials and the development of aerospace consortiums have multiplied the number of sources of research talent and manufacturing industries that a potential proliferant nation can tap for assistance in building an ICBM.

Highlights

- Strap-on boosters are an attractive method to develop ICBMs quickly.
- Serially staged missiles deliver the most payload per unit weight, but are more difficult to make.
- ICBMs cost a proliferant 20 to 60 times as much as a TBM for the same payload.
- Proliferants will need to manufacture Transporter-Erector Launchers (TELs) if they seek a mobile missile capability, or build hardened shelters if they wish to protect ICBM.
- Chemical and biological agents are difficult to dispense effectively from an ICBM.
- A proliferant may solve the ICBM re-entry heating problem by building a less accurate, low ballistic coefficient re-entry vehicle.
- A post-boost vehicle provides a means of delivering WMD accurately from an ICBM.

These foreign outlets have also exposed the proliferant world to the high expense associated with building an ICBM. In the late 1980's, Iraq could afford to trade some of its oil wealth for the cost of buying the entire corporate talent of one research and development (R&D) firm. Most economies that can sustain such a high level of funding are either already building space launch vehicles (France and China), are in a multilateral arrangement to build one (Germany, Great Britain, Italy), or have recently abandoned building one because of market forces (South Africa).

ICBM attacks must also be effective because a launching nation will get few opportunities to continue the attack. The simple cost of an ICBM limits the total size of a missile inventory. This decreases the potential for sustained firing of ICBMs, a tactic used to disrupt a society by the threat of repeated chemical weapons attacks by long-range missiles.

If a country seeks to launch an ICBM, it must either launch the missile from a vulnerable fixed launch site, harden the launch site for better survivability against attack, or invest the additional expense in building a mobile transporter-erector launcher (TEL). Use of vulnerable, fixed launch site ICBMs provides opportunity for opposing forces to eliminate most of these sites quickly. Hardened launch sites are difficult to reload quickly and thus damper a sustained firing tactic. Without the use of fixed launch sites, a nation must rely on mobile launchers. Making enough mobile launchers to support a long missile campaign is an expensive endeavor. It also lessens the possibility of a sustained firing. A small ICBM that delivers 500 kg of payload to a distance of 9,000 km will weigh between 15,000 and 22,000 kg, depending on the efficiency of the design and the sophistication of the technology involved. The FSU and the United States have built TELs to handle missiles of this mass.

Chemical or biological agents are not spread efficiently by the flight path that an ICBM follows. The high velocity along the flight azimuth makes it almost impossible to distribute airborne agents in an even and effective cloud. Submunitions make the problem somewhat more tractable, but the submunitions still require a very capable propulsion system if they are to cancel the azimuthal velocity and impart a cross range velocity to circularize the distribution of an agent cloud. Other problems abound: U.S. experience with fuzes for ballistic missiles showed that much less than 10 percent of chemical and biological agents survived the launch and delivery sequence. Iraq used fuzing for its chemical warheads on its TBMs that would have allowed less than 1 percent of the agent to survive.

The most sensible warhead for an ICBM to carry is a nuclear weapon, and the weaponization section concerns itself primarily with the weaponization of ICBMs to carry nuclear warheads.

Subsystems

Some of the same technologies for extending a TBM's range provide extra capability to build an ICBM. An ICBM may include strap-ons, a clustered combination of single-stage missiles, "parallel" staging, and serial staging. Iraq increased the range of its missile fleet by reducing the weight of the warhead in one case (the al Hussein missile) and extending the propellant and oxidizer tanks and increasing the burn time in another (the "al Abbas" missile). The particular path that Iraq followed in making the "al Abbas" out of SCUD parts is not technically practical for building an ICBM. An *airframe* must have a thrust-to-weight ratio of greater than one to lift off, and a SCUD airframe cannot be extended sufficiently to reach intercontinental ranges and still lift off with the current turbopump, given its low stage fraction (the ratio of burnout weight to takeoff weight—a strong measure of missile performance). Building a new turbopump that provides the needed take-off thrust and also fits within the airframe is a more difficult task than simply building a new and much more capable missile from scratch.

Both strap-ons and parallel staging provide ways for a proliferant to reach an ICBM capability. Many countries have built small, solid rocket motors that can be tailored to fit within the MTCR guidelines. A number of these motors strapped on to a reasonably capable main stage, such as the S-2, would resemble the Ariane launch vehicle. The country that pursues this path requires a firing sequencer that can ignite all the motors simultaneously. Strap-ons generally operate for a short fraction (roughly one-third) of the total missile burn time of an ICBM. If they are dropped off, the guidance and control requirement can be met by using the main engine thrust vector control to steer the whole assemblage. Aerodynamically, the strap-ons behave much as fins in the lower atmosphere, increasing the amount of total cycle time available for the guidance computer to operate.

Parallel staging offers many of the same advantages for liquid rockets that strap-ons do for solid rockets. The United States built the Atlas missile as a parallel staged rocket because, in the 1950's, it was the quickest path to developing an ICBM to meet the Soviet challenge. A liquid-fueled, parallel-staged rocket draws propellant and oxidizer from existing tanks but feeds it to several engines at once to sustain the proper thrust level. When these engines are no longer needed, they are dropped. The tanks, however, remain with the missile so a parallel-staged missile is not as efficient as a serially staged missile.

As many designers already know, and most textbooks prove mathematically, a serially staged missile is the best design to deliver a payload to long distances. Examples of an optimal, serially staged ICBM include the U.S. Peacekeeper missile and the Soviet Union's SS-24. Each of these missiles can reach 11,000-km range and carry up to 10 nuclear warheads. In an optimum serially staged configuration, each stage contributes about twice as much velocity as the stage that preceded it, though many effective ICBMs can be built without following any particular design guideline.

To be capable of an 11,000-km range, the ideal ICBM would be composed of four stages. The United States and the Soviet Union both ignored this consideration, though, because of concerns about the overall reliability of the missile. The ignition of each stage in sequence at the staging interval is difficult to time properly, and, inevitably, some period occurs during this staging event when the control authority over the missile is at its worst. To reduce these events and improve the overall reliably of the missiles, the superpowers chose to trade performance for fewer stages.

A proliferant that does not buy a fully equipped ICBM must solve this same staging sequence problem. The technologies to build event sequencers and the short duration, reproducibly timed squibs, exploding bridge-wires, or other stage separation shaped charges to support these sequencers are among the most sensitive material to be controlled in trying to prevent the proliferation of ICBMs.

If a proliferant clusters existing single-stage missiles together, it must consider the *guidance and control* implications of the design. Several ordinary single-stage missiles grouped together make a very stout planform with a high lateral moment of inertia. To *control* this missile, the thrust vector control system has to produce much greater torque on the airframe than it would for an equivalent mass that is long and thin, as are most missiles. The high moment of inertia, in turn, requires either higher actuation strokes in a thrust vector control system, which reduces the thrust available for range, or a much larger liquid injection system, which reduces the weight available for propellant and again reduces the range. On the other hand, simple thrust vector control strategies, such as vernier nozzles and fluid injection, can satisfactorily control the missile. A proliferant only needs to build the fluidics to support these schemes: fast acting valves and the actuators to control these valves. The same types of valve and piping concerns that are covered in the tables for TBMs apply to the fluid system of an ICBM.

A serially staged missile forces a designer to carefully consider the control of a more dynamically complex vehicle. The stages and interstage breaks make the structure of a serially staged missile behave under some loading conditions as a series of smaller integral segments attached at points with flexible joints. This construction has natural frequencies that are different than a single, integral body, such as a one-stage missile. If flight conditions excite any of these many and complex resonant modes in the missile stack, the guidance and control system must supply the correct damping motion, in frequency or duration, to prevent the missile from losing control. Some of the corrections affect the guidance of the missile, and the flight computer must determine the proper steering to return the missile to its predicted trajectory. A proliferator may use many existing finite element routines and modal analysis hardware to find or predict these frequencies.

In addition to the hardware, a requirement exists to test and validate the computer routines in wind tunnels and structural laboratories. Since these computer routines reduce the number of engineers needed to modify missiles, they are particularly key to reducing the cost of individual missiles. For this reason, automated engineering computer routines are ranked at the same level of threat in the technology tables as hardware items.

The guidance and navigation systems of an ICBM closely mirror those that are used in a TBM, and anyone who has passed through the phase of building a TBM can possibly scale up a version of the guidance system suitable from the earlier missiles. The mathematical logic for determining range is different for ICBMs than for TBMs if a digital guidance computer is used rather than a pendulous integrating gyro accelerometer, which is the standard for most TBMs. However, many text books derive the equations of motion for digital guidance computers. Errors created by the guidance system feedback instrumentation during the boost-phase can be corrected later in the flight with post-boost vehicles (to be discussed in the weaponization section). *Navigation* technologies, beyond the issues already discussed for TBMs, can be applied in this same post-boost vehicle.

The *propulsion* system of ICBMs can be either liquid or solid fueled (or in some cases a hybrid of the two). A proliferator that understands the principles of solid fuel burning and how to shape the configuration of the internal grain to achieve the desired thrust/time trace can build any of its stages for an ICBM indigenously. Larger motors, of course, are more difficult to manufacture. The outer case of a solid missile can be made from any conventional material, such as steel, but better propellants with higher burning temperatures often require the substitution of materials with higher strength-to-weight ratios, such as Kevlar and carbon or glass epoxy. Steel cases can be used with cross-linked, double-based solid fuels, but the need for additional liners and insulation to protect the case against the higher burning temperatures of these newer propellants compromises some of the range that can be achieved by using the better propellant in the first place. Most steel cases must be produced from a material having a thickness that closely or exactly matches the final thickness of the motor case to prevent excessive milling of the material.

Filament winding technology may lay the filaments in solid motor cases in longitudinal and circumferential plies, in bias plies, and in the most structurally efficient way of all—in helically wound orientations. Any European, former Soviet, or U.S. multi-axis filament-winding machine of sufficient size can be used to wind a solid rocket motor case. The ply's winding orientation determines the structural, or stage, efficiency of the solid rocket motor.

In a liquid-fueled missile, the supply pressure to feed fuel and oxidizer to the thrust chamber may come either from creating an ullage pressure or pumping the liquids to the thrust chamber with turbopumps. Large volume flow rate pumps, particularly those designed for caustic fuels, have unique applications to ICBM construction. A proliferant may avoid the need for pumps by building tanks within the ICBM to contain an ullage pressure, which forces the liquids into the thrust chambers when the tanks are exposed to this high pressure. In most cases, ullage pressure is structurally less efficient than modern turbopumps because the missile frame must cover the ullage tanks, which are maintained at very high pressure and thus are quite heavy. However, this decrement in range performance is small. Since the technology is simpler to obtain, it may serve the needs of a proliferant. In either case, a liquid missile generally requires valves and gauges that are lightweight, operate with sub-millisecond time cycles, and have a reliable and reproducible operation time. These valves must also accept electrical signals from standard computer interfaces and require little, if any, ancillary electrical equipment.

The choice of liquid propellant may also influence other technology choices. Some liquid propellants are storable, and others must be cryogenically cooled to temperatures approaching absolute zero. The cryogenic coolers make the missile less mobile and more difficult to prepare to fire. The superpowers long ago abandoned nonstorable liquid-propellant missiles for these reasons, but a country that can support the technology to manufacture and store liquid oxygen and hydrogen may find this to be one possible path to making an ICBM.

The ICBM trajectory creates the most stressing problem for *weapons integration*, mainly because of the enormous heat load that velocity imparts to the reentry vehicle (RV). A TBM reenters the atmosphere at about 2 km/sec, and an ICBM reenters at about 6 km/sec. This increase in velocity creates more than an order of magnitude increase in associated heating.

Traditionally, ICBMs have overcome the heat load with two reentry strategies: one using a very high ballistic coefficient and one using a very low ballistic coefficient. The choice has important and mutually exclusive implications for other aspects of the design. If a low ballistic coefficient is selected for RVs, it may only require that the heat shield be built from very simple and easy to obtain material, such as cork and phenolic. These materials provide sufficient thermal protection because the velocity of the RV is dissipated high in the atmosphere and the surplus thermal energy is transferred to the shock wave that the RV creates and the turbulence of the flow in its wake. Since the RV has slowed almost to terminal velocity, the unpredictable conditions of the winds aloft reduce accuracy. A low ballistic coefficient RV may have a circular error probability (CEP) as great as 20 km from the reentry phase of its flight alone. It has, however, slowed to the point where the dissemination of chemical and biological agents is more feasible.

On the other hand, if a high ballistic coefficient is selected, the nosetip of the RV must endure temperatures in excess of 2,000 °C. Temperatures in this range call for the best thermal insulating materials possible, such as 3-d or 4-d carbon/carbon. In addition to protecting the RV from extreme heating, the nosetip must also experience very little erosion of its contour as it travels through the atmosphere. Materials that provide both of these properties are rare and generally limited to manufacture in technologically advanced countries.

Either of these reentry strategies benefits from the aid of a post-boost vehicle (PBV). The use of a PBV makes a high ballistic coefficient RV especially accurate. The PBV operates in space after the missile has burned completely. It steers out the guidance errors that have accumulated during the boost phase of the firing and puts the RV on a more accurate ballistic path. It can also be used just before the RV reenters the atmosphere to correct any errors in the flight path that have occurred because of assumptions about the Earth’s gravitational field between the launch point and the target. In a sophisticated PBV, the vehicle may realign the RV so it reenters the atmosphere with little aerodynamic oscillation. It may also spin the RV to even out contour changes in the nosetip and, thereby, reduce unpredictable flow fields around the body. The spinning gives the RV a gyroscopic inertia that damps out small perturbations in the attitude of the RV.

With a PBV, a proliferator can achieve a targeting accuracy of 500 m over an intercontinental range. In general, the PBV costs about half of the total throw weight of a missile. For these reasons, its use is traded off with chemical and biological agents payload.

The tables include technologies for extending range by simple modifications to boosters, separating a warhead so it can re-enter, making a thrust vector control system that is consistent with the higher aerodynamic and thrust loads on an ICBM, and increasing the responsiveness of thrust vector control. The tables list first the most useful technologies for range extension and for building complete motors for an ICBM. Then, they list in descending order those technologies that advance capability to (1) build a large arsenal very quickly; (2) allow a warhead to reenter the atmosphere without burning up; (3) develop more accurate warheads from the post-boost phase through the reentry phase; and (4) support an ICBM arsenal with other military equipment, such as silos or other protected launch sites. As in other subsections, each of the tabulated technologies, or adaptations of technologies, applies to a specific subsystem of the missile: *airframe, propulsion, guidance control and navigation*, and *weapons integration*. The “Foreign Technology Assessment” paragraphs explore these programs in greater depth and evaluate the technical depth of various nations that are trying to build space launch vehicles and ICBMs.

RATIONALE

ICBMs create a true proliferation problem because they enable the proliferator to break out of a regional context and move toward potential global impact. Regardless of the origin of a conflict, a proliferator may involve the entire world simply by threatening to spread the war with an ICBM. In 1991, Iraq demonstrated this principle even with the limited-range “al Abbas” missile.

Whatever unspoken protocols existed during the Cold War, they will almost certainly cease to exist when an ICBM-armed proliferator makes threats against a target. Therefore, the ICBM subsection emphasizes technologies that pose the most immediate threat against the United States and its allies, assuming that no ballistic missile defenses are readily available.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.2-1)

Systems

Seven nations—the United States, Russia, China, France, Japan, India, and Israel—have launched space vehicles, demonstrating generalized capability to build an ICBM. Israel has demonstrated the clearest link between a space launch program and a missile delivery system with the Shavit, the first Israeli satellite, and a substantial copy and scaled-up version of the Jericho II missile. Although Ukraine has not “launched” any space vehicles, it has produced large space launch systems as well as the world’s only heavy ICBM, the SS-18. Brazil is developing a sounding rocket that has applications to an ICBM program, and Pakistan has made first-generation rockets that indicate an underlying objective of developing an ICBM. No country has yet sold ICBMs abroad.

Under United States pressure, Taiwan all but abandoned its space launch program in 1993. However, a residual infrastructure of knowledge and manufacturing capability remains in Taiwan. South Korea and Indonesia, once ICBM aspirants, have also dropped their development programs in recent years because of U.S. pressure and economic forces.

No one purchaser names a possible price for the purchase of an ICBM, since none have been sold as unregulated commodities in the way that SCUDs have. However, other sales provide some indication of the rough costs. The Brazilians reportedly expected to receive in excess of $10 million each for their Condor II, whose range of 1,000 km is much less than intercontinental, and the Chinese apparently received about $20 million for each of the 2,500-km range CSS-2s they sold to Saudi Arabia. Many studies within the United States indicate that the Peacekeeper, a highly capable and advanced missile, costs the military about $65 million per copy.

At $50 million per missile, a country would need to invest about $2 billion to purchase or build 40 missiles. When this is compared to the roughly $200 million the Iraqis paid to build their Saad 16 missile manufacturing facility, it becomes clear that the economies of many countries cannot support a nuclear weapons production capability and an ICBM launch capability.

Existing ICBMs and their countries of origin include: China, the CSS-4; France, the M5 and M4; the FSU, the SS-11, -13, -17, -18, -19, -24, -25, and the SSN-20 and -23; and the United States, the MM III, Peacekeeper, and Trident.

Subsystems

A determined proliferant can make an ICBM by substituting many technologies for the ones that have been listed so far as being militarily sufficient. The proliferants that have not been named as already capable of building an ICBM—Iran, Iraq, Syria, and Libya—need to seek out certain technologies on overseas markets. The nature of an acquisition program need not reveal its intention, if substitutions for certain materials are done properly.

Hardware

Iran, Iraq, Syria, and Libya can manufacture or import steel of an equivalent grade to the material found in the early Minuteman II ICBM. If these countries seek to build a composite motor case instead, they must purchase the filament-winding machine from the United States, the FSU, France, Germany, the UK, or South Africa. The Chinese may be able to supply a reverse engineered filament winding machine based on Soviet technology.

Other than the traditional solid-propellant manufacturing centers in France, Sweden, Norway, Germany, and the United States, many other European countries with arms manufacturing centers, such as the Czech Republic, have some solid-propellant capability. In addition, Pakistan can manufacture small, solid-propellant motors that can be used as strap-on boosters. South Africa also has an indigenous solid-propellant production capability, which, if it so desired, can export small solid-propellant motors.

Proliferators that may wish to follow the liquid-fueled path to ICBMs without using strap-ons are likely to purchase turbopumps primarily from Germany, Sweden, the United States, France, or Russia.

The guidance and control package that a country needs to support an ICBM depends upon the desired accuracy it expects to achieve with its missile. Without a PBV, this accuracy is going to be poor, and more rudimentary technology can be used. Any industrial/advanced nation manufactures equipment and parts that, when properly constructed, can be used to build an inertial measuring unit. In addition to the United States, a proliferant can turn to Belgium, Germany, France, Holland, Sweden, Norway, Finland, Austria, the Czech Republic, Hungary, Russia, Italy, China, North Korea, South Korea, Taiwan, Australia, New Zealand, Egypt, or India. In general, though, a guidance and control unit, using a digital guidance computer and consistent with a staged missile, cannot be built from cannibalized parts of older, analog guidance systems.

A PBV requires a small liquid rocket motor, cold gas thrusters, or many small total impulse solid rocket motors. These motors must be supported by a small guidance, control, and navigation unit that flies with the RVs until they are dropped. GPS units have wide application for this particular phase of the ICBM trajectory. Because of existing export controls, a proliferant would have to modify an over-the-counter GPS receiver to operate at high altitude and at ICBM velocities. The knowledge of how to build a GPS receiver is now widespread, however, and many individual hobbyists have built receivers that evade these restrictions. A modified GPS receiver or a GLONASS receiver is completely consistent with the needs of a PBV.

Technical Assistance

Besides supplying whole systems, many corporations and nations have offered technical assistance in the last 10 years to some emerging missile powers. German firms reportedly assisted the missile programs of Argentina, Brazil, Egypt, India, Iraq, and Libya. The Italians have offered assistance to Argentina, Egypt, and India. The French have participated in missile programs in Iraq and Pakistan. Israel has been accused by international arms regulators of participating in technology programs that lend a country the capability to build or modify a ballistic missile. The South Africans reportedly have received significant aid from the Israelis.

Most European countries can lend technical assistance to emerging missiles powers. The French have a long history of developing missiles, not only to support the Ariane space launch capability but to launch the *force de frappe* nuclear arsenal. The Italians have participated in the European Union space program that helped design the *Hermes* missile. While the British relied on American missile programs in the 1960’s to supply their TBM needs, a technical exchange program between Britain and the United States trained and educated a sizable pool of missile talent from the British Isles.

Country	Airframe			Propulsion			Guidance and Control			Weapons Integration		
	Serial Staging	Parallel Staging	Strap-on Boosters	High-Energy Solid Propel-lants	Large-Scale Cast Solid Grains	Large Turbo-pumps for Liquid Fuels	GPS for Post-Boost Vehicles (PBV)	Small Guidance Com-puters to fit on PBV	Terminally Guided Reentry Vehicles	Reentry Thermal Protection Materials	Post-Boost Vehicles	Bomblets
Argentina	♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦♦	♦♦	♦♦
Brazil	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦	♦♦♦	♦♦	♦♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦
Chile	♦	♦	♦♦	♦♦	♦	♦	♦	♦	♦	♦	♦	♦
China	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦	♦♦	♦	♦♦♦	♦♦	♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
India	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦♦	♦♦	♦♦
Iran	♦	♦♦	♦♦	♦♦	♦	♦	♦	♦	♦	♦♦	♦	♦
Iraq	♦♦	♦♦	♦♦♦	♦♦♦	♦	♦	♦	♦	♦	♦♦	♦	♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
Japan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦	♦
North Korea	♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦	♦♦	♦♦
Pakistan	♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦	♦	♦	♦♦	♦	♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦	♦♦♦	♦♦♦	♦♦♦
South Korea	♦♦	♦♦	♦♦	♦♦♦	♦♦	♦♦	♦	♦♦	♦	♦♦	♦♦	♦♦
Sweden	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦	♦♦♦♦
Syria	♦	♦	♦	♦♦	♦	♦	♦	♦	♦	♦	♦	♦
Taiwan	♦♦	♦♦	♦♦	♦♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦	♦♦	♦♦
Ukraine	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 1.2-1. Intercontinental Ballistic Missiles Foreign Technology Assessment Summary

Table 1.2-1. Intercontinental Ballistic Missiles Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
AIRFRAME					
Small solid strap-on boosters (Solid boosters with propellants having >86% solids)	Capable of producing a total system thrust of 10,000 lb (vacuum)	MTCR 2; USML IV; WA Cat. 9A; CCL Cat. 9A	None identified	Rocket test stands; Shaker facilities for environmental testing	Internal grain burn profile calculation software
Serial staging hardware	First stage thrust level of 100,000 lb (vacuum)	MTCR 3; USML IV	None identified	Rocket test stands; Shaker facilities for environmental testing	None identified
Parallel staging hardware	Capable of producing a total system thrust of 100,000 lb (vacuum)	MTCR 3; USML IV	None identified	Rocket test stands; Shaker facilities for environmental testing	None identified
PROPULSION					
Thrust vector control systems	Equivalent to trapped ball joint demonstrated at vector angles of ~5 deg consistent with solid rocket operations	MTCR 2; USML IV	None identified	Environmental test and evaluation	None identified
Extendible nozzle exit cones	Extendible cones that can increase the upper atmosphere expansion ratio to 30:1	MTCR 2; USML IV	None identified	Cold gas generators or dynamic test facilities to reproduce flight conditions and exit pressures	None identified
Solid-propellant motors	Total impulse of >50,000 lb-sec	MTCR 2; USML IV; WA Cat. 9A; CCL Cat. 9A	Liners, insulation, adhesives, and case materials to withstand temperatures of 1000 °C or higher	High-energy x-ray machines; rocket test stands; CT machines	None identified
Liquid-propellant engines	Total impulse of >50,000 lb-sec	MTCR 2; USML IV; WA Cat. 9A; CCL Cat. 9A	None identified	Rocket test stands; valves and piping with flow control deviation no greater than 0.5% and duty cycle timing deviation <20 msec	None identified
Solid propellants	Propellants, dopants and additives that produce Isp = 275 sec or greater in finished missile	MTCR 4; CCL Cat. 1C; USML V	Geometrically homogenous aluminum powder and metal hydrides	"T cell" propellant burners and equipment instrumented to detect flow oscillations in segmented solid rocket grains	Programs that calculate thrust time traces for given internal grain cutouts

(cont'd)

Table 1.2-1. Intercontinental Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Solid propellant oxidizers	Specialty oxidizers that increase burn rate or burn stability	WA ML 8; USML V; MTCR 4; CCL Cat. 1C	Geometrically homogenous ultra-fine (dia. <0.002 in.) ammonium perchlorate or equivalent	UFAP size filtration and size gauges	None identified
Solid propellant additives	Additives that modify missile emission spectra, aid in reducing flow instability, contribute to thrust vector control or increase burn rate	WA ML 8; MTCR 4; USML V; CCL Cat. 1C	MAPO, TEPAN, Catocene, Butacene	None identified	None identified
Turbopumps	Shaft speeds >8,000 RPM or discharge pressures >7,000 KPa	MTCR 3; USML IV	None identified	Large torsion shaft dynamometers	None identified
Rocket motor/engine test stands	Test stands capable of withstanding a thrust of >20,000 lb	MTCR 15; CCL Cat. 9B; USML IV	None identified	High frame rate cameras that are shock, vibration and thermal hardened; Thrust measurement hardware	None identified
Thrust vector control	Steering guidance for multiple- body missiles that produces in excess of 1 deg/sec pitch rate and control for <10 Hz oscillations	MTCR 2; USML IV, XV	High atomic weight injection fluid for steering and pitch control	Thrust stand with torsional force and moment measurement capability to determine pitch and roll forces and moments	Adaptive software to calculate theoretical positional change with measured position change in flight and compensate for the difference
Telemetry or encrypted telemetry data transmission hardware	Transmission rates of 20 kbyte/sec or analog equivalent and operation in a high vibration environment	MTCR 12; CCL Cat. 5A-P1; CCL Cat. 5A-P2 USML XV; WA Cat. 5A-P1; WA Cat. 5A-P2; WA ML 11	None identified	Calibration equipment with 100 kbyte/sec sample and hold capability	Encryption algorithms of DES standard 40 bit and higher
Fluid energy mills for grinding and mixing highly energetic materials	Explosion-resistant equipment designed to handle energetic materials	WA ML 18; MTCR 5; USML XXI	None identified	Frictionless closure valves and valves without pinch closure	None identified

(cont'd)

Table 1.2-1. Intercontinental Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Propellants	Utilization of hydrazine and nitrogen-tetraoxide families	WA ML 8; MTCR 4; USML V	None identified	Propellant scrubbing equipment and vapor control technology; production equipment for hydrazine and nitrogen tetraoxide	None identified
GUIDANCE, CONTROL, AND NAVIGATION					
Vernier motor controls	Boost cut off command signals within 0.25 deg of programmed injection angle, 2% of burnout altitude and 1% of burnout velocity	USML XXI	None identified	Valves and valve control solenoids	Efficient software algorithms that support major cycle time of 50 msec
Small, lightweight, IMUs consistent with post-boost vehicles	IMUs capable of solving the Lambert guidance equations and updating PBV positions in a 50 ms major cycle time	EAR; MTCR 9; USML XV; CCL Cat. 7A	None identified	Flight test vehicles that allow subscale velocity and vibration calibrations; Small computers	Digital implementation of common guidance laws such as the Lambert guidance laws. Calculations of positions in space such as the range insensitive axis or the time insensitive axis
Stage timing sequencers for hot fly out staging	Operation times of staging events including squib firing in less than 250 ms with a repeatability of error of less than 25 ms	USML XXI; MTCR 3	None identified	None identified	Nonlinear multiple equation solving algorithms based on matrix mathematics and Doppler corrections
Propulsion/airframe/ flight control system integration	Provide optimum system performance within confines of airframe/propulsion system architecture to meet mission requirements	MTCR 9; WA ML 11; USML IV	None identified	None identified	None identified
WEAPONS INTEGRATION					
Nose tip material	Nose tip heat protection for RVs with ballistic coefficient in excess of 1,500 psf with 3 mm/sec or less of ablation at 2,000 °F	MTCR 8; USML IV	Carbon Carbon material or 3d carbon carbon material that can be exposed to temperatures in excess of 3,500 °F	Autoclave and furnaces capable of carbonizing and graphitizing materials	None identified

(cont'd)

Table 1.2-1. Intercontinental Ballistic Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Radar altimeter fusing	Fusing and firing accuracy of less than 1,000 ft regardless of trajectory or elevation of target	MTCR 2; WA ML 4; USML IV	None identified	Flight test vehicles that allow subscale velocity and vibration calibrations; radar antennas capable of operation in highly ionized environments	None identified
Submunitions separation or dispensing mechanisms	Circular pattern dispersal of chemical or biological submunitions of greater than 0.5-km radius at mean target elevation	WA ML 4; USML IV	None identified	Aerodynamic braking hardware, parachutes, split flap control hardware	None identified

Table 1.2-2. Intercontinental Ballistic Missiles Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
AIRFRAME			
Small solid strap-on boosters (Solid boosters with propellants having >86% solids)	Integration of booster strap-ons	Ranges above 1,000 km allow proliferants to reach targets of United States interest	Parallel staging; Serial staging
Serial staging hardware	Proper sequencing of staging	Maximum range for given missile weight, lower launch accelerations	Strap-on boosters; Parallel staging
Parallel staging hardware	Staging coordination	Reduces overall burn time of ICBM and therefore complicates tracking	Serial staging; strap-on boosters
PROPULSION			
Thrust vector control systems	Controlling and directing the high thrust of an ICBM first stage	Highly capable thrust vector control systems support a variety of targeting strategies	Less capable TVC systems adapted from theater missiles with very constrained trajectories
Extendible nozzle exit cones	Making a lightweight nozzle design that is rigid enough to accommodate moving parts	Increases range without motor modifications on solid rocket motors	Larger exit cones and related longer stage lengths
Solid-propellant motors	Casting and curing either case bonded or cartridge loaded propellant without cracking or delaminations	Indigenous production of second stages for existing missiles allows a proliferant to extend range	Liquid propellant engines
Liquid-propellant engines	Increasing the propellant flow rate and combustion chamber pressure/ temperature, by using such processes as regenerative cooling, without damaging the engine	Engines in existing missiles can be replaced with higher performance engines for extended range or payload	Solid propellant motors
Solid propellants	Increasing the Isp of the propellant	Solid propellant missiles are difficult to locate and target because of their simplicity, storability and smaller support train	Liquid propellants
Solid-propellant oxidizers	Increasing the oxidizer efficiency and supporting faster burn rates by the reduction in particle size	Better oxidizers provide a more efficient, longer range missile	None identified
Solid-propellant additives	Achieving the desired propellant properties (e.g., burn rate, deflagration control, flow stability) with unconventional materials	Propellant signature modification disguises a launch for cueing satellites, which direct missile defense batteries	None identified
Turbopumps	Increasing propellant and oxidizer flow to the thrust chamber	Modern, higher performance turbopumps make liquid propellant engines more reliable	Ullage tanks

(cont'd)

Table 1.2-2. Intercontinental Ballistic Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Rocket motor/engine test stands	Accurately measuring the force and torsional response of the stand to generate an accurate thrust time profile; flame containment and explosion isolation	Thrust time profiles allow proliferants to fly on unusual trajectories (e.g. depressed or lofted)	None identified
Thrust vector control	Predicting the proper mixture ratios and flow rates under dynamic conditions to precisely control the flight	Control the flight path of the missile	Aerodynamic surfaces
Telemetry or encrypted telemetry data transmission hardware	Real time encryption and transmission of data from a moving vehicle	Prevents observers from understanding the intention of missile flight and static test programs	Open channel communication
Fluid energy mills for grinding and mixing highly energetic materials	Modern solid propellants detonate in shock and spark environments and destroy facilities	Manufacture of high Isp propellants and oxidizers	Older, more dangerous facilities
Propellants	Adequate production and storage facilities	Increased range and payload	Other propellants
GUIDANCE, CONTROL, AND NAVIGATION			
Vernier motor controls	Flow control of steering motors or engines	Rocket-powered missiles	None identified
Small, lightweight, IMUs consistent with post-boost vehicles	Placing a capable IMU on a small final stage with limited thrust	Highly accurate guidance for reduced CEP	None identified
Stage timing sequencers for hot fly out staging	Signal timing and transmission	Increase reliability of ICBMs	None identified
Propulsion/airframe/flight control system integration	Aligning guidance and control system inertial space reference with geometric reference of vehicle	Reduced CEP and higher azimuth accuracy	Post-boost vehicles and ACMs which steer out boost inaccuracy

(cont'd)

Table 1.2-2. Intercontinental Ballistic Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
WEAPONS INTEGRATION			
Nose tip material	Dealing with severe aerothermal environment associated with high ballistic coefficients	All reentry vehicles	Low ballistic coefficient reentry vehicles with less advanced materials
Radar altimeter fusing	Transmitting and recovering signals through a highly ionized environment and through a radar window in the RV	Weapons requiring detonation at specific above ground altitude	Multiple step firing and fuzing circuits including G sensitive circuits that detect the point where aerodynamic and gravitational forces balance and then time a command signal
Submunitions separation or dispensing mechanisms	Releasing the submunitions at a velocity to disperse agent without destroying it	Increase dissemination efficiency when used in conjunction with low ballistic coefficient reentry vehicles	Low ballistic coefficients reentry with spherical reentry vehicles that reduce the reentry velocity high in the atmosphere. The acceptance of a large loss in accuracy is implied

SECTION 1.3—CRUISE MISSILES

Highlights

- Existing over-the-counter technology allows a proliferant to assemble a threatening cruise missile.
- Cruise missiles are ideally suited for the delivery of biological agents.
- Subsonic cruise missiles can survey a target for meteorological conditions before spreading agent.
- Supersonic cruise missiles may increase the probability of penetrating defenses.
- A supersonic/subsonic hybrid cruise missile is difficult for a proliferant to build.
- Wind tunnels, computer design routines, and spray flow field modeling all assist a proliferant to build a more capable cruise missile.

OVERVIEW

The Cruise Missiles subsection reviews the many ways a proliferant can construct a cruise missile to deliver a WMD. The term cruise missile covers several vehicles and their capabilities, from the Chinese Silkworm (HY-2), which has a range of less than 105 km, to the U.S. Advanced Cruise Missile (ACM), which can fly to ranges of up to 3,000 km. These vehicles vary greatly in their speed and ability to penetrate defenses. All, however, meet the definition of a cruise missile: “an unmanned self-propelled guided vehicle that sustains flight through aerodynamic lift for most of its flight path and whose primary mission is to place an ordnance or special payload on a target.” This definition, when applied to the delivery of WMD, can include unmanned air vehicles (UAVs) and unmanned control-guided helicopters or aircraft. Proliferants can achieve a cruise missile capability by simply buying existing cruise missiles from supplier states and modifying them to meet a particular need, or they can make a complete system from readily available parts.

European aerospace firms, the FSU, and the Chinese have all sold many cruise missiles of one description or another to customers in proliferant and industrialized countries. In most cases, the performance of missiles is range limited and, in some cases, even payload limited, and their use as a carrier of WMD is probably confined to tactical applications. With the introduction of new guidance technologies, particularly the GPS, future cruise missiles will be more accurate and attractive to proliferants.

The United States introduced cruise missiles into its inventory when a combination of technologies reached a critical point in their development. Taken together, these same technologies can easily form the underpinnings for a capable unmanned aerial system. Except for Terrain Contour Matching (TERCOM), the 1990’s have seen these technologies, or the knowledge of how to reproduce them, become widespread among industrialized and newly industrializing nations. The introduction of GPS and GLONASS eliminates the need for a country to rely on TERCOM navigation. A proliferator is not forced to seek out any other technologies to build a cruise missile, though many, such as rocket-assisted take-off units, may give a combatant more flexibility in using a cruise missile for a variety of combat operations.

Many proliferants have the scientific and research base to design airframes and build them to meet the needs of a cruise missile program. Arms control officials in the U.S. State Department and many of its overseas counterparts are attempting to reduce high volume serial production of cruise missiles, particularly ones that support a chemical or biological weapons infrastructure. Consequently, the tables identify technologies that assist the mass production of cruise missiles. Once a country has an assured supply of engines and guidance components, the path to a capable cruise missile fleet becomes easier.

Of the four major subsystems that compose a cruise missile—*airframe*, *propulsion*, *guidance, control, and navigation*, and *weapons integration*—none is expensive in and of itself, and a steady supply of each is available. In the late 1960’s, the United States first introduced turbine *propulsion* systems that weighed less than 100 lb and produced many hundreds of pounds of thrust. These turbine engines, or their lineal descendants, powered most of the early U.S. cruise missile designs and were one of the least costly items. Depending upon the range a proliferant desires for its cruise missile, the powerplant may even be as prosaic as a reciprocating engine with a propeller. The latter, of course, has little hope of disguising its signature from defenses, but the mission profile may allow it to disguise itself as another platform. Even if no signature modification is considered, this type of missile has applications in regional wars where the technology of the defense is not as important as it is to an attacking proliferant.

Currently, GPS receivers provide more capability and accuracy than any targeting strategy requires of the *guidance, control, and navigation* subsystem. Cruise missiles, being aerodynamic vehicles, do not need the rapid response cycle time that ballistic missiles must have to keep the vehicle under *control* and on an appropriate track. Avionics systems available for first-generation commercial aircraft are both light enough and accurate enough to keep a cruise missile under control for long periods of time. For *navigation*, civilian code GPS is priced for the civilian hobbyist market, so purchasing an off-the-shelf navigation unit capable of obtaining 20 m of CEP is within the range of the common pocketbook. This level of accuracy is better than that of the early TERCOM systems installed on U.S. cruise missiles, which made them practical for the first time in the late 1970's.

For long cruise missile flight paths, a country without access to GPS systems must develop a mapping guidance logic for its cruise missile or accept highly degraded performance from an inertial measurement unit (IMU). A proliferant using one or two cruise missiles in an isolated attack from a standoff platform can achieve all of its targeting aims with an IMU, but long flight paths allow errors in the IMU to become so great that the missile may stray far from its target. Also, without an updated mapping system, the cruise missile must fly at an altitude high enough to avoid all manmade obstacles, thereby exposing itself to detection.

Even with GPS, the autonomous cruise missile carrying an on-board map must be supplied with the latest terrain and physical feature changes that have occurred along its course if it flies near the ground. Updated autonomous map guidance systems require large computer storage memories aboard the aircraft with units that can withstand the flight vibrations and possible thermal extremes of the missile over a long-duration flight. These units must be supplied with the latest maps that the delivering nation can obtain. Few nations have the space flight vehicles or high-altitude aircraft to build radar maps from overflights alone. Consequently, these maps will have to be purchased, or the proliferant will have to accept the attrition from missiles lost because of outdated information. The United States and Russia understand the key position that radar maps play in cruise missile guidance and are unlikely to allow the information stored in these maps to be released on the world market. Even if these maps are sold through some clandestine channel, they will quickly become outdated since cultural features change rather rapidly. As an alternative, a country may try to develop another guidance scheme, but the costs for developing a new infrastructure to support a map-based guidance system probably rivals that of the original TERCOM or a GPS constellation itself.

In the absence of GPS, the reliability of the cruise missile targeting philosophy becomes increasingly more problematic. As an alternative, a country may attempt to fly its cruise missile with radio guidance or other commands. Usually radio guidance uses frequencies high enough to operate only on line-of-sight reception. If the country expects to operate in hostile territory or attack at very long ranges, it must control the intervening repeater station to contact these missiles by real-time transmission of flight controls signals and position information.

Since cruise missiles fly relatively slowly and with only gentle accelerations, at the entry level, the *airframes* of these delivery systems can be built out of inexpensive aluminum of a grade as simple as 2024 - T1. Most proliferants with a basic metal production facility and an access to textbooks on metallurgy have a ready supply of this grade of aluminum. As proliferants design and build more sophisticated cruise missiles, they will undoubtedly substitute composite materials and other more elaborate structural elements in the airframe, but, for the most part, these materials are not needed.

A cruise missile airframe does not undergo particularly severe stress on its flight to a target, it does not pull any high “g” maneuvers, and it does not experience propulsion accelerations associated with gun or ballistic missile launches. Virtually any airframe that is structurally sound enough to be used in an ordinary airplane is adequate for a cruise missile. A designer can use factors of safety of 1.5 or 2 in the design to ensure structural integrity under all dynamic conditions without recourse to structural finite element computer codes, which generally only assist a designer to shave four or five percent from the weight of a design. Still, these technologies are included in the tables because their use does allow a proliferant to build a more capable cruise missile.

Technologies that advance the large serial production of inexpensive cruise missiles threaten current defenses built against missile attacks. These technologies include sheet metal processing machines that could form complex shapes, such as those found on the airframe or leading edge of cruise missiles; hydraulic presses or stamping mills that shape the nose cones or turbine inlets; and numerically controlled machines for parts production.

If a country wants to increase the penetrability of its cruise missiles, it must identify technologies that aid in signature reduction, signature masking, or other means to confuse detection systems. Some of these technologies include radar jamming and spoofing technologies; infrared suppression of engine exhaust; paints and coatings that disguise the thermal signature of leading edges; computer routines that predict the flow field around aerodynamic surfaces and the methods to change those surfaces to reduce heat transfer and turbulent flow fields; wind tunnel technology that supports the computer prediction; and computer routines that predict the RCS from a given geometry and predict redesign methods to achieve certain design specifications.

The cruise missile is suited for the delivery of chemical or biological agents if it does not fly at supersonic or transonic speeds. Most cruise missiles designed to fly at high speeds are not similarly able to fly at slow speeds without dramatic changes in the wing planform in flight. These changes in wing planform are generally not consistent with cruise missile geometries or packing volumes in the same way they might be in manned aircraft, such as the FB-111. Supersonic missiles generally cannot dispense chemical and biological agents from sprayers since the airstream itself will destroy the agent by heating or shock, but they do deliver nuclear weapons with great efficiency. None of these considerations are exclusive impediments to a proliferant's cruise missile development program. It is only a general guideline that high-speed cruise missiles make sense as a means to deliver nuclear weapons and low-speed cruise missiles are better suited for chemical and biological weapons.

Bomblets can also be included on transonic or supersonic missiles. These bomblets can be released over a target to ameliorate the airstream problem. After release, the bomblets decelerate, float to the target, and spray their agent into the air. Bomblets reduce the packing fraction of agent within the cruise missile airframe and, therefore, reduce the overall payload of a cruise missile. A subsonic cruise missile equipped with a sprayer dispensing agent from a single tank onboard the missile may simply release the agent into the airstream. In most cases, a large fraction of this agent will be destroyed before it reaches its target. To be more effective, the sprayer must dispense the agent so that it avoids the vortex from the tips of the wings and the disturbed airflow from the fuselage. Technologies that are required to develop bomblets, predict their flight path, or enhance the capabilities of sprayers as a means for a proliferant to deliver WMD from a cruise missile are highlighted.

Three key concerns of the cruise missile threat are (1) range extension to ranges greater than 500 km, (2) the ability to penetrate defenses, and (3) any technologies that reduce the cost of manufacture and therefore increase the size of a cruise missile inventory. In order of priority, the tables first list technologies that assist a country in building long-range cruise missiles. The tables then cover technologies that reduce the signature of a cruise missile and list those technologies that decrease the per unit cost or increase the total serial production of cruise missiles for a fixed price. Finally, the tables include support technologies that may make cruise missiles easier to use, package, or launch. As with each of the other delivery systems subsections, the tables are organized by specific subsystem of the aircraft: *airframe, propulsion, guidance, control, and navigation,* and *weapons integration.*

Cruise missiles differ from ballistic missiles as a potential threat because they share so many common technologies with existing vehicles that have been designed for other purposes. As a consequence, a proliferant can obtain much of the hardware to construct a cruise missile by cannibalizing existing commercial aircraft or by purchasing parts and components for the missile from legitimate suppliers. The technology tables serve only as a guideline to alert and inform export control regulators of general categories of technologies as opposed to specific performance specifications.

RATIONALE

Cruise missiles pose perhaps the gravest delivery system proliferation threat to U.S. worldwide interests. They are inexpensive to build and can, therefore, overwhelm current defenses by sheer numbers. They can be designed to be small with low-thrust engines and can penetrate radar and infrared-detection networks. The technology to build them is simple and available to any country that builds even rudimentary aircraft. Finally, since cruise missiles are unmanned, they require no flight crew training, expensive upkeep programs, special hangars for housing, or large air bases for basing. These factors make it especially difficult to collect intelligence on the development of indigenous cruise missiles and to anticipate the developing threat.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.3-1)

Systems

At least 12 exporting countries—Great Britain, the United States, China, France, Germany, Israel, Italy, Japan, Norway, Russia, Sweden, and Taiwan—have developed cruise missiles with some capability in the hands of proliferants to threaten U.S. worldwide interests.

Generally, these cruise missiles are small and have a limited range. While it is possible that they can be converted to deliver WMD, their short range limits their possible targets of interest. They may deliver biological or chemical agents against ports and airfields in regions of concern such as the Persian Gulf, but are not able to attack longer range targets. In addition, cruise missiles, such as the Chinese Silkworm, have many other limitations besides short range that restrict their utility as a WMD delivery system. The missiles leave a turbulent airflow in their wake, which makes it difficult to deliver a sprayed pathogen or chemical agent cloud. They fly along a predictable path towards the target rather than one that can realign itself to match the geometry of the target.

The following cruise missiles are a sample of missiles that are available legitimately on the world market and pose less threat as possible candidates for conversion to WMD delivery: the British Sea Eagle, the Chinese Seersucker and Silkworm, the French Exocet, the German Kormoran, the Israeli Gabriel, the Italian Otomat, the Japanese SSM-1, the Norwegian Penguin, the Soviet SSN-2C and its derivatives, the Swedish RBS-15, the Taiwanese Hsiung Feng 2, and the U.S. Harpoon. Older missiles, such as the Silkworm, have cumbersome and slow-moving control surfaces that do not readily adapt to the improvement in position calculation that GPS provides. Moreover, their guidance systems are intended mostly for the missiles in which they are placed and have little transference to a new airframe if they should be cannibalized. In most cases, the ease with which a cruise missile can be built leads a proliferant to build a new missile from scratch rather than attempting to adapt these older missiles for WMD delivery.

Even if the missiles do not pose a significant threat against U.S. worldwide interests, some aspects of their manufacturing base may migrate to more capable missiles and require close scrutiny. Missiles that contain small turbojet engines can be cannibalized, and the engines can be used in more threatening applications. A proliferant can also glean the knowledge to build these turbojets by reverse engineering the engines or setting up indigenous co-production facilities. Examples of exported missiles with small turbojet engines include the British Sea Eagle and the Chinese HY-4. Israel is offering an upgraded Gabriel, which features the latest in propulsion technology, to overseas customers. Other missiles in this class include the U.S. Harpoon, the

Swedish RBS-15, the Soviet SS-N-3, the Soviet SS-N-21, and the Otomat Mark-II. Cruise missiles that have immediate application to nuclear, chemical, and biological delivery include the U.S. Tomahawk and ACM, the Russian SSN-21, the AS-15, and the French Apache.

Harpoons have been exported to 19 countries, including Egypt, Iran, Pakistan, South Korea, and Saudi Arabia. India has received Sea Eagles, while Egypt, Iraq, Iran, Pakistan, and North Korea have Silkworms and Seersuckers, a version of which North Korea now manufactures. Italy has Kormorans, and Taiwan, South Africa, Chile, Ecuador, Kenya, Singapore, and Thailand have Gabriel Mark-IIs. Italy has exported turbojet powered Otomats to Egypt, Iraq, Kenya, Libya, Nigeria, Peru, Saudi Arabia, and Venezuela, while the Swedes exported the RBS-15 to Yugoslavia and Finland. In addition, the Soviets sold the long-range (500 km, 850 kg) turbojet powered “Shaddock” to Syria and Yugoslavia. At the next notch down in technological capability, the Soviets have flooded the world market with 1960’s-generation liquid-fueled “Styx” (SS-N-2C) missiles. Algeria, Angola, Cuba, Egypt, Ethiopia, Finland, India, Iraq, Libya, North Korea, Somalia, Syria, Vietnam, Yemen, and the former Yugoslavia have the Styx missile in their inventories.

As the list of customers for the Styx demonstrates, the cost of a cruise missile is within the financial resources of even the most basic defense budgets. Even highly capable cruise missiles such as the Tomahawk only cost around $1.5 million per copy. This cost reflects the most advanced avionics systems and TERCOM guidance. At least one congressional study has shown that with the substitution of GPS, a proliferant could build a cruise missile with a range and payload capability roughly equivalent to the Tomahawk, for about $250,000. Unlike production of the heavy bomber, many countries have the economic resources and technical base to produce this kind of delivery system indigenously.

Subsystems

Though the sale of complete systems on the world market is a concern, that threat is much smaller than the possibility that a country could indigenously design and build a capable cruise missile by cannibalizing other systems for parts it cannot build on its own. Of particular concern are components and parts that reduce the cost of the missile in serial production, reduce the cost of position mapping navigation systems, and increase the range of these missiles.

Navigation and guidance continues to be the pacing item in threatening cruise missile development. The Standoff Land Attack Missile (SLAM) is a derivative of the Harpoon and contains in its nose a video camera that acts as a terminal guidance system. If a proliferant adopts this technology and can position a transmitter and receiver within line-of-sight to the missile from anywhere in the theater, it can dispense with the need for any other kind of guidance system. Israel has developed a capable guidance system that can be used in this application.

The next major subsystem component that enhances the capability of a cruise missile is the powerplant. The United States pursued the cruise missile long before the development of the first lightweight engine technology, so this is not a critical path item towards developing a cruise missile. Still, more capable engines increase the threat of a cruise missile. First, they reduce the RCS of the missile. Next, they increase the range by reducing the drag and power required for control surface actuation. Finally, they reduce other flight signatures, such as infrared cross-section and acoustic emission, that might be exploited in a defense network.

Country	Airframe		Propulsion			Guidance and Control			Weapons Integration	
	Control Surface Actuators	High Wing Loading Aerodynamic Designs	High Thrust-to-Weight Jet Engines	Small Turbine Engines	Advanced High-Energy Fuels	Radar Maps to Support Terrcom	Digital Topographical Maps to Support GPS	Dynamic Test Equipment	Sprayers Adapted to Airstream	Small Nuclear Weapons
Argentina	♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦	♦♦	♦♦♦	♦♦♦
Brazil	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦	♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
Chile	♦	♦♦	♦	♦♦	♦	♦	♦	♦	♦♦♦	♦
China	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦	♦♦	♦♦	♦♦♦	♦♦♦	♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
India	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦	♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
Iran	♦♦	♦♦	♦	♦♦	♦♦♦	♦	♦♦	♦♦	♦♦♦	♦♦
Iraq	♦♦	♦♦	♦	♦♦	♦♦♦	♦	♦♦	♦♦	♦♦♦	♦♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦
Japan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦	♦	♦	♦	♦♦♦	♦	♦	♦	♦♦	♦
North Korea	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦♦
Pakistan	♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦♦	♦♦	♦♦♦	♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
South Korea	♦♦	♦♦	♦♦	♦♦	♦♦	♦	♦♦♦	♦♦♦	♦♦	♦♦♦
Sweden	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
Syria	♦	♦	♦	♦	♦	♦	♦	♦	♦♦	♦
Taiwan	♦♦	♦♦	♦♦	♦♦♦	♦♦	♦	♦♦	♦♦♦♦	♦♦	♦♦♦♦
Ukraine	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 1.3-1. Cruise Missiles Foreign Technology Assessment Summary

Table 1.3-1. Cruise Missiles Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
AIRFRAME					
CFD design optimization routines	PC and workstation codes that optimize physical properties such as vehicle weight per payload	CCL EAR 99; MTCR 16	None identified	None identified	Operating systems for high speed computers that reduce repeated instruction set calls to the CPU
CFD inverse design routines	PC and workstation codes that generate NC machine tool instructions	WA Cat. 2D; CCL Cat. 2D	None Identified	High-speed computing facilities or parallel processor operating systems	Operating systems for high speed computers that reduce repeated instruction set calls to the CPU
Finite element structural computer routines	PC-based routines capable of making more than 1,000 node calculations and containing automatic mesh generators	CCL EAR 99	None Identified	High-speed computing facilities or parallel processor operating systems	Operating systems for high speed computers that reduce repeated instruction set calls to the CPU
Hydrodynamic computer routines	Codes with automatic equations of state calculations	CCL EAR 99; MTCR 16	None Identified	High-speed computing facilities or parallel processor operating systems	Operating systems for high speed computers that reduce repeated instruction set calls to the CPU
Fluid mechanics finite element routines	PC based routines with mesh generators and Lagrangian logic	CCL EAR 99	None Identified	High-speed computing facilities or parallel processor operating systems	Operating systems for high speed computers that reduce repeated instruction set calls to the CPU
Metal stamping equipment	Capable of forming fuselages and leading edges in metal of 0.020 in. thickness or less	CCL EAR 99	None Identified	None identified	None
Composite filament-winding equipment	Two or more coordinated axes	MTCR 6; CCL Cat. 1B; WA Cat. 1B	None Identified	None identified	NC head control for winding patterns
Composite tape-laying equipment	Two or more coordinated axes	MTCR 6; CCL Cat. 1B; WA Cat. 1B	None Identified	None identified	NC feeder controls

(cont'd)

Table 1.3-1. Cruise Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Composite weaving or interlacing equipment	Two or more coordinated axes	MTCR 6; CCL Cat. 1B; WA Cat. 1B	None Identified	None identified	NC feeder controls
Radar absorbing material	Material that reduces complete design RCS by more than 10 dB	USML XIII; MTCR 17	None Identified	Radar ranges	Radar signal return prediction software
Structurally efficient radar absorbing material	Coatings and structural shapes that add less than 10% to the gross lift-off weight of an air vehicle	USML XIII; MTCR 17	None Identified	None identified	None identified
Aerodynamic design concepts which reduce IR signature	IR reduction paints and coatings	USML XIII; WA ML 17	Low latent heat of vaporization dopants and additives	None identified	None identified
Flow instrumentation	Sensors, and data acquisition equipment capable of measuring 2 kHz or higher signals in wind tunnels	WA Cat. 9B; CCL Cat. 9B	None identified	Sample and hold data acquisition boards for small computers	Data reduction from sample and hold boards
Innovative flow effectors	Adequate control power for vehicle range and speed improvement; lateral (directional) control without vertical stabilizers	MTCR 10; USML IV	None identified	None identified	None identified
PROPULSION					
Turbofan engines	Lightweight engines with bypass ratios greater than 6% and weights below 400 lb	MTCR 3; USML VIII	None identified	None identified	None identified
Turbojet engines	High thrust-to weight ratio engines (5:1) with weights below 400 lb	MTCR 3; USML VIII	None identified	None identified	None identified
Ramjet engines	Ramjet engines weighing less than 1,900 lb	WA Cat. 9A; MTCR 3; USML VIII	None identified	None identified	None identified
Small solid rocket engine for takeoff assistance	Motors weighing less 100 lb with thrust in excess of 1,000 lb	USML IV	High specific impulse solid rocket fuels and burn rate enhancers	Rocket motor test stands	None identified

(cont'd)

Table 1.3-1. Cruise Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
GUIDANCE, CONTROL, AND NAVIGATION					
Digital radar maps	Digital representations of the Earth's surface with height resolution <=20 m	MTCR 11; USML XI	None identified	Methods to measure radar images of the Earth's surface	Data compression software
Digital topographical maps	Digital representations of the Earth's surface with height resolution <= 20 m	MTCR 11; USML XV	None identified	Over the counter high resolution digital topographical maps	Data compression software
GPS receivers	Receiver capable of reducing civil use code signals to position and velocity within 50 msec	MTCR 11; USML XV; WA Cat. 7A; CCL Cat. 7A	None identified	None identified	Civil use code to protected use code calculation algorithms
Stellar optics	Equipment and hardware supporting daylight stellar observations with better than 1 microradian resolution	MTCR 9; USML XV	Low chromatic aberration lenses and specialized optical coatings	Optical test benches capable of calibration to within 0.1 microradian; methods to coat optical surfaces	None identified
Other guidance set design and radio inertial guidance	Any complete system or subset with 10 km or less accuracy at a range of 300 km, or 3.33% or less of range over 300-km range	MTCR 2, 9; USML XV	None identified	Instrument test range	None identified
Propulsion/airframe/ flight control system integration	Time control along with vehicle trajectory control to provide accurate location information along mission flight path	MTCR 9; WA ML 11; USML VIII, XV	None identified	Six degrees of freedom computer models	Source code for CAD/CAE
Vibration test equipment using digital control techniques	Equipment providing vibration at 10 g rms. between 20 and 20,000 Hz	MTCR 15; CCL Cat. 9B; WA Cat. 9B	None identified	Sample and hold data acquisition boards for small computers	Software capable of 4 times oversampling at 20,000 Hz
WEAPONS INTEGRATION					
Weapons separation design and prediction	Aerodynamic and trajectory prediction codes validated to within 1% of measured properties	MTCR 2, 16; USML XV	None identified	High-speed computing facilities or parallel processor operating systems	None identified
Submunitions separation or dispensing mechanisms	Submunitions with packing densities exceeding 75%	WA ML 4; USML IV	None identified	None identified	None identified

(cont'd)

Table 1.3-1. Cruise Missiles Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Biological sprayers	Specially designed airstream independent sprayers with nozzles and tankage to maintain live agent viability, with a dissemination efficiency of 10% or greater	USML XIV	None identified	Wind tunnels	None identified
Chemical sprayers	Specially designed airstream independent sprayers with a dissemination efficiency of 10% or greater	USML XIV	Corrosion-resistant materials	Wind tunnels	None identified
Advanced state vector calculation routines	Codes with validated results that predict submunition bomb case and aero glide vehicle variables within 1% of measured variable	WA ML 21; USML XXI	High-speed computing facilities or parallel processor operating systems	None identified	None identified

Table 1.3-2. Cruise Missiles Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
AIRFRAME			
CFD design optimization routines	Multivariate optimization procedures and their implementation	All flight vehicle structures	Parallel processors for PCs and work stations
CFD inverse design routines	Manufacturability and potential alternatives of design code solutions	Nozzles, turbine blades, and other complex components of cruise missile systems	Parallel processors for PCs and work stations
Finite element structural computer routines	Mesh generation and element geometry and dimensional parameters	Warhead lethality calculation	Parallel processors for PCs and work stations
Hydrodynamic computer routines	Proper solution of the energy balance in state change calculations	Effective delivery of chemical and biological weapons	Parallel processors for PCs and work stations
Fluid mechanics finite element routines	Simultaneous solution of Navier Stokes equations	Meteorology studies for effective delivery of chemical and biological weapons	Parallel processors for PCs and work stations
Metal-stamping equipment	None identified	Production of any vehicle parts that have military applications such as TELs	Conventional sheet metal brakes used with less complex shapes
Spin, flow, and shear forming machines	Proper laminar flow control of material	Nozzle and inlet manufacture	Composite technology and materials
Composite filament-winding equipment	Control of winding tension and material supply	Missile airframe manufacturing	Metal fuselages
Composite tape-laying equipment	Control of material feed tension	Control surfaces	Metal fuselages
Composite weaving or interlacing equipment	Geometric and elastic uniformity of supply material	Control surfaces	Metal fuselages
Radar-absorbing material	None identified	Low observables or stealth applications	None identified
Structurally efficient radar absorbing structure	Maintaining reasonable factors of safety—fuselage, wing at high stress points	Any combat air vehicle	None identified
Aerodynamic design concepts which reduce IR signature	Maintaining proper aerodynamic properties under all flight conditions and speeds	Any combat air vehicle	None identified
Flow instrumentation	Calibration and measurement readings in a dynamic environment	Any combat air vehicle	Less capable wind tunnels

(cont'd)

Table 1.3-2. Cruise Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Innovative flow effectors	Vehicle 3-axis stability and control with minimal cross-coupling	Increased range, maneuverability, and survivability	Traditional vertical tail configuration
PROPULSION			
Turbofan engines	Inefficiency of low-level cruise flight	High- level cruise missile applications	Turbojets, ramjets, internal combustion engines
Turbojet engines	Long flights increase stress and temperature levels on engines—lowers thrust	Better engine performance during long flights	Turbojets, ramjets, internal combustion engines
Ramjets	Initial boost to achieve ramjet operating speed	Surface-to-surface missiles	All other cruise missile technology
Small, solid rocket engine for takeoff assistance	Achieving high grain burn rates to accelerate a cruise missile without nozzle erosion or high stress on the missile	Longer range, more reliable	Air drop from large-capacity airplanes
GUIDANCE, CONTROL, AND NAVIGATION			
Digital radar maps	Making the original radar maps from satellite or other overhead surveillance methods	Autonomous guidance of aircraft	GPS guidance
Digital topographical maps	Resolution of maps to achieve flight through high relief terrain, cities, or other cultural clutter	Land-based autonomous navigation	GPS guidance
GPS receivers	Correcting civil use code to protected use code by numerical calculation of ionosphere correction	Any application requiring precise position knowledge	GLONASS receivers
Stellar optics	Multiple azimuth shots of known stars without interference of other bodies	Night-time azimuth sightings for artillery pieces or missile firing tables	None identified
Other guidance set design and radio inertial guidance	Communication with the moving platform to make real time corrections	Autonomous ship and tank navigation	Inertial, positional, or way point guidance
Propulsion/airframe/flight control system integration	Alignment of the guidance set within the airframe and calibration of the control corrections	High-performance air vehicles	None identified

(cont'd)

Table 1.3-2. Cruise Missiles Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Vibration test equipment using digital control techniques	Digital control of shakers and other equipment	Environmental testing of equipment in high vibration environments	Extensive flight testing
WEAPONS INTEGRATION			
Weapons separation design and prediction	Flight and mechanical properties prediction	Effective dispersal of weapons	Extensive flight testing
Submunitions separation or dispensing mechanisms	None identified	Effective dispersal of weapons	Cold gas thrusters; extensive flight testing
Biological sprayers	Keeping the agent from coagulating or breaking up in the wake of the delivery vehicle	Effective sprayers for any platform	Bomblets or other dispensers that disperse agent after the release from the cruise missile
Chemical sprayers	Keeping the agent from coagulating or breaking up in the wake of the delivery vehicle	Effective sprayers for any platform	Bomblets or other dispensers that disperse agent after the release from the cruise missile
Advanced state vector calculation routines	Numerical integration algorithms	Flight path prediction for cruise missiles	Way point flight with many vehicles

SECTION 1.4—COMBAT FIXED-WING AIRCRAFT

OVERVIEW

The Combat Fixed-Wing Aircraft subsection addresses the technologies that a nation needs to deliver a WMD by an aircraft. Unlike the cruise and ballistic missile subsections, which describe the additional burden a country may face to build the delivery system, this discussion assumes that most proliferants already possess aircraft or can purchase them legitimately on world markets.

Three key attributes of an aircraft pose the greatest threat: (1) reliable delivery of WMD, (2) ability to penetrate defenses, and (3) all-weather, day and night capability. The aircraft subsection describes and lists those technologies that allow a proliferant to carry out a targeting objective. The tables first list technologies that assist a country in weaponizing its aircraft fleet to accept WMD. Then they cover technologies that enable all-weather, day and night aircraft operations. Finally, the tables address the hardware and technical expertise that are needed to assist in penetrating defenses. Each of the tables is organized to categorize technologies, or adaptation of technologies, under the specific subsystem of the aircraft: *airframe, propulsion, guidance, control, and navigation*, and *weapons integration*.

Proliferants can pursue at least four technological advances to manned aircraft: (1) methods to increase range, (2) methods to weaponize WMD for reliability, (3) methods to mask or otherwise disguise flight signatures to detection networks, and (4) methods to launch an aircraft attack around the clock and in all-weather conditions.

Methods to Extend Range

All the identified proliferants maintain some manned aircraft systems. As total delivery systems, any of these aircraft can carry and drop almost any nuclear, chemical, or biological payload that the proliferant is capable of making or purchasing. Proliferants that possess limited-range aircraft have already begun to upgrade the severity of threat these aircraft pose by investigating the world market for in-flight refueling capability. In 1987, Libya purchased in-flight refueling tankers that are capable of extending the range sufficiently to strike European targets. Libya’s only impediment to expanding its aircraft range is the availability of interim staging bases from which the tanker aircraft can fly.

Because of the physical isolation and political posture of many proliferants, few, if any, countries will act as host for proliferants to stage refueling tanker aircraft that could aid any WMD strike against U.S. worldwide interests. To do so would invite retaliation from the United States and the probable loss of the asset to U.S. counterforce operations. Given this geographical constraint, a proliferator may undertake to make modifications to an existing aircraft to extend range without in-flight refueling.

To accomplish any range extension to its aircraft fleet, the country must add additional fuel tanks, reduce the aerodynamic drag, or change the propulsion system to consume less fuel. Modifications to the *airframe* or *propulsion* subsystem of an aircraft may augment its range at the margins, but none of the realistic modifications a proliferant might make add to the range in the same dramatic way that an in-flight refueling capability does. Thus, if sales of in-flight refueling aircraft are limited and the use of foreign airfields for tanker traffic are monitored, the WMD aircraft threat can be limited to a regional theater of operation. The technology tables have been organized to highlight these considerations.

Methods to Increase Targeting Reliability

With a manned crew, targeting reliability is expected to be high. In the event of any problems en route to the target, the crew may be able to take action to change its target. Similarly, most manned aircraft crews usually visually confirm the position of

Highlights

- The widespread sale of manned aircraft throughout the world reduces the need for a proliferant to build its own aircraft to deliver WMD.
- Existing aircraft can be modified to increase their range. In-flight refueling offers the best method to greatly extend aircraft range.
- All-weather, round-the-clock WMD delivery with manned aircraft is a significant threat.
- Technologies that assist a proliferant to acquire glide, terminally homed, and aerodynamically steered bombs can threaten U.S. worldwide interests.
- Existing and readily available avionics, autopilots, and navigation units are compatible with WMD delivery from manned aircraft.

a target (except when dropping stand-off weapons, such as cruise missiles). *Guidance* and *navigation* subsystems are important to aid in navigation to the target. Significant errors in targeting occur from unpredictable winds, incorrect fuzing information, or poor aerodynamic design. The proper *weapons integration* of WMD warheads can eliminate most of these problems.

An aircraft can often be tracked and shot down by existing defense batteries. At some point, a proliferant aircraft will likely display itself to any tracking sensor as it approaches a target. A proliferant aircraft may, however, delay this detection to radar tracking networks by following contours in the terrain and by employing electronic countermeasures. Neither of these two changes requires modifications to the aircraft's propulsion or airframe and, therefore, they take less effort.

Aircraft can be flown to the target using only visual cues if meteorological conditions permit. A technology that allows an aircraft to operate in any weather condition or during any time of the night or day greatly enhances the threat this delivery system poses. In addition, if a technology allows an airplane to fly outside of its normal operating environment, while following the contours of the terrain, the aircraft then complicates defense strategies. Some technologies that can be fitted onto aircraft to accomplish these objectives are (1) an avionics unit that senses position and position rate; (2) small onboard computers capable of automated flight planning, targeting, en route navigation, and ensured terrain avoidance; and (3) addition of stealth.

Many flight-qualified control systems produce sufficient force (sometimes known as command authority) and response time (or phase margin) to steer any existing aircraft autonomously. These actuators must be coupled to a flight computer, which detects position and position rates and compares them to an on-board stored radar or topographical map of the terrain. In a fully autonomous system, the flight computer must predict the course far enough in advance to give the aircraft time to maneuver and avoid any obstacles within performance constraints, such as climb rate and roll rate. Complete guidance and control subsystems and the components that comprise them are sufficient technology to constitute a proliferation threat.

Methods to Increase Attack Flexibility

Navigation systems traditionally compare either analog or digital representations of the Earth's surface to the radar or topographical scene through which the airplane flies. In recent years, these computers have relied almost exclusively upon digital representations. While reversion to an analogue scene comparison is not ruled out, digital maps are by far the most militarily threatening. They have better resolution, are more accurate, and are updated frequently by contractors, which removes from the proliferant the burden of generating the databases for these maps. Computers that support digital navigation and scene generation require highly sophisticated storage devices and rapid random access to the stored information.

Methods to Increase Penetration

Once an aircraft is within range of defense radars, it may use electronic countermeasures in several ways to spoof defense assets. Sophisticated countermeasures may alter the signal returned to the defense radar to make the aircraft appear to be some other type of aircraft. This technique is especially effective against radars that present thematic rather than actual RCSs to defense personnel evaluating the surroundings. Simpler electronic countermeasures may make an aircraft appear to be much larger or spread out over a greater region of the sky. Consequently, hit-to-kill interceptors may miss the actual aircraft as they fly to intercept the large region within the predicted target area. A proliferant's electronic countermeasures may not prevent the aircraft from being ultimately targeted and eliminated, but they delay the interception to allow the aircraft to release its weapon on the actual target or an adjacent target of near equivalent value. As a result, electronic countermeasures are listed as an important technology to be denied to proliferants.

As a last resort, a proliferant may attempt simply to overwhelm the defense by saturating a target with too many aircraft to intercept. This is a less attractive alternative with aircraft than it is with cruise missiles because of the high cost of purchasing the aircraft, maintaining them, and training a capable crew. Moreover, since a proliferant cannot predict which aircraft will penetrate and which will be intercepted, it must equip all of them with WMD. For chemical and biological agents, this may not be too difficult, but few proliferants can currently manufacture nuclear weapons in sufficient quantities to threaten a saturation attack.

All aircraft require *weapons integration*, whether they arrive at the point of sale in their weaponized state or not. Indigenously produced WMD will probably differ from their foreign counterparts. A proliferant must discover, on its own, the idiosyncrasies of the interaction of a weapon and the aircraft that carries it to plan for these modifications. For example, bomb bay doors opening at certain velocities sometimes cause severe aircraft vibration. Similarly, once the bomb bay doors are open the airflow around the weapon may cause it to vibrate uncontrollably. Again, modern computational fluid dynamics (CFD) codes and their aerodynamic equivalents streamline the redesign process to achieve clean stores separation under all circumstances. Wind tunnels assist a proliferant in estimating the extent of any needed modifications.

The weapons, on the other hand, may need to undergo significant refinements, depending on the ultimate intentions of the country. Some simple standoff weapons, such as glide bombs, may provide a proliferant a unique penetration capability. As an example, a country can target its neighbor without violating its airspace by using a glide bomb that has a lift-to-drag ratio of 5 and dropping it from an aircraft operating at a ceiling of 50,000 ft. The girth of the weapon or its aerodynamic surfaces may create a release problem that forces the proliferant to consider designing folded aerodynamic surfaces. However, a glide bomb is both more accurate than an ordinary gravity bomb and has a greatly reduced RCS compared to the aircraft which drops it, thus solving many of the problems of penetration.

To hit in the vicinity of the target, even a large area target such as a city, the post drop vehicle may need an autonomous guidance and control unit. This unit does not need to meet the specifications of a missile-grade IMU, but it must be good enough to provide simple feedback control to the aerodynamic control surfaces. Systems for aircraft using GPSs are being made available on the world market. Many European and U.S. manufacturers make avionics equipment that can control a split flap or simple aileron.

The tables include technology items directly tied to accurate aerodynamic bombs, control surfaces for a bomb, and steerable aerodynamic devices suitable for releasing airborne agents.

RATIONALE

Fixed-wing aircraft used for the delivery of WMD are of significant concern. Most potential proliferants have reasonable numbers of tactical aircraft and have trained pilots to fly them. The aircraft available usually have a short strike range, suitable for their limited geographical area. Longer range capability, while possible with modifications to existing aircraft and the development of in-flight refueling capabilities, involve introduction of new technologies and systems.

With the advent of the GPS, proliferants now have a technique to improve the navigational capability of their aircraft significantly. Also, even though state-of-the art signature reduction is not readily available, more conventional countermeasures would still be of considerable value, particularly in regional conflicts.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.4-1)

Systems

Since the end of the Cold War, widespread sales have been made of aircraft capable of delivering WMD. China owns SU-27 Flankers, and North Korea has SU-25 Frogfoots. Syria and Libya possess SU-24s, and Iraq, at one time, had the Mirage F1-C. India has 15 Jaguars. The SU-24 has a combat radius of 1,000 km, giving it the most threatening range capability in a regional conflict. However, since they can trade payload, speed, fuel, and range, any of these aircraft can execute a WMD delivery.

Effective use of aircraft in a combat role requires ongoing training, maintenance, and functioning of a substantial infrastructure. Key needs include trained people, availability of spare parts, and realistic exercises. The case in which Iran lost U.S. support is instructive in the limits to keeping aircraft viable as a means of delivery.

China, India, Pakistan, and Israel can maintain and support a tactical aircraft infrastructure, train and recruit pilots, and sustain their aircraft in a threatening posture. North Korea has great difficulty in training pilots and maintaining its aircraft but could mount a single attack against South Korea with its SU-25 Frogfoots. As the Gulf War showed, when the coalition achieved air supremacy, Iraq did not mount even a single sortie against a coalition target, and in all likelihood Iran is in similar straits. Syria has the ability to maintain its aircraft with foreign assistance from either the former Soviet Union or elements of the former Soviet Bloc. The United States has no way of limiting this assistance as it did in post-Revolutionary Iran because its does not control the market for parts and personnel relevant to the air fleet.

All members of the G-7, Sweden, and Poland can supply technical expertise and maintenance personnel to proliferants. South Africa or its agents can funnel spare parts for aircraft to proliferants facing severe shortages. Former Cold War enemy production entities have created licensed co-production facilities for aircraft in China, Israel, South Africa, South Korea, Taiwan, and other countries. Any of these facilities can produce some parts of interest to a proliferator. Many other newly industrialized countries—including Argentina, Brazil, Chile, and Egypt—produce indigenous whole aircraft. A country with an indigenous aircraft production capability may supply custom-made parts or reverse engineered replacement parts for grounded aircraft.

Subsystems

Because of the ubiquity of the aircraft industry in the United States, Russia, and many other countries, virtually every nation in the world has available to it tactical aircraft (or civil aircraft of equivalent range and payload capacity) through legitimate purchase. Smaller aircraft, such as business jets and jet trainers, sold overtly to proliferants can be cannibalized for subsystems, particularly navigation and control subsystems. As a result, no proliferant has a compelling need to build an independent, indigenous aircraft industry solely for delivering its WMD by aircraft. In fact, because of the availability of suitable aircraft on the world market, such an independent capability would be a waste of resources and draw funds away from other needs. A proliferant pursuing aircraft delivery systems needs only the capability to make modest modifications to existing military or civilian aircraft, including bomb bays or bomb racks, associated weapons initiation systems, and research flight conditions for delivering weapons.

To complete the stockpile-to-target delivery cycle at the subsystem level, a proliferant needs to build and test the WMD device that will be delivered by aircraft. Every nation of the FSU, with the exception of Bulgaria, has a trained work force and either existing wind tunnels or structural dynamics laboratories capable of required testing. In the former Yugoslavia, parts of this infrastructure are scattered about the various component states, with most of the research laboratories concentrated in Croatia and Slovenia. India has similar facilities and a tradition of education that can adapt the facilities to unconventional design concepts. The Baltic Republics can perform R&D into flight dynamics and have computer facilities available that can host 1980's vintage U.S. software for advanced structural designs. The industrialized nations of South America (Argentina, Brazil, and Chile) are capable of either building comparable facilities indigenously and performing experiments and analyses for a third party or exporting the technical talent to build such facilities elsewhere.

These same entities can design and build a variety of warhead systems, consistent with tactical aircraft delivery, including aerial bombs, spray systems, glide bombs, terminally steered or guided bombs, and cruise missiles. These devices have the common requirement of aerodynamic flight through a defined mission profile. For chemical and biological weapons, the designer must also provide some mechanism for air braking the warhead, such as fins, or other glide devices that allow the warhead to disseminate agent over a broad area, and a method to keep biological agents in an active condition through the delivery cycle. Failing this, the proliferator must accept the greatly reduced efficiency from dissemination initiated by a burster charge.

At the most rudimentary level, a proliferator must produce an aerodynamic warhead configuration that has a repeatable and predictable flight profile, does not induce severe vibration from air stream buffeting, and can detonate at a predetermined altitude or upon ground contact. Iran, Iraq, Yemen, Indonesia, Bulgaria, the Czech Republic, Slovakia, the Baltic Republics, Pakistan, Mexico, and Cuba can design and build these weapons. Those capabilities that support or further weapon system design are included as “sufficient” technologies.

Country	Airframe		Propulsion		Guidance and Control			Weapons Integration		
	Modifica-tions to Comercial Aircraft	Low-Observable Modifica-tions to Existing Aircraft	Propulsion System	Advanced High-Energy Fuels	All-Weather Guidance and Flight Modifica-tions	Digitally Driven Acutators for Existing Autopilots	Military-Grade GPS Receivers	Bomb Sights	Simple Steered or Homed Bombs	Bomb Flight Mechanics R&D
Argentina	♦♦♦	♦♦	♦♦♦	♦♦	♦	♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦♦
Brazil	♦♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Chile	♦	♦	♦	♦	♦	♦	♦	♦♦♦	♦♦♦	♦♦
China	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
India	♦♦♦	♦♦	♦♦♦	♦♦	♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
Iran	♦	♦	♦	♦♦♦	♦	♦♦	♦♦	♦♦♦	♦♦♦	♦♦
Iraq	♦	♦	♦	♦♦♦	♦	♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Japan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦	♦	♦	♦♦♦	♦	♦	♦	♦♦	♦♦	♦♦
North Korea	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Pakistan	♦♦♦	♦	♦♦	♦♦	♦	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦
South Korea	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦♦
Sweden	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Syria	♦	♦	♦	♦	♦	♦	♦	♦♦	♦♦	♦♦
Taiwan	♦♦	♦	♦♦	♦♦	♦	♦♦	♦♦♦♦	♦♦	♦♦	♦♦♦♦
Ukraine	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate
an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 1.4-1. Combat Fixed-Wing Aircraft Foreign Technology Assessment Summary

Table 1.4-1. Combat Fixed-Wing Aircraft Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
AIRFRAME					
Finite element structural computer routines	PC-based routines capable of making 1,000 node calculations and containing automatic mesh generators	USML VIII	None identified	High-speed computing facilities or parallel processor operating systems	Operating systems for high-speed computers that reduce repeated instruction set calls to the CPU
Fluid mechanics finite element routines	PC-based routines with mesh generators and Lagrangian logic	MTCR 16; USML VIII	None identified	Flow tables and hydrodynamic test facilities that exploit the hydrodynamic similitude approximations to compressible flow; high-speed computing facilities or parallel processor operating systems	Operating systems for high-speed computers that reduce repeated instruction set calls to the CPU
Vibration shakers and other environmental test equipment	Vibration power spectral density output of 10 g rms. between 20 and 20,000 Hz, with forces >=50 kN (11,250 lb)	MTCR 15; CCL Cat. 9B	None identified	Piezoelectric force transducers and sample and hold data acquisition boards for computers; high-speed computers	Fourier transform, chirp, and other advanced signal processing software and modal analysis software
Aerothermal wind tunnels	Input heat flux levels >100 BTU/ft^2-sec	MTCR 15; CCL Cat. 9B; WA Cat. 9B	None identified	Hot wire anemometers or wind vector and stability devices with directional response <1 deg and time response <0.1 msec.	Finite element and hydrodynamic software
Conventional wind tunnels	Wind tunnels producing Reynolds Numbers in excess of 2.5 million per foot	MTCR 15; CCL Cat. 9B; WA Cat. 9B	None identified	None identified	None
Structural modifications for thrusted munitions release or glide vehicles with stored aerodynamic surfaces	Glide vehicles with L/D >5 or thrust missile with >0.1 km/sec velocity change	WA ML 4, 5; USML IV, XII	None identified	None identified	None identified
Propulsion/airframe/flight control system integration	Techniques that provide tradeoffs on range, maneuverability, and safety with complexity and weight	MTCR 2, 9; USML VIII	None identified	Six degrees of freedom computer models	Source code for CAD/CAE

(cont'd)

Table 1.4-1. Combat Fixed-Wing Aircraft Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
In-flight refueling—receiver technology	Any technology level is reason for concern	WA ML 10; USML VIII	None identified	None identified	None identified
Innovative control effectors	Adequate control power for vehicle range and speed improvement; lateral (directional) control without vertical stabilizers	CCL EAR 99; USML XIII	None identified	None identified	None identified
Metal-stamping equipment	Capable of forming fuselages and leading edges in metal of .020 in. thickness or less	CCL EAR 99	None identified	None identified	None identified
Low observables external stores carriage	Structural design with RCS reduction >=3 dB over equivalent volume and give between 1 GHz and 30 GHz	WA ML 17; MTCR 17; USML XIII	Composites	None identified	None
Signature reduction techniques, IR and RF	RCS reduction of 10 dB or greater across frequency range of 1 GHz to 30 GHz; design and coatings for IR and radar signature reduction	WA ML 17; MTCR 17; USML XIII	Special polymers and fibers	Radar range, IR detectors	RCS, signal return prediction software
PROPULSION					
Turbofan engines	Lightweight engines with bypass ratios greater than 6%	MTCR 3; USML VIII	None identified	None identified	None identified
Turbojet engines	High thrust-to weight (6:1) engines	MTCR 3; USML VIII	None identified	None identified	None identified
Technology for high temperature and erosion protection coatings for engine parts	Temperature change through material >=150 °C/in.; erosion resisting technologies that insulate against temperature of >2,000 °C	WA Cat. 2; CCL Cat. 2	Ceramics (e.g., alumina and magnesia) and $ZrO_2 + Y_2O_2$	None identified	None identified
Inlets for transonic and low supersonic flight speeds	Inlet designs or modifications that reduce the ratio of shock standoff to inlet diameter or turning angle by no more than 10% at constant Mach numbers	CCL EAR 99	None identified	None identified	None

(cont'd)

Table 1.4-1. Combat Fixed-Wing Aircraft Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Propulsion integration for subsonic, transonic, and low supersonic flight speeds	Modifications to enable flight below 200 ft AGL	CCL EAR 99; USML VIII	None identified	Load and load rate force simulators to apply flight conditions to controls surfaces	None
Thermal spray forming equipment	Power levels >150 kW, gas velocities of 3,000 m/sec and spray rates of >15 kg/hr	CCL EAR 99	None identified	None identified	None Identified
GUIDANCE, CONTROL, AND NAVIGATION					
Digital radar maps	Digital representations of the earth's surface with height resolution <=20 meters	MTCR 11; USML XI	None identified	Methods to measure radar images of the earth's surface	Data compression software
Global Navigation System	Accuracy of <20 m. in position and <200 nano-seconds in time	MTCR 11; WA Cat. 7A; USML XI; CCL Cat. 7A	None identified	GPS signal simulators	Algorithms that use GPS signals to compute steering commands based on the flight characteristics of the bomber
Map guidance technology	Automatic terrain avoidance, efficient route planning and defense evasion hardware and software	MTCR 11; USML XI; WA Cat 7E; CCL Cat 7E	None identified	None identified	Data compression algorithms
GPS receivers	Receiver capable of reducing civil code signals to position and velocity within 50 msec	MTCR 11; USML XI; WA Cat. 7A; CCL Cat. 7A	None identified	None identified	Civil code to protected code calculation algorithms
Full authority flight control systems	Techniques to tradeoff stability, maneuverability and safety with complexity and cost	WA Cat. 9D, 9E; CCL Cat. 9D, 9E; USML VIII	None identified	Six degrees of freedom simulation combined with pilot in the loop	Source codes for control logic
Vibration test equipment using digital control techniques	Equipment providing vibration at 10 g rms between 20 and 20,000 Hz	MTCR 15; CCL Cat. 9B; WA Cat. 9B	Sample and hold data acquisition boards for small computers	Piezoelectric force transducers and sample and hold data acquisition boards for small computers	None identified

(cont'd)

Table 1.4-1. Combat Fixed-Wing Aircraft Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
WEAPONS INTEGRATION					
Weapons separation design and prediction	Aerodynamic and trajectory prediction codes validated to within 1% of measured properties	USML VIII	None identified	High-speed computing facilities or parallel processor operating systems	None identified
Advanced state vector calculation routines	Codes with validated results that predict submunition bomb case and aero glide vehicle variables within 1% of measured variable	WA ML 21; USML XXI	None identified	High-speed computing facilities or parallel processor operating systems	None identified
Submunitions separation or dispensing mechanisms	Submunitions with packing densities exceeding 75%	WA ML 4; USML IV	None identified	None identified	None identified

Table 1.4-2. Combat Fixed-Wing Aircraft Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
AIRFRAME			
Finite element structural computer routines	Mesh generation and element geometry and dimensional parameters	Needed for higher performance engines and airframes	Parallel processors for PCs and work stations
Fluid mechanics finite element routines	Simultaneous solution of Navier Stokes equations	Meteorology studies for effective delivery of chemical and biological weapons	Parallel processors for PCs and work stations
Vibration shakers and other environmental test equipment	Producing and measuring frequency response and relating the information to flight performance	High performance air vehicles	Expanded flight test program; subsystem and component testing
Aerothermal wind tunnels	Generating sufficient cooling and air replacement to prevent temperature change effects on measured parameters	Performance increases	Expanded flight test program and empirical design modifications
Conventional wind tunnels	Flow straightening and flow visualization of subsonic and supersonic effects	Range increase resulting from lower drag profiles for external munitions stores	Expanded flight test program and empirical design modifications
Structural modifications for thrusted munitions release or glide vehicles with stored aerodynamic surfaces	Predicting and correcting for flow field on bomb bay doors as they open to release munitions and external stores flow fields in flight	Increased reliability of delivery systems and munitions	Additional weight and aerodynamic drag for struts, fillets, and other nonoptimum load-bearing surfaces
Propulsion/airframe/flight control system integration	Pilot acceptance; maintaining adequate gain and phase margins; incorporating response time in maneuver parameters	Increased range and maneuver performance	Pilot integration of parameters
In-flight refueling	Carry and deliver equipment; training and rehearsal of flight crews	Longer range offers more targeting opportunities	Drop tanks, extra fuel capacity tanks fitted in the fuselage
Innovative control effectors	Vehicle 3-axis stability and control with minimal cross-coupling	Increased range, maneuverability and survivability	Traditional vertical tail configuration
Metal-stamping equipment	Bending complex shapes in low modulus of elasticity materials	Higher production quantities	Simpler contours produced by conventional sheet metal brakes
Low observables external stores carriage	Reducing radar cross-section in a manner consistent with low drag profiles	Better radar penetration to allow aircraft to move closer to target and drop glide vehicle or cruise missile	Internal munitions storage at a decreased payload or volume
Signature reduction techniques	Adding materials and coatings that will not affect structural integrity or flight performance	All air vehicles	None identified

(cont'd)

Table 1.4-2. Combat Fixed-Wing Aircraft Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
PROPULSION			
Turbofan engines	Decrease in net thrust at low altitudes makes low level cruise fuel inefficient	Improved range and ceiling	Any propulsion unit consistent with range and payload needs, e.g., internal combustion engines
Turbojet engines	Thrust is dependent on the maximum stress and temperature levels the engine can sustain for long flights	Improved range and ceiling	Any propulsion unit consistent with range and payload needs, e.g., internal combustion engines
Technology for high temperature and erosion protection coatings for engine parts	Thrust is dependent on the maximum stress and temperature levels the engine can sustain for long flights	Increased reliability and improved range	Ceramics and carbon carbon inserts
Inlets for transonic and low supersonic flight speeds	Forming aerodynamically sound designs that do not choke	Increased range and better defense penetration	Increased drag and reduced range
Propulsion integration for subsonic, transonic, and low supersonic flight speeds	Upgrading existing airframes with more modern engines that may have higher thrust levels or improved fuel consumption	All air vehicles	None identified
Chemical Vapor Deposition (CVD) equipment	Manufacturing equipment maintenance to ensure reproducibility	Improved reliability	None identified
Thermal spray forming equipment	Maintaining thermal control and flow consistency	Improved reliability	None identified
GUIDANCE, CONTROL, AND NAVIGATION			
Digital radar maps	Reducing radar images to digital representations that can be stored and retrieved efficiently	Delivery of a munitions within a lethal radius	GPS topographical maps
Global Navigation System	Time required to calculate position and corrections to position to obtain desired flight path	Delivery of a munitions within a lethal radius	IMUs; radio controlled or preprogrammed flight profiles
Map Guidance Technology	Resolution of the surface of the Earth particularly in height in order to ensure all obstacles are cleared by the flight vehicle	Increased operations envelope to include night and all weather flight	More restrictive operational conditions
GPS receivers	Correcting civil code to protected code	Navigation	GLONASS receivers
Full authority flight control system	Maintenance of adequate gain and phase margins; adequate response time over flight envelope; redundancy vs. safety	Increased reliability and accuracy	Pilot integration of parameters
Vibration test equipment using digital control techniques	Properly shock isolating the test equipment so that test results are meaningful	Reliable weapons delivery	Flight testing under highly stressed conditions

(cont'd)

Table 1.4-2. Combat Fixed-Wing Aircraft Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
WEAPONS INTEGRATION			
Weapons separation design and flight prediction	Vibration and shock from interference with the main body both upon release and in a bomb bay or cargo hold with the doors open	Reliable weapons delivery	Flight test program to gather information empirically
Advanced state vector calculation routines	Prediction of non-linear effects from spinning and unsymmetrical parts within the weapon	Delivery within a lethal radius	Conventional bomb sights
Submunitions separation or dispensing mechanisms	Proper release under realistic conditions	Reliable weapons delivery	Flight test program to gather information empirically

SECTION 1.5—ARTILLERY

OVERVIEW

In the Artillery subsection, two military strategies for using artillery to deliver WMD are discussed. Traditionally, artillery has been a battlefield weapon rather than a long-range attack weapon, although the United States, Russia, France, and Britain have demonstrated that conventional artillery tubes can deliver nuclear, chemical and biological agents. Each of these countries had a specific battlefield application for WMD of the 30-km range. Few of the strategic, technical, economic, and political forces that led the superpowers to develop this highly specific capability apply to conditions within proliferants. However, artillery may be attractive to proliferants for other reasons, including the availability of designers and parts and the possibility that a WMD shell from one of the superpower's arsenals could suddenly become available.

As an indigenous product, artillery can be applied as a *strategic* WMD delivery system. Iraq demonstrated imaginative use of artillery in the large investment it made in the Supergun project. In this case, a proliferant chose to develop a strategic delivery system that happened to be a scaled-up version of a well-known artillery delivery system. These vastly different applications of the same basic technology show that a proliferant that pursues artillery as a means of delivery must choose either to use existing artillery pieces and solve the technical problems of designing a shell to accommodate these weapons or design a new weapon for the shell they intend to deliver. The United States, as an example of the former approach, built nuclear and chemical rounds compatible with their existing 155-mm guns. These shells had flight properties that exactly matched the flight properties of conventional ammunition. Iraq, as an example of the latter approach, built the Supergun specifically to fire a single, special nuclear round.

Using Existing Artillery Pieces

When a country can manufacture a WMD shell to exactly match a conventional round, it solves all of the technical problems of gun manufacture because many suppliers on the world market provide artillery pieces in standard 155-mm, 203-mm, and 406-mm caliber gun tubes. Still, the proliferator must solve unique technical problems associated with the WMD warhead.

Nuclear

To use existing artillery pieces, a proliferant must be sufficiently advanced in its nuclear design to make a warhead with a diameter small enough to fit a standard caliber tube. Consequently, to be used in a conventional tube, a nuclear round must match the inertial and aerodynamic properties of conventional shells and be able to withstand the acceleration produced by the firing charge and the high spin rates (up to 250 Hz) of modern artillery shells. If it does not closely meet these characteristics, the shell will suffer from poor range and accuracy.

Since nuclear shells have components made of high atomic-number materials and these materials are traditionally configured in a spherical shape, aeroballisticians must frequently add supplemental materials to match the mass of nuclear artillery shells and the ratios of the moments of inertia. Countries that have solved this problem have used highly dense materials, such as depleted uranium, as a ballast.

As an alternative, a country can ignore the question of range loss and high dispersion and accept reduced performance. Often, this means that their military can only fire the shell to its maximum range, and an extensive testing program is required to determine the limits of the dispersion. Since the surrogate shells used in this test program must inertially match the real nuclear rounds and a statistically meaningful

Highlights

- Artillery pieces for possible delivery of WMD exist in virtually every military organization in the world.
- A proliferant must harden WMD shells against high spin rates and accelerations to use an artillery piece to deliver WMD.
- Existing artillery pieces have insufficient range to allow a proliferant to use artillery as a strategic WMD delivery system except in special circumstances.
- Nuclear warheads are difficult to fit into existing conventional artillery tubes.
- Several proliferants have the technical capability to custom-build long-range guns, similar to the Iraqi Supergun, to deliver WMD.
- Superguns are expensive and have limited sustained firing potential.
- Use of Multiple Launch Rocket Systems overcomes some artillery limitations.

test program requires many firings, the proliferator must have a ready source of high atomic-number (non-nuclear) material to use in its test rounds.

A nuclear-capable proliferant must also be able to build a nuclear round that can withstand the high acceleration produced by the firing charge. For example, in most full-range 155-mm rounds, the initial acceleration on the shell may exceed 10,000 g's. The proliferant that builds its nuclear shell indigenously must be able to form insensitive high explosives in complex shapes that resist cracking and spalling under these accelerations. They must also be able to build a special nuclear fuze, which differs from the fuze in a conventional round, and the fuze electronics that can withstand the acceleration and still perform normally at the end of the trajectory.

Since the aerodynamic shape of the shell must also match a conventional round, few, if any, changes can be made to overall shell design. If the artillery shells are made indigenously, the proliferant has the means to make any type of casing for a nuclear shell. For a nuclear shell, a proliferant can make one concession to the warhead when the shell must be stored for a long period of time. The designers may have to substitute a new outer casing material that is less sensitive to embrittlement from a low-level nuclear radiation environment.

Chemical

Since the specific gravity of most chemical agents is near to that of conventional high explosives, a chemical round for an existing artillery piece requires even fewer design concessions than a nuclear round. With only minimal ballasting, designers can match the inertial properties of chemical and conventional shells quite easily.

Because the materials involved have mid-range atomic numbers, ballasting can be made from many materials. In flight, though, chemical WMD, being a fluid, has a tendency to change its inertial properties because of the centrifugal force created by the spinning shell. Binary chemical agents take advantage of this spinning to mix the compounds. But the spinning momentum forces the fluid to migrate to the outer casing wall of the shell and alter the inertial properties in a way that conventional high explosives—most often being solid—do not. As the shell flies, this fluid migration has a tendency to cause large coning angles and increase the drag on the body.

Liquid migration is a function of many properties of the WMD, but the most important is the viscosity of the liquid. Proliferants may solve the variable inertial problem by modifying the viscosity of the liquid with liquid additives or by including internal baffles that dampen the motion of the liquid when the shell is fired.

The liquid material is fairly insensitive to the shock of firing and virtually no accommodation needs to be made for WMD rounds beyond that already made in conventional rounds. The fuzing and firing circuits of chemical rounds do not require the high energy and precise timing of nuclear rounds; thus, one can manufacture a high explosive detonator for an artillery shell and use this same detonator on a chemical round with little modification. Both chemical and biological rounds do require efficient dissemination mechanisms since the agents must be spread over a large area. Submunitions and the technologies that remove them from an artillery shell in flight and decelerate them or alter their flight path support the more efficient dispersion of agent. Radar fuzes or timers that can open a shell and release submunitions must have a firing precision of better than 50 ms to be effective.

Biological

Biological agents have properties similar to chemical agents and the design considerations for artillery shell delivery follow similar reasoning. Biological toxins generally withstand the shock of firing from an artillery tube with little degradation in performance. Live biological agents, on the other hand, degrade significantly when placed in this high acceleration environment. Virtually any proliferant that can manufacture an artillery shell for special purposes, such as incendiaries or flares, has all of the technological sophistication at its disposal to deliver biological toxins in this manner. On the other hand, the high acceleration experienced by all artillery shells means live biological agents are unlikely candidates for this means of delivery unless microencapsulation or other buffers are used to alter the susceptibility of the agent to shock. Spores of certain pathogens, such as anthrax, resemble toxins in their ability to withstand shock.

Most deliverable biological agents, however, have lower specific gravities than existing conventional rounds. The light weight of the biological material, which may include fillers, release agents, protective coatings, and agglutinating matter to accrete a respirable particle, requires a country to consider carefully means to ballast the shell to match the inertial properties of conventioanl rounds.

Ancillary Technologies Common to All Types of WMD

The two technical hurdles that must be overcome to use WMD in artillery shells—protection against acceleration and matched inertial properties—can be replicated in a laboratory setting or simulated on a computer. Flight trajectory prediction programs with 6-degree-of-freedom modeling will reveal to an analyst the degree of uncertainty in a shell's flight path when inertial properties are mismatched with conventional shells. Less computer-intensive point mass models predict with a high degree of accuracy this same information. Since any user of conventional artillery shells knows in advance the aerodynamic properties of the shell, little, if any, need exists for wind tunnels or finite element fluid modeling. Devices that measure the moments of inertia for many applications other than military purposes are easily adapted for use in measuring artillery shells. Any entity that does not already possess this equipment can purchase it legitimately on the open market.

Reproducing the high accelerations of a gun launch in a laboratory setting is difficult, so experimentalists often resort to subscale tests using small bore cannon or other energy producing devices such as rail guns. A proliferator that wishes to test the response of a new pathogen to high acceleration can use these techniques and then assume that incremental increases in full-scale models follow an extrapolation of the results they have measured.

A proliferator with a slightly more advanced design capability can extend the range of the 155-mm shell to approximately 50 km, either by using base bleed supplemental blowing to shape the aerodynamics over the boat tail or by lengthening the barrel. A lengthened barrel increases the spin rate proportionately and exaggerates all of the problems formerly identified with spinning shells. For use beyond 50 km, the proliferant must manufacture both the gun and the shell. Fifty kilometers is sufficient range for a proliferant to threaten coastal cities or an adversary's territory adjacent to a common border.

The "Foreign Technology Assessment" paragraphs will discuss which countries can develop WMD to fit existing artillery pieces. It also discusses which countries have the technical wherewithal to continue to pursue research into a Supergun.

The tables that follow this text list, in order of priority, technologies that a proliferant needs to produce WMD artillery shells that fit into existing guns and then cover the more stressing task of building a new artillery piece on the scale of the Supergun.

Multiple Launch Rocket System as a Means of Delivery

In many cases, the flight dynamics limitations imposed on the use of WMD with artillery shells can be mitigated by employing a Multiple Launch Rocket System (MLRS). MLRS batteries launch a salvo of missiles against a target from a collection of launch tubes mounted on, or towed by, a highly mobile vehicle. Generally, the delivery systems constituting a MLRS have a range of less than 50 km, but the exact range can be extended depending on the circumstances. Since the MLRS uses a rocket as its basis, the accelerations that a warhead endures at launch are much less than those for an equivalent range artillery shell. Similarly, the rocket uses aerodynamic stability with fins or airframe shape so the warhead is not subjected to the high spin rates that an equivalent range artillery shell needs to maintain gyroscopic stability. Also, the rocket does not travel as fast as an artillery shell, so fuzing and firing operations can be less precise than with an equivalent artillery shell. This long flight time also gives submuntions an opportunity to be dispensed properly.

In the field, the MLRS offers many logistical and tactical advantages for delivering chemical and biological agents. Since the attacker uses the MLRS in a salvo mode, the individual missiles can be launched to cover a large area when they arrive at a target. This could lay down an effective cloud of chemical or biological material, which may deny large areas of a battlefield to a defender. However, care must be taken to ensure that the close proximity of salvo round detonations does not have a negative effect on agent vitality or dispersion. Consequently, this tactic makes MLRS an unlikely choice for nuclear munitions.

Since MLRS systems have widespread applications for anti-personnel, anti-tank, and anti-armor operations, knowledge of their design, manufacture, and use is widely available to many U.S. allies and trading partners. Many derivative versions of the system have been built to accomplish special targeting objectives that have application to the use of WMD. For instance, the Army Tactical Missile System (ATACMS) used with the MLRS uses a special, long-range missile while the anti-tank version deploys a submunition in mid-flight, similar to the deployment that would be required to deliver chemical or biological agents efficiently.

In the U.S. version of the MLRS, which has been widely studied overseas, the rocket can accept a warhead weight of up to 156 kg on a system with a total weight of 306 kg. This is about twice the payload that a 155-mm shell delivers and at a price of about three times the system weight. Hence, the warhead structural efficiency factor is less than that for artillery shells, but the simplicity of the operation more than compensates for the loss of efficiency. An MLRS rocket, as built by the United States, has a diameter of 227 mm and a length of 3.937 m, making it easy to ship, stockpile, and deploy.

The United States has sold MLRS systems that theoretically can be retrofitted for chemical or biological use to many trading partners abroad. A Memorandum of Understanding among the United States, Germany, France, the UK, and Italy allows for joint development, production, and deployment of the United States design. Currently, the United States and others have sold and deployed the MLRS in Bahrain, Denmark, France, Germany, Greece, Israel, Italy, Japan, the Netherlands, Norway, Turkey, the UK, and the United States. Russia and the FSU have several variants of an MLRS in production and service. In fact, in the latter half of the decade, a clear competition has emerged between the United States and the Russians to sell MLRS systems as part of their arms packages. The Russian systems are made by the SPLAV consortium and are called the SMERCH: a 300-mm rocket, the Uragan, a 220-mm system, and the Prima, which is 122 mm in diameter. The Russians also wish to market two other systems, which are both 140 mm in diameter. The Russians have sold the 300-mm Smerch to Kuwait and the United Arab Emirates (UAE), and the Uragan system has been sold to Syria and Afghanistan. Many other variants still exist in the former Eastern Bloc states.

RATIONALE

Artillery shells present the exception to the rule that a proliferant must pursue some technological capability to deliver WMD. Artillery pieces are ubiquitous in any military; thus, armies are fully trained in their use. The United States and the Soviets built a large arsenal of nuclear and chemical shells to fit these existing artillery pieces and designed them so that all of the preparations and firing procedures associated with them closely mirror conventional rounds. The United States is in the process of destroying its chemical shells, but some do exist and many nuclear artillery shells are still in Russia. Consequently, the possibility that a proliferator could find a way to acquire a fully weaponized WMD shell and use it in existing military hardware cannot be ruled out.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 1.5-1)

Since virtually every country in the world with a military has artillery pieces and the training to accompany their use and theory of operation, a proliferant must only manufacture the WMD shells for these guns if it intends to deliver the munitions at ranges less than 50 km. As an alternative, proliferants may clandestinely acquire shells to use in their artillery pieces. The United States, Russia, and, by common belief, Israel have made nuclear shells. The United States, Russia, reportedly France, and possibly Israel have made chemical and biological shells. The United States builds its shells in standard 155- and 203-mm caliber. Most European countries use the same bore. In the Russian tradition, the Soviet Union built its shells in 152- and 202-mm caliber. A shell from these stocks fits and can be fired from the larger bore U.S. and European guns, but the reverse is not true. When the smaller Russian shells are fired from U.S. and European guns, there is a small additional blow by and consequent loss of acceleration to the shell. Even then, care must be taken to ensure that the close proximity of salvo round detonations does not have a negative effect on agent destruction or dispersment; therefore, this configuration produces a slight range loss and additional wobble upon exit from the gun.

The United States, Canada, Sweden, Denmark, Finland, Austria, Norway, Belgium, France, Germany, the Czech Republic, all the Baltic Republics, Ukraine, Belarus, Italy, Spain, Greece, elements of the former Yugoslavia, China, North Korea, South Africa, Israel, Egypt, Cuba, Vietnam, South Korea, Taiwan, Iran, Iraq, Pakistan, India, and Afghanistan have all built artillery pieces or have the infrastructure to build them according to either the U.S. and European standard or the former Soviet one. Most of these countries' military officers have been trained on the weapons and are capable of advising a proliferant on methods to either build the guns or obtain them legitimately from a supplier nation. If a proliferant found itself in possession of a standard WMD artillery shell, any of these countries could supply the gun to fire it for less than $250,000, without even needing to understand the nature of the shell.

A proliferator may decide to manufacture its own gun, particularly if it designs a WMD device employing a gun-assembled, as opposed to an implosion, nuclear weapon. An entry-level, gun-assembled, nuclear weapon requires a gun barrel diameter of approximately 650 mm rather than 155 mm. There are some 16-inch (406-mm) guns in many nations' arsenals, and an innovative gun-assembled nuclear weapon may have a diameter this small. But the 16-inch guns are not as readily available as the 155-mm guns, and a proliferant would generate the attention of export control authorities if it tried to purchase one.

Several proliferants have the technical capacity to build a gun approaching the Supergun if they can find a supplier of specialty steels for the barrel and large action hydraulic cylinders for the recoil mechanisms. The specialty steel tubes must have interior surfaces with deviation in diameter of less than 50 μm per 20 mm of tube diameter and deviation from a true longitudinal axis of less than 1 mm per meter of length. Oil-producing nations that produce their own pipelines, as a rule, have no reason to make tubes that meet the standards of gun barrel manufacture. Pipelines generally carry oil under a pressures of several atmospheres, rather than the several hundred atmospheres that are required for a gun barrel. Moreover, there are no stringent requirements on pipelines for interior surface finish, diametrically, and straightness.

Egypt, Israel, Pakistan, South Korea, and India either have the capability or could quickly obtain the ability to build large bore gun barrels. Many South American nations, in particular Argentina and Brazil, also have the industrial and metallurgical industry to support large bore gun manufacturing.

Country	Weapons Integration			Artillery Place		Aiming and Firing			Propulsion		
	Inertially Matched Shells	High-Energy Burster Charges	Fuzing and Firing Circuits That Withstand Spin and Shock	Barrel Extension for Extended Range	Indigenous Manufac-turing of Gun	Develop-ment of Firing Tables for WMD	Automated Gun Sights Using GPS to Aim	Wind Tunnel and Other Laboratory Equipment to Measure Flow Field	Indigenous Manufac-turing of Large Bore (<400 mm) Guns	Indigenous Manufac-turing of Propelling Charges	Base Bleed Range Extension
Argentina											
Brazil	♦♦♦	♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦	♦♦	♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Chile	♦♦	♦	♦	♦♦	♦	♦♦	♦♦	♦♦	♦	♦♦♦	♦
China	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt											
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
India	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦♦
Iran	♦♦♦	♦♦	♦	♦♦	♦♦	♦♦♦	♦♦	♦	♦	♦♦♦	♦♦
Iraq	♦♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Japan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦♦♦	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦
North Korea	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦♦	♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦
Pakistan	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦	♦♦♦♦	♦♦	♦♦	♦♦♦	♦♦♦♦	♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
South Korea											
Sweden	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Syria	♦♦	♦♦♦	♦♦	♦	♦	♦♦♦	♦	♦	♦	♦♦♦	♦♦
Taiwan	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦
Ukraine	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦	♦♦♦♦	♦♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 1.5-1. Artillery Foreign Technology Assessment Summary

Table 1.5-1. Artillery Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
High capacitance batteries	Resistant to 250 Hz spin rate, and 10,000 g's acceleration, 30V output @ 300 mA	WA Cat. 3A; CCL Cat. 3A	Non-fluid electrolytes, or fluorboric acid in copper ampules	None Identified	None Identified
Radar altimeters	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	MTCR 11; WA Cat. 7A; CCL Cat. 7A; USML XI	None Identified	None Identified	Altitude calculation cycle time <50 msec
Radio timing fuze	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	WA ML 11; USML XI	None Identified	High-speed data acquisition equipment and computer boards	Timing accuracy <5% of set time for set times of 5 to 150 seconds
Electronic timers (e.g., US M724 electronic fuze)	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	WA ML 11; USML XI	None Identified	High-speed data acquisition equipment and computer boards	Event sequencing capability <5 msec.
Bursters	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	WA ML 11; USML XI	None Identified	None Identified	None Identified
Expelling charges	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	WA ML 11; USML XI	None Identified	None Identified	None Identified
Casing material	Resistant to low level radiation background	CCL Cat. 1	Phenolics	None Identified	None Identified
Dual canister burster charge	Resistant to 250 Hz spin rate, and 10,000 g's acceleration	WA ML 11; USML XI	None Identified	None Identified	None Identified

Table 1.5-2. Artillery Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
High capacitance batteries	Nuclear firing circuits require high energy initiation, which must be contained in a lightweight package to fit on an artillery shell	Reliable detonation	None Identified
Radar altimeters	Altitude must be sensed with sufficient accuracy to release aerosol under the atmospheric shear layer but before ground impact	Chemical or biological weapon detonation	Timing circuits, barometric sensors, acceleration detectors
Radio timing fuze	Range and range rate must be calculated in a moving reference frame	Any airborne conventional, chemical, or biological weapon	Timing circuits, barometric sensors, acceleration detectors
Electronic timers (e.g., US M724 electronic fuze)	Designing electronic circuits with piezoelectric crystals that remain unaffected by high shock loads	Reliable detonation	High-speed data acquisition equipment and computer boards.
Bursters	Bursters must not fire prematurely in high shock environment	Reliable detonation	Any insensitive high explosives
Expelling charges	The expelling charge must decelerate submunitions sufficient so that air brakes or parachutes may be deployed; often this must be done in a short times span and high energy charges may damage biological or chemical agents.	Submunition dispensing	None Identified
Casing material	Embrittlement occurs when some steels are exposed to intrinsic radiation for long periods of time	Applications requiring resistance to nuclear radiation environments	None Identified
Dual canister burster charge	Binary materials are mixed in flight; in order to be mixed, two canisters are usually opened with shaped charges or other HE technology, but the charge can not compromise the chemical or biological agent	Binary chemical munitions	None Identified

SECTION II

INFORMATION SYSTEMS TECHNOLOGY

SECTION 2—INFORMATION SYSTEMS TECHNOLOGY

Scope

Highlights

- Information Systems capabilities, built on the grid of existing military and commercial technologies, enable most WMD operations
- Large damage envelopes of WMD minimize precision weapon guidance, delivery, and information systems dependencies.
- Information Systems (in some form) can be anticipated to be used by most proliferators.

BACKGROUND

There are many different definitions for Information Systems (IS). The following definition is used for Part II:

> *People, technologies, and machines used to capture or generate, collect, record, store, retrieve, process, display and transfer or communicate information to multiple users at appropriate levels of an organization to accomplish a specified set of functions.*

This definition suggests the wide range of technologies incorporated in different Information Systems.

Since Information Systems are likely to be used in most WMD weapons systems, this separate IS section promotes a more consistent, thorough, and effective assessment. These assessments emphasize countries, other than the United States, which might be adversaries. Consideration is also given to coalition arrangements for both adversaries and allies. Enabling IS capabilities relevant to subnational activities are treated insofar as those activities might target nations or nation-states.

Subsets of Information Systems are commonly referred to as Functional Areas. A large information system may have as many as seven functional areas. IS requirements are normally allocated to functional areas (or system segments). For instance, functional area specifications allow system architects to select the best hardware or software implementation solutions available at the time of fabrication and production. Specifications written in terms of bandwidth, signal quality, reliability, availability, and other generic performance parameters leave designers free to make optimum selections. In the media area, for example, metallic or fiber-optic cable or satellite or terrestrial radio can be selected depending on the speeds and accuracies specified as requirements.

Assessing technologies in terms of IS functional area capabilities, as opposed to specific hardware/software composition, minimizes the requirement for revised MCTL assessments as new products or devices are introduced or older ones withdrawn. For example, a new WMD weapon delivery or damage assessment requirement might be discovered for real-time video observation of battlefield or target areas at a remote command center. If no prior real-time video requirement existed in a proliferant’s information systems, then in all likelihood channel bandwidth or bit-rate revisions to the Information Communications functional area capability parameters would be necessary. A real-time observation capability would mean that there is possession of or access to guided or unguided (terrestrial or satellite, radio or optical transmission through the atmosphere or outer space) media technology, with the ability to support video traffic.

Figure 2.0-1 illustrates the extensive scope of what qualifies as an information system and shows the seven traditional functional areas: (1) Information Processing, (2) Information Security, (3) Information Exchange, (4) Information Communications, (5) Information Management and Control, (6) Information Systems Facilities, and (7) Information Systems Sensors. The information system examples in Figure 2.0-1 include large, complex entities such as enterprise management information systems (MIS), telecommunications systems, and even the worldwide Internet. The list could be extended to include numerous smaller systems such as those based on personal computers.

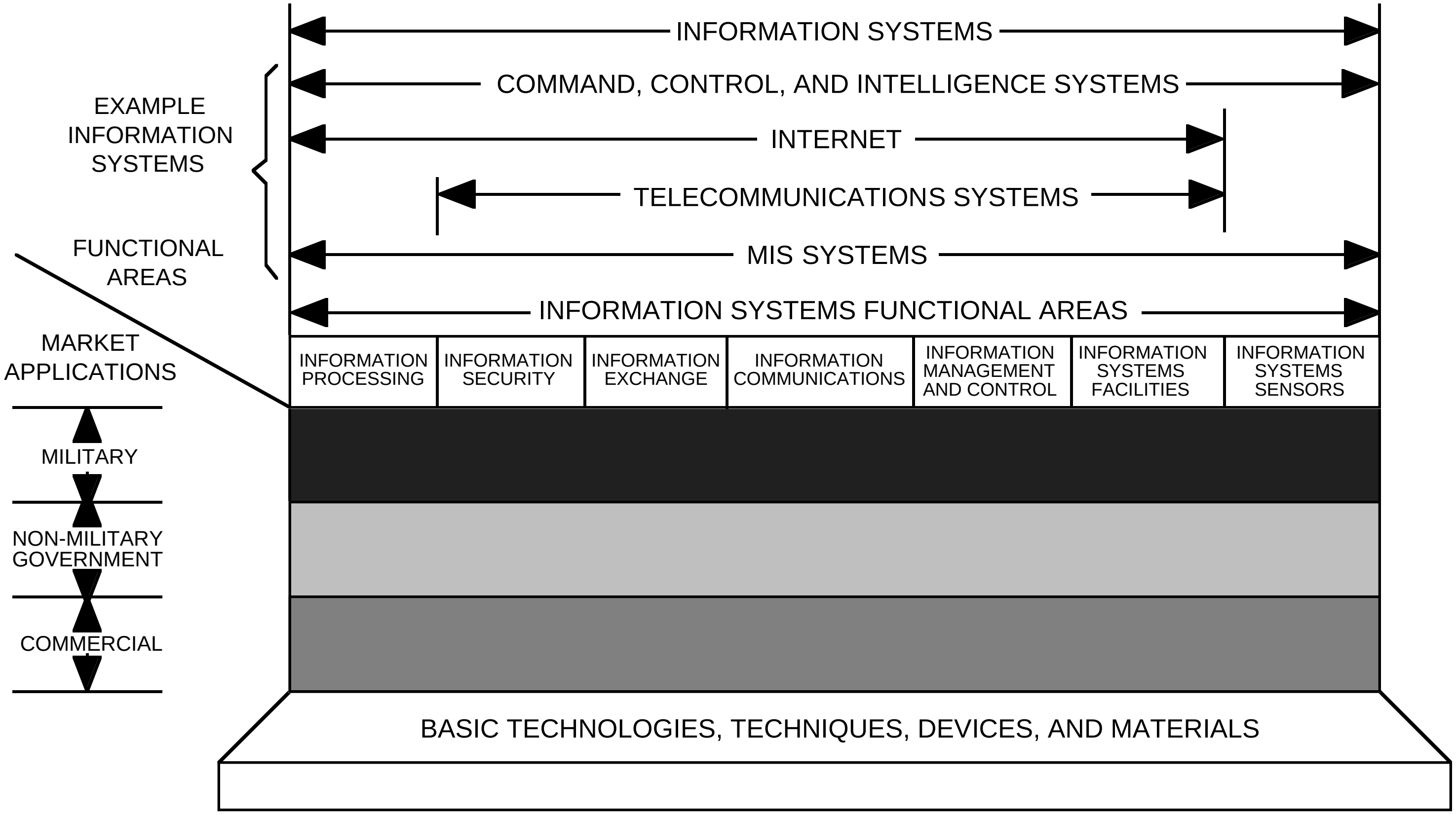

Figure 2.0-1. Information Systems

OVERVIEW

This section identifies IS technologies that have potential utility in implementing and enabling critical WMD operations. Of special interest in this section are Information Systems built on the grid of existing technologies, including those of World War II vintage, as opposed to those depending on development that requires an extensive industrial base. In particular, this section focuses on the minimum set of technologies required for the development, integration, or employment of WMD and their means of delivery. This is in contrast with Part I of the MCTL, in which performance levels ensuring superiority of U.S. military systems were provided.

In Part II, the innovative use of commercial-off-the-shelf (COTS) technology, perhaps in combination with advanced and older military IS technologies, dominates the assessments. In this COTS category are systems that are procured for civilian purposes, which are rapidly re-programmable for military operations. Modern, fiber-optic-based, software-defined telecommunications networks are a prime example. Properly designed, they provide multimedia voice and data service to the general population and can also constitute a highly survivable backbone for equipment that is optimized for military operations.

IS functional areas for WMD capabilities often overlap those cited in MCTL Part I, Section 8. They differ principally in that performance levels ensuring superiority of U.S. systems are not imposed. However, MCTL Part I provides complementary technical assessment information.

RATIONALE

Recent experience demonstrates the value of both military and commercial IS techniques. Unlike the past when DoD, NASA, and other USG agencies dominated and sponsored frontier developments, the vast majority of technologies supporting today's information systems are driven by civil requirements. Increasingly, the government is specifying "off-the-shelf" mainstream commercial "open-systems, standards-based technologies" as the method of choice for avoiding obsolescence in a fast-changing technology environment.

Overall, strategic and tactical military use of information systems encompasses a range of applications from wide-area switched networks serving an entire theater of operations (often countrywide with global interties), to local processing and communications systems including transportable and personal hand-held devices, to IS systems embedded in smart weapons and sensors. Proliferator possession of critical technologies supporting such a diversity of applications can have decisive significance. In areas of direct combat support, information systems sustain the performance advantages of management, command and control, surveillance, and guidance and control systems for weapons of mass destruction.

It should be noted that most of the technology capabilities cited are those that could be of interest to proliferant countries with large numbers of weapons and relatively capable delivery systems. Countries with fewer resources may employ their weapons with minimal IS support. In fact, one reason why WMD are appealing to even subnational groups is that their large damage envelopes and lethal radii reduce the need for precision weapon delivery and other IS dependencies.

In many cases, U.S. military countermeasure capabilities and techniques may be ineffective when used against commercial IS systems. For example, it may be extremely difficult or impractical to successfully electronically jam large metropolitan area cellular communications systems or all commercial satellite systems that an adversary may have at its disposal.

The tables in this section that identify technologies should be interpreted in the following manner. Proliferants with only a small number of WMD and no intention or capability of sustaining a long-term WMD attack may not be strongly dependent upon the availability of any supporting IS technology. When IS technology is required or helps facilitate WMD, under the column titled "Sufficient Technology Level," the statement depicts technology items that meet most requirements identified during analysis of the wide range of WMD scenarios considered in this document. For COTS technology items, the statements generally indicate that commercial-application performance requirements for capacity, service, quality, availability, etc., generally exceed those encountered in WMD application scenarios.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 2.0-2)

The United States currently leads in system engineering and integration of complex information systems, closely followed by the UK, France, Germany, Canada, and Japan. Underlying technologies for Information Systems and wide-area integration of such systems are driven largely by commercial requirements. A significant number of countries have developed capabilities equivalent to those of the United States in network switching and transmission. The United States has sustained its lead in computer hardware because it enjoys superior microprocessor design and fabrication capabilities (see Sections 5 and 10 in MCTL Part I).

While the United States continues to be the only country with critical capabilities in all IS technology Functional Areas (FAs), equivalent capabilities are found in one or more other countries in every FA. The growing multi-nationalization of information systems developments has increased the worldwide availability of advanced IS technologies. U.S. technology leadership in communications and computer systems has declined in recent years relative to Europe and Japan.

Country	Sec 2.1 Information Communications	Sec 2.2 Information Exchange	Sec 2.3 Information Processing	Sec 2.4 Information Security	Sec 2.5 Information Systems Management and Control	Sec 2.6 Information Systems Facilities
Australia	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
China	♦♦	♦♦	♦♦♦	♦♦	♦♦	♦♦
Cuba	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦
Czech Republic	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦
Denmark	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦♦
Finland	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Hungary	♦♦	♦♦	♦♦	♦♦	♦	♦♦
India	♦♦	♦♦	♦♦♦	♦♦♦	♦	♦♦
Iran	♦	♦	♦♦	♦♦♦	♦	♦
Iraq	♦	♦♦	♦♦	♦♦	♦	♦
Israel	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦
Italy	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
Japan	♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Libya	♦	♦	♦	♦	♦	♦
North Korea	♦	♦♦	♦♦	♦♦♦	♦	♦
Norway	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Pakistan	♦	♦	♦♦	♦♦	♦♦	♦♦
Poland	♦♦♦	♦♦	♦♦	♦♦	♦♦♦	♦
Russia	♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦
South Africa	♦♦♦	♦♦♦♦	♦	♦	♦	♦
South Korea	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦	♦♦♦
Sweden	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Switzerland	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦	♦♦♦
Syria	♦♦	♦♦	♦♦	♦♦	♦♦	♦♦
Taiwan	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Vietnam	♦	♦	♦	♦	♦	♦
Subnationals	♦	♦	♦	♦	♦	♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 2.0-2. Information Systems Foreign Technology Assessment Summary

SECTION 2.1—INFORMATION COMMUNICATIONS

OVERVIEW

The Information Communications Functional Area (FA) as generally defined includes transmission facilities, that is, the medium (free space, the atmosphere, copper or fiber-optic cable) and electronic equipment located at nodes along the medium.

In this context, equipment amplifies (analog systems) or regenerates (digital systems) signals and provides termination functions at points where transmission facilities connect to switching or multiplexing systems. Multiplexers combine many separate sources of traffic into a single signal to enhance transmission efficiency. In modern designs, transmission termination, switching, multiplexing, and other functions may be integrated in a single piece of equipment and, in combination, play a major role in defining network capacity and latency, communication services, grade of service, maintenance, reliability, availability, and survivability.

This section addresses a wide range of equipment used in local and long-distance communications. Included in the nonintegrated types are simple repeater/amplifiers, channel service units (CSUs), and data service units (DSUs). CSU/DSUs are termination equipment required to connect customer premises equipment (CPE) to telecommunications networks and typically provide transmit and control logic, synchronization, and timing recovery across data circuits.

Other examples include satellite, terrestrial microwave, and cable transmit and receive terminals (transceivers), which, in most instances, include multichannel capabilities. Modern, fourth-generation and beyond switches and digital cross-connect systems (DCSs) incorporate switching, multiplexing and line-termination functions.

In the case of public cellular or specialized mobile radio (SMR) equipment, Information Communications FA capabilities are combined with traditional application-level functions such as call set-up and take-down dialing, signaling, etc.; advanced features like caller identification; and acoustic and other human interface capabilities.

Thus, it is apparent that basic requirements for communicating information between two nodes can be accomplished through the use of a wide variety of COTS products, each with greater or lesser abilities to support WMD operations. Moreover, whether implemented in modern integrated or prior-generation products, Information Communications Functional Area capabilities are critical for WMD missions of any significant complexity or duration.

RATIONALE

Information Communications Functional Area capabilities, including beyond line-of-sight (BLOS) and secure communications, can be important to WMD operational missions and objectives.

Highlights

- Long-distance, beyond-line-of-sight communications are essential for:
  - – Remote reconnaissance and damage assessment,
  - – Aerial strikes launched from one country on targets in an adversary country, and
  - – Battlefield command and control within large tactical arenas.
- In mixed WMD and conventional conflicts survivable communications are critical to sustaining chemical or biological offensives.

Requirements for BLOS communications arise in both strategic and tactical battlefield WMD warfare. For missile and manned or unmanned aircraft attacks, where the distance between launch points and target designated ground zeros (DGZs) exceeds point-to-point line of sight, there is a need for some form of long-distance communications. Operational situations in which this occurs include aerial strikes launched from one country to targets in another country. Typical targets might be civilian shipping and transportation ports, industrial centers, military command centers, supply depots, and actual battlefield areas. For example, during an ongoing conflict, an aggressor might attempt to create a “plague port” to inhibit an adversary’s ability to receive supplies or disembark allied or peacekeeping forces.

BLOS communications are needed to relay information generated by sensors or individuals in the vicinity of the DGZ back to the strike-force headquarters. Such information may include force status reports; micro-meteorological, indications, and other intelligence data; situation reports; and, damage assessment reports. In the near term, voice or low-rate data communications capabilities from ground-based individuals or manned or unmanned airborne reconnaissance platforms may suffice. In the future, a sophisticated adversary may have a requirement for BLOS communications to relay data from disposable, possibly air-dropped, wide-area, array sensors systems.

Long-distance communications are implemented using terrestrial or satellite relays, long-wave (below 3 MHz) radio transmission, or a combination of these media. Military long-distance systems can be based on either dedicated facilities or shared facilities obtained from public or other common-user networks. Increasingly, modern facilities of either dedicated or shared design, are able to provide integrated voice, data, facsimile, imagery, and video.

At the low-cost end, single-channel long-distance connections can be made today with standard cellular telephones, interconnected to local and long-distance switched networks. In the near future, mobile service from one or more of the following satellite systems—Iridium, Teledesic, Global Star, Odyssey, and Inmarsat—will become available. Tables 2.1-1 and 2.1-2 illustrate pertinent long-distance communications transmission capabilities.

As an example, in the Gulf War, Iraq was unable to sustain its air defense capability after the United States destroyed its air defense communications network. This resulted from direct attacks on communications facilities with conventional, albeit "smart" weapons. WMD conflicts that escalate to nuclear levels impose the possibility of additional "nuclear effects" communications degradation and destruction.

One advantage of chemical or biological warfare is that it does not necessarily threaten physical facilities and infrastructure plants. When employed in combination with conventional or nuclear warfare, many realistic scenarios arise in which the ability to *sustain* any offensive depends critically on survivable communications, which often come under physical attack in mixed conflicts. Under these conditions, home-country communications among various command centers and depots are required to direct long-term WMD assembly and transport to battlefield and/or launch points.

In-country telecommunications systems with extraordinary availability and survivability can be implemented using emerging commercial fiber and Synchronous Digital Hierarchy (SDH)-based telecommunications technologies. In the United States and elsewhere, these systems are built to Synchronous Optical Network (SONET) standards, equal, though not identical, to International Telecommunications Union (ITU) standards.

As noted above, these systems are expected to be procured for civil use. But, with appropriate Information Exchange switching, multiplexing and digital cross-connect facilities (see Section 2.2), and Information System Management and Control capabilities (see Section 2.5), they can (1) be easily used for military applications and (2) achieve acceptable survivability and robustness in the face of physical attack.

The reason for the extraordinary programmability and survivability of modern commercial telecommunications is twofold. First, the flagship and most profitable telephone carrier offerings today are their Software Defined Network (SDN) offerings. SDN allows carriers to offer large customers, who in the past may have opted for private, dedicated facilities-based networks, the option of equivalent "virtual private networks" using shared public network facilities.

These networks not only offer large industry or military customers service indistinguishable from dedicated facilities-based private networks, but deliver those services at lower cost. Moreover, SDNs greatly augment capabilities to modify, optimize, and customize carrier services, in accordance with changing requirements.

Modern commercial telecommunications networks exhibit unparalleled survivability because the market demands it. One of the major U.S. carriers supports the equivalent of 300,000 Washington-to-New York voice circuits. Loss of that connection translates into revenue losses of $30,000 or more per minute. The advent of high-capacity fiber transmission makes it possible to carry an enormous number of voice conversations over a single fiber. Yet that funnel factor means that to ensure profitability and network availability, one must not concentrate that much traffic without extensive back-up or redundant connections. Fortunately, SDH/SONET standards addressed this problem from the outset.

With automated Management and Control and appropriate switching and multiplexing facilities, SDH/SONET networks can be designed to tolerate massive switch and cable-cut failures. In many instances, service restoration can be virtually automatic—accomplished in 15 milliseconds—a time span short enough to prevent disconnect of existing calls.

For example, dual homing and two or four fiber-based bi-directional line-switched ring (BLSR) diversity among switching/multiplexing hubs, along with designed-in capabilities (like embedded SDH/SONET protection routing and automated performance monitoring and diagnostic management functions), yield survivability features that older dedicated military systems with precedence, priority, preemption, and even dynamic non-hierarchical routing (DNHR) cannot approach.

The explanation for this is that these older techniques basically preserved or restored service on a call-by-call basis. On the other hand, one company has announced its U.S. network plan for 38 interlocking rings, with 16 nodes per ring, that will enable hundreds of thousands of equivalent voice circuits to be restored, almost instantaneously.

Since SDH/SONET systems can accommodate the world's largest common-user network traffic loads, bandwidth or channel capacity requirements encountered in WMD or conventional warfare scenarios can be met without resorting to state-of-the-art switching speeds or ultra-broadband transmission systems.

Satellite-based services offer commercial communications exhibiting significant availability and survivability. One class of service that provides virtually undeniable service is mobile communications via hundreds of satellites through Iridium, Teledesic, and the other systems mentioned earlier. Another class of satellite service supports very small aperture terminals (VSATs) which employ small suitcase-packaged antennas 1.5 to 6 feet in diameter. Finally, high-capacity, multichannel trunk satellite service can be supported with larger but still transportable earth terminals.

Not only is it difficult to electronically jam or physically disable the large numbers of satellites providing such services, but to do so may interrupt service to thousands of worldwide users, whether or not they are involved in a conflict. For practical purposes, satellite-based communications exhibit dual, BLOS and equivalent high-survivability capabilities.

FOREIGN TECHNOLOGY ASSESSMENT

The first column of Figure 2.0-2 contains a comparative representation of foreign technology assessments for the Information Communications Functional Area by country and for subnational groups. All of the developed Western nations in the G8 (Canada, France, Germany, Italy, Japan, Russia, the United States, and the UK), except recently joined Russia, plus the Scandinavian countries, Israel, and Taiwan, have capabilities in all elements of the Information Communications Functional Area, including transmission facilities and required electronic equipment located at nodes along the medium, in their installed base. Of the G8, only Russia has considerable development ahead before she becomes comparable to the other members. However, like China, this comparatively late development may be an advantage to Russia because she is not burdened with a large installed base of outmoded analog equipment and bandwidth-limited non-fiber-optic transmission. Therefore, Russia, China, and other lesser developed countries can more readily expand their capabilities with modern equipment, avoiding performance penalties involved with hybrid facilities. The China assessment may be low since one indicator of China's Information Communications Functional Area capabilities is that the United States alone takes up 40 percent of China's exports. Part of this 40 percent, in which China's trade surplus with the United States is greatest, is telecommunications equipment, and China manufactures its own fiber-optic cable.

Most of the other countries with lesser developed telecommunications (Cuba, the Czech Republic, Egypt, Hungary, India, Iran, Iraq, Libya, North Korea, and Vietnam) have lower Information Communications Functional Area capabilities, which tend to be concentrated around the larger population centers; however, these deficiencies could be corrected in a comparatively short period of time with supplemental satellite systems. For example, Iran's telecommunications installed base is limited to Tehran and its surrounding area. An exception to this generality is Iraq. Iraq's baseline telecommunications capabilities are much less concentrated on the population centers and are more country-wide. See subsection 8.11 in Part I of the 1996 MCTL.

Table 2.1-1. Information Communications Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Very-small-aperture terminals (VSATs)	Transport service provided via commercial satellites or via proliferant-owned satellite. Bandwidth sufficient to transmit imagery to mobile stations. Long range, highly available.	CCL EAR 99	None Identified	None Identified	None Identified
Public cellular, local and long-distance exchange, or specialized mobile radio service.	Interference resistant, but limited bandwidth may not support all required traffic types and volume for advanced employment	CCL EAR 99	None Identified	None Identified	Capabilities beyond normal commercial practice.
Long wavelength radio communications	Beyond-line-of-sight (BLOS), greater than 100 m wavelength (below 3 MHz)	CCL EAR 99	None Identified	None identified	Empirically validated code for predicting propagation characteristics of BLOS radio and advanced data encryption for compression of algorithms for rapid transfer of data.
Public mobile service via multi-satellite systems, e.g., Iridium and Teledesic, Inmarsat, Odyssey, and Global Star.	Limited bandwidth may not support all required traffic types and volume for advanced employment	CCL EAR 99	None Identified	None Identified	Capabilities beyond normal commercial practice.
Fiber-optic cable installations (See Sections 2.2, 2.5)	Configured to support 2- or 4-wire-based Synchronous Digital Hierarchy (SDH)/ SONET enhanced survivability requirements	WA Cat. 5E, P1; CCL Cat. 5E, P1	None Identified	Specially designed, commercially available fiber-optic cable test equipment.	None Identified

Table 2.1-2. Information Communications Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Very small aperture terminals (VSATs)	Mobile, COTS, mass-produced, low cost (~ $25K). Transport service provided via commercial or proliferant-owned satellite. Satellites subject to jamming and physical attack, but commercial impact may deter attack except under extreme situations.	Long-distance, beyond-line-of-sight (BLOS) communications between target vicinities and C^2I headquarters.	Transport service via proliferant-owned satellite; public cellular, local exchange (LEC) and Inter-exchange (IXC) carriers; public mobile multi-satellite communications, BLOS radio.
Public cellular, local and long-distance exchange, or specialized mobile radio service.	Vulnerability of management and switching centers.	Long-distance, beyond-line-of-sight (BLOS) communications between target vicinities and C^2I headquarters.	VSATs with transport service via commercial or proliferant-owned satellites; public mobile multi-satellite communications; BLOS radio.
Long-wavelength radio communications	Susceptible to jamming and radiometric transmitter position location; limited bandwidth.	Long-distance, beyond-line-of-sight (BLOS) communications between target vicinities and C^2I headquarters.	Public cellular, LECs and IXCs; public mobile multisatellite communications; VSATs via commercial or proliferant-owned satellites.
Public mobile service via multisatellite systems, e.g., Iridium and Teledesic, Inmarsat, Odyssey and Global Star	Service not yet available; multiplicity of satellites decreases vulnerability. Limited mobile channel bandwidth may not support all required traffic and volume types.	Long-distance, beyond-line-of-sight (BLOS) communications between target vicinities and C^2I headquarters.	Public cellular; LECs and IXCs; VSATs via commercial or proliferant-owned satellites; BLOS radio.
Fiber-optic cable installations (See Sections 2.2, 2.5)	SDH/SONET enhanced survivability designs needed to achieve needed availability levels.	Local and long-distance communications for in-country communications.	Metallic or other local and long-distance transmission media.

SECTION 2.2—INFORMATION EXCHANGE

OVERVIEW

Information Exchange (IX) is an IS functional area to which switching and multiplexing are usually assigned. As illustrated in Figure 2.2-1, all forms of circuit, packet, and SDH/SONET transport network-based line and path routing and switching are implied. In circuit switching, the IX functional area encompasses call-by-call [e.g., central office (CO) telephone exchange] as well as channel switching.

In the past, channel switching was implemented manually at technical control centers. In the United States, by the late 1980's, digital cross-connect systems (DCS) began to be installed in 24-channel ("T1," or more properly, DS-1) group-based Asynchronous Digital Transmission Systems (ADTS). Some DCS equipment provides not only channel switching at DS-1 rates (1.544 MBps), but also (1) "add and drop" multiplexing without "breaking out" each 64 Kbps DS-0 channel, and (2) supergroup (DS-"n") channel switching. Moreover, it achieves these functions in compact, programmable equipment. Much of this vintage equipment is still in operation.

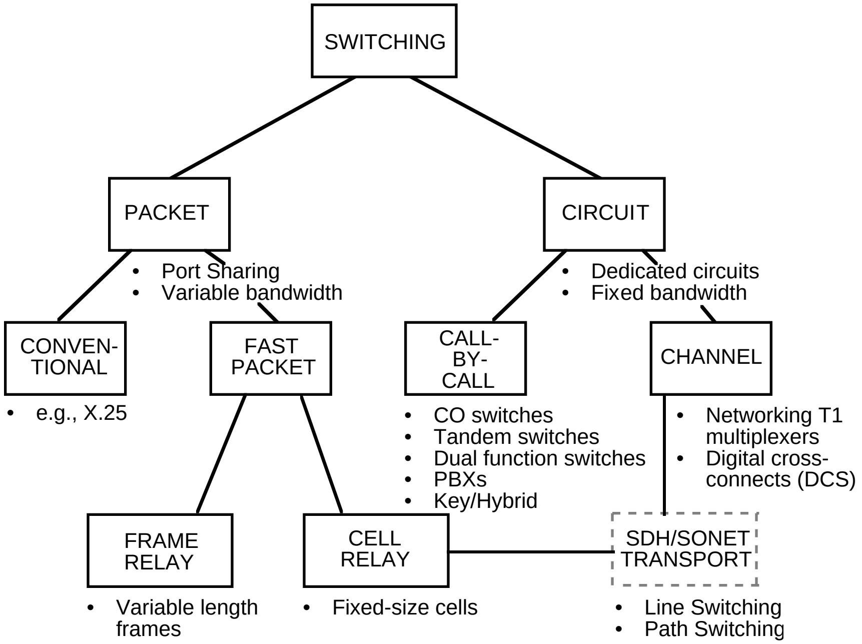

Figure 2.2-1. Routing and Switching Systems

> ***Highlights***
>
> - Circuit switching, packet switching, and multiplexing are Information Exchange Functional Area capabilities generally available and installed worldwide, and require constituent elements in all but stand-alone, desktop information systems.
> - Stored program control central office and digital cross connect switching are key to Software Defined Networks that can be used for survivable communications capabilities supporting WMD operations.
> - Transportable and dual (Central Office and tandem) function switches further enhance network survivability.
> - Fast packet, Asynchronous Transfer Mode-based switching and multiplexing support voice, data, graphics, imagery, and video requirements.

Today, ADTS DCS equipment is being replaced by SDH, International Telecommunications Union (ITU) G-Series or SONET-compliant synchronous byte interleave multiplexer equipment. SDH/SONET-based DCS equipment exhibit all basic asynchronous DCS features.

Beyond basic features, SDH/SONET DCSs capitalize on all of the considerable advantages of synchronous transmission and multiplexing. Among these advantages is the ability to support synchronous payload envelopes (SPEs) that extend "add and drop" capabilities across all SDH multiplexing hierarchy levels.

In addition, to enhance survivability and availability, SDH/SONET-based bi-directional line-switched rings (BLSRs) provide reusable bandwidth for more efficient inter-node transport in evenly meshed networks. A meshed network means traffic is more or less evenly distributed among all nodes rather than being funneled through a few hubbing locations.

Half the available bandwidth in a BLSR is allocated as a working rate evenly distributed among all nodes rather than being funneled through a few hubbing locations, and the other half is reserved for protection routing. Thus, in an optical carrier, OC-48,[1] application, working traffic is placed in the first 24 STS[2]-1 time-slots, with time-slots 25 through 48 serving as the protection facility. In conjunction with ITU Telecommunications Management Network (TMN)-based management functions, this can result in unparalleled recovery from transmission failures, whether failures occur naturally or from intended or collateral enemy attack damage.

Network designs using early versions of these techniques have dramatically improved restoration from man-made or natural outages. For example, in 1991 it typically took 120 minutes after a failure to restore 35 DS3 circuits (about 24,000 equivalent DSO (or voice circuits). On July 30, 1996, more than 200,000 circuits were taken out of service when a water department crew bored into a fiber-optic cable in North Carolina. In this case, 92.8 percent of the service was restored in three minutes, nearly 10 times the number of circuits in 3 percent of the time. See Section 2.5 for a discussion of automated Information Systems Management and Control Functional Area technologies that can lead to this kind of performance in networks used to support WMD missions.

What makes performance improvements of this magnitude possible is not just programmable switching, multiplexing, and computer-based network control technologies, but the fact that with broadband fiber optic cable and capacity-extending wavelength division multiplexing, for availability and survivability purposes, designers can virtually assume that spare or reserve capacity is “free.” That is, in large commercial or public networks, the 50-percent BLSR “call fill-rate” has no appreciable negative cost or revenue impact.

Another technology category included in the Information Exchange Functional Area is the wide variety of equipment generally described under the rubric of packet switching. As Figure 2.2-1 shows, packet switching encompasses conventional and fast packet realizations in both frame and cell relay appearances. Although it is generally appreciated that modern telecommunications systems are increasingly able to integrate voice, data, video, and other services, as noted earlier an even more systemic form of integration is occurring: that is, the integration of switching and multiplexing within single equipment envelopes.

This development trend is a logical one: early digital circuit switches employed time-division multiplexing techniques (augmented in larger switches with space division multiplexing) to accomplish switching functions.

The most recent, and perhaps the most promising manifestation of the integration of switching and multiplexing functions in common equipment, is the Asynchronous Transfer Mode[3] (ATM) digital facility. However, more common so-called local area networks (LANs) and satellite access schemes also provide means for sharing common circuits among multiple traffic channels (multiplexing), and provide either connection-oriented or connection-less switching and call establishment functions.

In addition to the switching and integrated switching-multiplexing equipment described above, equipment assigned to the Information Exchange Functional Area also includes older non-switching “channel bank” and flexible digital time division multiplexers, as well as all forms of analog electronic and photonic multiplexers (e.g., modern, wavelength-division multiplexers).

RATIONALE

The reason that IX Functional Area capabilities are so important to WMD operations is the same reason that they have commercial significance. Quite simply, IX capabilities are required constituent interconnection elements for any information system that extends beyond a “stand-alone” desktop installation.

Stored program control central office and digital cross-connect switching is key to Software Defined Networks (SDNs). One of the principal advantages of SDNs is that they permit near-real-time network reconfiguration to optimize performance for a wide variety of traffic types and loading or in response to network damage or outages. These same programmability features allow peacetime civilian networks to be rapidly converted to highly survivable communications assets supporting crucial WMD operations.

Equally valuable for WMD operations is the increased accessibility that end-user organizations have to telephone-company-based SDN management and control facilities that allow them to create and optimize individual subnetworks in accordance with unique customer (in this case, WMD force elements) service and configuration profiles.

In fact, with the exception of long-wave radio, all BLOS and wide-area communications network survivability capabilities described in the Section 2.1, depend critically upon IX capabilities. You don’t build terrestrial or satellite, fixed, cellular, or specialized mobile telecommunications systems without switching and multiplexing. A recent urban warfare study revealed that the Russians in Chechnya, the Israelis in Lebanon, and the British in Northern Ireland all resorted to commercial cellular services for mobile troop communications when military-issue portable radio performance proved unsatisfactory within cities.

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[1] OC “n,” the “nth” level in an optical carrier multiplexing hierarchy.

[2] Synchronous Transport Signal Level 1, basic SONET building block, electrical equivalent of OC-1.

[3] ATM, a cell relay-based form of fast packet switching, uses fixed, 53-byte packets, suitable for voice, data, and other services, in either fixed or variable bit-rate formats.

When operational, Iridium, Teledesic, or other satellite-based capabilities will be even more relevant in satisfying military urban mobile communications requirements since the service will involve reduced reliance, or none at all, on indigenous telecommunications facilities. Clearly, all these systems depend critically on highly sophisticated Information Communications, Information Exchange, and Information Systems Management and Control functional area technologies.

Satellite-based mobile telecommunications of the type just described is one example of commercial technology for which there appears to be no practical military alternative. This statement is true unless one wants to defend the position that there exists in the world a country willing and able to deploy an Iridium or Teledesic-like satellite constellation for dedicated military use only.

COTS dual-function switches that combine central office and tandem switching capabilities are also available. This means that in combination with SDH/SONET transmission systems discussed above, the physical location of switching within a network no longer needs to be fixed or pre-assigned. This results in enormous survivability and service restoration benefits. In the same vein, dual-function switches also enable cost-effective means of time-phased upgrading of obsolete telephone systems in urban areas such as Moscow or in many third world metropolitan areas.

Transportable central offices used for disaster recovery by telephone companies represent another commercial technology with significant WMD operations survivability potential. Tables 2.2-1 and 2.2-2 list specific Information Exchange technology capabilities.

FOREIGN TECHNOLOGY ASSESSMENT

The second column of Figure 2.0-2 contains a comparative representation of foreign technology assessments for the IX functional area by country and for subnational groups. The IX functional area capability profiles of most countries are similar to their Information Communications capabilities. There are, however, some exceptions in the cases of smaller or less-developed countries. Iraq's IX functional area is assessed as greater than its Information Communications capabilities, as is Germany's, Japan's, North Korea's, Russia's, and South Africa's, whereas Israel, Poland, and Taiwan are assessed as having fewer IX functional area capabilities than their Information Communications Functional Area capabilities. These lesser IX functional area capabilities can significantly affect the overall performance of their information systems.

The switching and multiplexing capabilities associated with the IX functional area are common to both military and civil systems and have become readily available through joint developments or through foreign sales. The ranking of IX functional area capabilities largely reflects the effects of international standardization. Australia, Canada, Denmark, Finland, France, Germany, Japan, Norway, South Africa, Sweden, Switzerland, and the UK have overall IX functional area capabilities equal to those of the United States, although U.S. capabilities may surpass them in some niche technologies such as optical systems. All of these countries, plus Italy, sell switching equipment worldwide. In most cases, their export equipment is technologically advanced; however, their equipment may incorporate somewhat limited capabilities. For example, their multi-level switching and preemption equipment may contain only two levels rather than three to five levels.

Table 2.2-1. Information Exchange Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
International Telecommunications Union (ITU) Synchronous Digital Hierarchy-based/ Synchronous Optical Network (SDH/SONET) switching and multiplexing	Programmable digital byte interleave multiplexers implementing bidirectional line switched rings (BLSRs) providing "reusable bandwidth" in "meshed networks" and protection routing and switching for efficient and self-healing, survivable transmission.	WA Cat. 5E, P1; CCL Cat. 5E, P1	None Identified	Specially designed, commercially available SDH/SONET test equipment	None Identified
Asynchronous digital transmission hierarchy (DS-"n")	Programmable digital cross-connect system (DCS) multiplexers and automated diagnostic management and control.	CCL EAR 99	None Identified	Specially designed, commercially available digital transmission test equipment	None Identified
Conventional and dual-function central office and PBX switching.	Flexible, programmable, tandem, central office, and PBX switching; dynamic non-hierarchical routing, priority and pre-emption.	WA Cat. 5A, P1; CCL Cat. 5A, P1	None Identified	Voice traffic generators	None Identified
Flexible, programmable, variable bit rate-capability, multimedia asynchronous transfer mode (ATM)	Multiplexing and switching for local area network (LAN), metropolitan area and wide-area networks (MAN/WANs).	WA Cat. 5A, P1; CCL Cat. 5A, P1	None Identified	Specially designed, commercially available ATM test equipment	None Identified

Table 2.2-2. Information Exchange Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
International Telecommunications Union (ITU) Synchronous Digital Hierarchy-based/Synchronous Optical Network (SDH/SONET) multiplexing and switching	Public capabilities exceed most military requirements. Bandwidth required for WMD is less than commercial networks provide.	Survivable communications among command centers, depots, transportation facilities, industrial centers necessary for WMD operations.	Asynchronous digital transmission hierarchy (DS-"n"). See item below; Public mobile service via multi-satellite systems (see item in Table 2.2-1 above)
Asynchronous digital transmission hierarchy (DS-"n")	Public capabilities exceed most military requirements. Bandwidth required for WMD is less than commercial networks provide.	Survivable communications among command centers, depots, transportation facilities, industrial centers necessary for WMD operations.	An ITU SDH-based broadband transmission system described above; (2) Public mobile service via multi-satellite systems (see item in Table 2.2-1 above)
Conventional, dual-function central office and PBX switching	Requires combined use with synchronous digital hierarchy (SDH) or DS-"n" transmission items to realize benefits.	Survivable communications among command centers, depots, transportation facilities, industrial centers necessary for WMD operations.	SDH and DS-"n" transmission for service restoration
Flexible, programmable, variable bit rate, multimedia for local area network (LAN), metropolitan area and wide-area networks (MAN/WANs)	Public capabilities exceed most military requirements. Bandwidth required for WMD is less than commercial networks provide.	Support for multi-phenomena, wide-area array sensors as they become available; survivability adjuncts to transmission items above.	Less efficient and flexible conventional switching and multiplexing.

SECTION 2.3—INFORMATION PROCESSING

OVERVIEW

Information Processing (IP) is an IS functional area to which computers, peripherals, servers, end-user or terminal equipment such as displays, keyboards, and other devices are normally assigned. Operating system, application and utility software are also considered elements of the IP functional area. This section discusses many of these technologies, consisting mainly of computer software and hardware.

The following are among an extensive list of IP-based commercial capabilities with WMD application:

- Computer-aided design (CAD) software, hardware suite, and complex system engineering and integration tools;
- A rich variety of IS design, performance and environmental modeling, simulation, test, and evaluation products;
- On-line Analytical Processing (OLAP);
- Streamlined object-oriented programming (reusable programs, classes and objects), fourth-generation languages, and intelligent database management system development/modification products;
- Conventional and advanced multimedia (acoustic, voice, graphics imagery, video, tactile and haptic), user-friendly, human interfaces;
- High-performance virtual reality and other home entertainment products;
- Mature hardware and software products supporting client/server, distributed processing, and database system architectures; and
- Data Warehousing.

In examining the role of commercial technology in WMD applications, it is necessary to understand DoD's overall acquisition policy. Section 2501 of Title 42 of the Defense Appropriations Act for 1993 declares:

> *It is the policy of the Congress that the United States attain its national technology and industrial base objectives through acquisition policy reforms that have the following objectives:*
>
> - *Relying, to the maximum extent practical, upon commercial national technology and industrial base that is required to meet the national security needs of the United States;*
> - *Reducing the reliance of the Department of Defense on technology and industrial base sectors that are economically dependent on Department of Defense business; and*
> - *Reducing Federal Government barriers to the use of commercial products, processes, and standards.*

The implication is that through such policy initiatives, the proliferator seeking to acquire IS can become aware of a wider array of choices.

Just as there is a need to plan for failure or destruction of switching centers in the Information Exchange IS functional area, availability of WMD IP functions ideally must not depend on the survivability of a small number of high-value information-processing centers. Insurance, airline reservation, and other industry segments have developed a wide variety of fail-safe redundancy and back-up technologies, including disaster recovery techniques and plans, that can easily be adopted with great advantage for WMD missions.

Highlights

- In view of the rapid pace of commercial technology development, the performance of COTS information processing technology is generally far superior to military standard counterparts.
- COTS information-processing design, development, test, and evaluation tools facilitate adaptation and upgrade of older military and commercial information systems, delivery systems, and other WMD elements.
- Extraordinary performance growth in ever smaller, lighter, lower power packaging makes the introduction of powerful IP products possible, and greatly augments survivable transportable command centers.

RATIONALE

Although COTS capabilities are intrinsically capable of supporting WMD missions, constructing automated strike planing, damage assessment, battle management, sensor and intelligence data fusion, modeling and simulation, weapon inventory and control, and numerous other IP functional capabilities requires significant customization.

However, there is no question that COTS design, development, test, and evaluation technologies outlined above, which are available on the open market, facilitate the adaptation and technology infusion or upgrade of older military and commercial IS, delivery system, and other WMD elements.

Inasmuch as COTS technology transfer to the WMD *Information System* baseline capabilities does not involve composite material, fuel processing, propulsion system, weapon payload integration, and similar structural and mechanical dependencies, much can be accomplished at reasonable levels of effort and within aggressive schedules by rogue countries such as Iran, Iraq, North Korea, and others.

COTS products such as Internet and Intranet capabilities, distributed computing environments (DCE), client-server structures, on-line analytical processing (OLAP), on-line transaction processing (OLTP), an ever-growing family of enterprise software developments, and other commercial developments offer tremendous potential in streamlining and enhancing WMD and conventional warfare operations.

Multimedia personal power-computers are of particular significance for conflict situations in which transportability and information-supported weapons (e.g., remotely piloted vehicles) are crucial to mission success. High-performance laptop PCs can be conveniently taken to temporary maintenance and repair depots, flight decks, launch vehicles, and battlefields. Slightly larger suitcase-size packaging, augmented with survivable communications and GPS capabilities, extends information-based, war-fighting potential even further.

At desktop/workstation capability levels, it is possible today to achieve in single-van, transportable command centers what 10 years ago demanded a convoy of vans and support vehicles. This advancement reflects increased IP performance and reliability, all accomplished with greatly reduced computer processor and peripheral size, weight, volume, power consumption and, consequently, scaled-down prime power and environmental control support facilities. Tables 2.3-1 and 2.3-2 list specific IP capabilities with WMD relevance.

FOREIGN TECHNOLOGY ASSESSMENT

The third column of Figure 2.0-2 contains a comparative representation of foreign technology assessments for the IP Functional Area by country and for subnational groups. The IP capability profiles of most countries are similar to their Information Communications and Information Exchange capabilities. There are, however, some significant exceptions. India and Iran are assessed as having IP capabilities greater than those in both their Information Communications and Exchange functional areas. Iraq’s IP capabilities exceed their Information Systems Management and Control and Information Systems Facilities. Japan, North Korea, and Pakistan have IP capabilities that exceed their Information Communications and Exchange functional areas. Only Australia, South Africa, and Switzerland are assessed as having IP capabilities that are less than their Information Communications and Exchange functional areas.

Some of the country capability assessments that appear in Figure 2.0-2 may be conservative because the IP capabilities in almost all countries are growing so rapidly due, in large part, to the rapid expansion of the Internet. IP technology status statistics by country are difficult to locate; however, some indication of various country’s capabilities were revealed by a recent world survey of the Internet host and PC populations. This survey reported that Finland, with a population of 4 million, has the world’s largest Internet host density, with ~535 per 1,000 population. The United States still leads the world in PC density with ~ 390 PCs per 1,000 population; however, Denmark, Norway, and Switzerland are close behind the United States in PC densities, with more PCs per 1,000 than Japan, Germany, the UK, and Canada. Software is changing the economic and military balances in the world. There is an accelerating intellectual capital transfer of software development know-how now in progress through the Internet, Intellectual capital transfer takes place through aggressive computer hardware and software marketing, conferences, trade journals, and technical literature on software development, and through the graduates of colleges and universities, which teach IP skills and abilities, in the United States and other countries. IP know-how transfer also takes place in personnel transfers overseas and training conducted by U.S. multinational companies. However, the United States still currently leads, and is forecast to continue to lead, the world in software innovation, the development of large complex systems, and in system engineering and integration through at least the year 2005 or 2010. The United States has sustained its lead in computer hardware because it enjoys superior microprocessor design and fabrication capabilities. See Sections 5 and 10 in Part I of the 1996 MCTL.

The United States is having a great deal of software developed by foreign nationals, either within their own country or as part of a team in the United States. For example, communications software is being developed in India by a subsidiary of a U.S. communications company. In another case, a critical DoD system being developed under contract in the United States has Russian nationals on the development team. Software developed today is so complex that any programmer(s) could put in viruses, Trojan horses, back doors, and time bombs that could go undetected all the way through installation, particularly if there is a cooperative group effort.

Table 2.3-1. Information Processing Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Distributed computing environment (DCE), and client-server architectures and structures	Enterprise-wide, compatible information processing functions, preferably with platform independent, WEB/Internet, multimedia plug-in and human interface compatibility.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/military DCE environments, if not indigenous, are readily available on the open market.
On-line analytical processing (OLAP) and supporting data bases	Using hierarchically organized, n-dimensional databases designed for live *ad hoc* data access and analysis, including consolidation, drill down, vector arithmetic, definable complex variables, time-series data handling, and other capabilities that reduce database size, yield orders-of-magnitude improvement in query response time, and make possible real-time data analyses not possible with conventional designs.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/military OLAP environments, if not indigenous, are readily available on the open market.
Object oriented technologies (OOTs)	Incorporating class, subclass, inheritance, encapsulation, abstraction and other capabilities such as higher quality software and database products, lower cost and faster development, easier maintenance and upgrade, and reduced lifecycle cost.	CCL EAR 99	None Identified	None identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/military OOTS environments, if not indigenous, are readily available on the open market.

(cont'd)

Table 2.3-1. Information Processing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test Production and Inspection Equipment	Unique Software and Parameters
On-line transaction processing (OLTP) with supporting databases	Supports object-oriented, relational databases and intelligent database management systems to facilitate high volume creation, updating and retrieval of individual records.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/ military OLTP environments, if not indigenous, are readily available on the open market.
"Data Warehousing"	Transforming data into useful and reliable information that supports enterprise decision-making through analytical processing capabilities and applications such as point-in-time data analysis, trend analysis, and data mining.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/ military "data warehousing" environments, if not indigenous, are readily available on the open market.
Data compression and signal processing technologies	Minimizing bandwidth and storage requirements for voice, data, facsimile and other imagery, and video information; implementing optimum matched filter communications components; and enhancing imagery and facilitating pattern recognition and target detection.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/ military data compression and signal processing environments, if not indigenous, are readily available on the open market.
Modeling, prediction, and simulation technologies	Supporting: product design and development; training and evaluation; and enterprise and battlefield planning and decision-making.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications.

(cont'd)

Table 2.3-1. Information Processing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test Production and Inspection Equipment	Unique Software and Parameters
Computer-based training, distance learning, and group decision support system (GDSS)	Terminal/server/network/teleconferencing technologies incorporating explicit and implicit hypermedia navigation, natural language processing, voice recognition, a variety of "search" engines, an array of person-machine interfaces, and other technologies.	CCL EAR 99	None Identified	None Identified	Proliferators have the ability to use COTS products in industry-standard applications. Engineering and integration capabilities to adapt COTS products to WMD/military GDSS environments, if not indigenous, are readily available on the open market.

Table 2.3-2. Information Processing Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Distributed computing environment (DCE), and client-server architectures and structures	Highly efficient enterprise-wide information-processing functions, preferably with platform independent, WEB/Internet, multimedia plug-in and human interface compatibility; COTS technology exceeds C^2I requirements but modification, adaptation, and extension may be required to support specific military applications.	Enhanced, distributed, survivable intelligence and sensor data fusion, decision support, strike and re-strike planning, strike and damage assessment, micro-meteorological and other modeling and simulation.	Less efficient hardware and software.
On-line analytical processing (OLAP) and supporting databases	Substantial development may be required to adapt military databases and procedures to secure the benefits of this technology.	Military logistic and other warfare planning and decision support. Particularly applicable for strike and re-strike planning, strike and damage assessment, in time-constrained, hot-conflict scenarios.	Less efficient hardware and software.
Object-oriented technologies (OOTs)	Substantial development may be required to adapt military databases and procedures to secure the benefits of this technology.	Enhanced, distributed, survivable C^2I information systems.	Less efficient hardware and software.
On-line transaction processing (OLTP), with supporting databases	Substantial development may be required to adapt military databases and procedures to secure the benefits of this technology.	Military logistic and other warfare planning and decision support. Particularly applicable for strike and re-strike planning, strike and damage assessment, in time-constrained, hot-conflict scenarios.	Less efficient hardware and software.
"Data Warehousing"	Substantial development may be required to adapt military databases and procedures to secure the benefits of this technology.	Military logistic and other warfare planning and decision support. Particularly applicable for strike and re-strike planning, strike and damage assessment, in time-constrained, hot-conflict scenarios.	Less efficient hardware and software.
Data compression and signal processing technologies	Some development may be required to adapt military databases and procedures to secure the benefits of this technology.	Enhanced, distributed, survivable C^2I IS systems	Less efficient hardware and software.
Modeling, prediction, and simulation techniques	Some development may be required to adapt military databases and procedures to secure the benefits of this technology.	Enhanced, distributed, survivable C^2I IS systems and decision-making.	Less efficient hardware and software.
Computer-based training, distance learning, and group decision support system (GDSS)	Some development may be required to adapt military databases and procedures to secure the benefits of this technology.	Enhanced, distributed, survivable C^2I IS systems and decision-making.	Less efficient hardware and software.

SECTION 2.4—INFORMATION SECURITY

OVERVIEW

Technologies in the Information Security (INFOSEC) Functional Area are those designed to safeguard information privacy or secrecy and to ensure information integrity. Encryption, scrambling, protected wire, and steganographic techniques are used to protect the privacy and secrecy of data at or en route among information processing or storage nodes. Hash functions protect information integrity by alerting owners to data manipulation or tampering.

This section deals principally with information in electromagnetic format contained within electronic or photonic devices or en route over suitable media. Physical access control capabilities are included to the extent that they provide protection against attacks intended to illegally acquire information and not merely to physically destroy the facilities in which it resides.

Protecting information while it resides in processing, storage, server, and interface terminal nodes—yet making it readily available to authorized users—is accomplished with access control, authentication, non-repudiation, and electronic signature techniques. All of what has come to be known as "trusted system" INFOSEC capabilities can be used by proliferators.

The cost of trusted systems and other associated COTS INFOSEC products is comparatively small and within the reach of most proliferators. Associated COTS INFOSEC systems that might be used by proliferators for their trusted systems are standard physical and electronic access limiting techniques. Unique badges or cards, which include name, picture, individual personal identification numbers (PINs), other identification numbers, and passwords are in this category. Of Operations Security (OPSEC) interest are advanced local and remote identification and authentication mechanisms. In this latter category are thermogram, hand or eye scanning, voice printing, keyboard rhythm, fingerprint, signature dynamics, and other biometric technologies.

Today there are quality COTS INFOSEC products of such strength that effective communications and signal intelligence countermeasure operations against them are practicable only for government agencies or other large, well-funded organizations. Readily available COTS secure communication products include line and trunk encryption devices, secure voice and data end-instruments, encrypted common channel and per-channel signaling systems, and a rich variety of encryption software.

The availability of powerful and effective INFOSEC products and techniques does not guarantee that any country's computer-dependent enterprise infrastructures are invulnerable. In fact, many of today's computer-dependent utilities such as telecommunications systems and electrical power systems, as well as financial services systems and other civilian and military systems, are known to have been penetrated by competent hackers. Well-funded adversarial government or industrial espionage activities pose an even greater threat to these systems.

Highlights

- Commercial INFOSEC products are available on world markets with capabilities deemed adequate for WMD operations.
- Significant progress is being made toward open, market-based INFOSEC development of public-private key architectures, related standards, and the functional specification of certification authority structures.

Many infrastructure systems are vulnerable, not because they cannot be protected using available COTS products and techniques, but because risk-benefit analyses are not persuasive. Due to their perception of the threat, decision-makers accept the risk rather than bear the attendant investment costs, operating efficiency losses, and time-consuming access restrictions associated with protecting their systems. A knowledgeable proliferator intent on achieving surprise or concealing its identity may be expected to be willing to pay the price of strong INFOSEC.

New and more capable INFOSEC capabilities and techniques continue to appear in both commercial and military environments. And certainly, potential proliferants have ready access to commercial technologies to implement whatever level of security they deem necessary to protect their WMD warfare operations. Commercial technology developments that promise to augment today's capabilities and allow WMD proliferators to implement even higher levels of information security are outlined below.

The use of fiber-optic cable, even in the absence of encryption, greatly complicates the old-fashioned wire-tapping procedure. Intrusion-resistant fiber cable makes undetected eavesdropping almost impossible. Similarly, common-channel signaling defeats automated, in-channel, “search-on-number” intercept techniques, since signaling and subscriber traffic take different signal paths. Proliferants able to use commercial fiber-optic systems would realize these benefits.

Perhaps the most significant open, market-based INFOSEC development is the progress made towards the adoption of public key cryptography and protocols, related standards, and the establishment of certification authority structures. As improved standards and overall architectures emerge, there appears to be more than an adequate supply of scientific and professional competence available for assistance in the development and integration of systems of whatever strength proliferators require, from algorithm and protocol development to encryption and key management.

The financial services industry’s interest and the intense interest of business in electronic commerce on the Internet have accelerated development of commercial tools and technologies with broad WMD application. Among them are means to protect (while selling) intellectual property rights, safeguard databases, restrict access, prevent false repudiation, safely transfer funds, and execute binding contracts electronically, as well as numerous other secure capabilities.

RATIONALE

Because all businessmen and government decision-makers have not implemented measures to correct vulnerabilities in many of today’s nonmilitary systems, the opinion is often advanced that commercial capabilities are unsuited for military applications and their importance to WMD warfighting is minimized. It is unlikely that these arguments will persuade astute WMD proliferators who are free to convert commercial INFOSEC products normally used to protect civilian dual-use information systems to WMD use.

Virtually all commercial INFOSEC capabilities have direct WMD application for weapon storage, custody and release as well as other military command and control operations. In conducting successful nonattributable WMD attacks, covertness is mandatory. In such situations, even the appearance of encrypted traffic may compromise missions by tagging information.

A proliferator may avoid encryption altogether using one-time codes and steganographically concealed messages buried in innocuous text or bitmapped images to prevent adversaries from intercepting intelligible data. This ancient coding method is ideal in high-volume traffic voice and Internet-type data networks. Steganography is within the reach of all proliferators. Even prisoners with no equipment but their minds have developed essentially undetectable means of transmitting embedded decoding templates with the concealed messages.

A complementary approach for maintaining secrecy and covertness involves the use of secure, intrusion-resistant, low probability of detection and interception communications technologies. Of course, if a WMD or conventional attack strategy critically depends on the element of surprise, overt encryption using any of the commercial technologies remains an option.

FOREIGN TECHNOLOGY ASSESSMENT

Complete INFOSEC and OPSEC technical data appears in open source U.S. and foreign trade journals and technical literature and also can be obtained from vendors. Cryptographic systems are widely available. A Russian vendor will deliver a complete package with a 2-year service provision to anyone, and Sun is fielding a whole suite of strong cryptographic products supplied by a Russian manufacturer for their customers anywhere in the world.

National and international export regulations can be circumvented in those countries that prohibit the export of robust information security systems, including strong cryptography. In addition, there are now many countries that have at least a limited capability to produce, or at least use, robust information security products.

The Information Security Functional Area column of Figure 2.0-2 contains a foreign technology assessment by country and for subnational groups. One-third of the countries assessed have capabilities in all INFOSEC Functional Area technologies. Australia, Canada, France, Germany, the UK, and the United States are the world INFOSEC technology leaders. Denmark, Finland, India, Israel, Japan, Norway, Russia, South Korea, Sweden, Switzerland, and Taiwan are close behind the leaders. Iran and North Korea are believed to have all essential INFOSEC functional area capabilities. Most countries and subnational groups, have at least a limited INFOSEC technology capability. A limited capability includes the ability to use INFOSEC products obtained on the world market with little or no direct technical support from the manufacturers. Note that Libya, Vietnam, and the subnationals are among those credited with a limited INFOSEC technology capability and all of them should be able to purchase robust INFOSEC systems, which are comparatively inexpensive.

See Section 2.3 (page II-2-16) for a description of COTS software vulnerability.

Table 2.4-1. Information Security Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Commercial trunk and line encryption system hardware and software	Technologies and products that provide strong link encryption for networks, end-user-to-end-user encryption, and encryption for voice, imagery, video, text, files, and data, all of which could be adapted for C^2I.	WA Cat. 5A, P2; CCL Cat. 5A, P2; WA ML 11; USML XI	None Identified	None Identified	None Identified
One-time operational codes or commercial software steganographic encoding techniques	Proven COTS products are available for concealing messages in innocuous text or bit-mapped images to transmit covert, low probability of detection and interception politico-military messages. May be used in conjunction with other security measures by any but lowest level proliferant.	WA Cat. 5A, P2; CCL Cat. 5A, P2; WA ML 11; USML XI	None Identified	None Identified	None Identified
Trusted systems to protect data, processing, and other information systems resources.	Proven COTS products are available which include encryption and hash algorithms, certification authorities, and key management and distribution. Multi-level access control mechanisms including resource segmentation and combined use of unique badges or cards, and local and remote personal identification numbers, passwords, thermogram, hand or eye scanning, voice printing, keyboard rhythm, fingerprint, signature dynamics and other biometric technologies.	WA Cat. 5A, P2; CCL Cat. 5A, P2; WA ML 11; USML XI	None Identified	None Identified	Pattern recognition algorithms and programs for analysis of biometric features.

Table 2.4-2. Information Security Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Commercial trunk and line encryption system hardware and software	Traffic is susceptible to decryption and spoofing by defending countries with intelligence and information warfare infrastructures. The time scales of WMD operations are typically very short relative to the protection provided by commercial encryption.	Secure C^2I communications for concealing intent during the preparation phase of WMD operations and achieving surprise, controlling force application and obtaining rapid damage assessment in the execution phase of WMD operations.	Wealthy adversaries may choose from a variety of strong COTS technologies and products; poorer adversaries and terrorists may find inexpensive COTS that will provide adequate security.
One-time operational codes or commercial software	Traffic is susceptible to decryption and spoofing by defending countries with intelligence and information warfare infrastructures.	Secure C^2I communications for concealing intent during the planning and preparation phase of WMD operations and achieving surprise, controlling force application and obtaining rapid damage assessment in the execution phase of WMD operations.	None, except for low probability of interception and detection radio transmission techniques.
Trusted systems to protect data, processing and other information systems resources.	COTS equipment exceeds requirements for the WMD planning and preparation phase, but substantial customized modification may be required to provide a secure, end-to-end military system.	Secure C^2I communications for concealing intent during the planning and preparation phase of WMD operations and achieving surprise, controlling force application and obtaining rapid damage assessment in the execution phase of WMD operations.	Less efficient (and less expensive) 3rd generation COTS hardware and software applications are widely available. An alternate to "trusted" systems and products for a minimum WMD capability might be personal recognition and trusted couriers.

SECTION 2.5—INFORMATION SYSTEM MANAGEMENT AND CONTROL

Highlights

- With inadequate Information System Management and Control capabilities, no WMD proliferator can rapidly convert civil telecommunications or other complex IS systems to military use.
- Information Systems Management and Control functional area capabilities are of seminal importance to both normal day-to-day and stressed-mode, complex system operations.
- As information systems grow, add more components, more functions, and more users, IS Management and Control itself becomes more difficult and complex, yet increasingly crucial.

OVERVIEW

Information System Management and Control (IM&C) is the IS Functional Area capability for planning, organizing, designing, optimizing, engineering, implementing, provisioning, monitoring, directing, controlling, and accounting for IS activities and resources. Here, "controlling" is understood to subsume operations, maintenance, configuration and change management, and security. Within the military, IS IM&C is but one element of mission-level Command, Control, and Intelligence functional capabilities. With inadequate IM&C capabilities, a WMD proliferator would have difficulty in rapidly converting civilian telecommunications complex Information Systems to military use or in taking advantage of the survivability Information Systems are able to furnish.

This section addresses IS technologies necessary to control normal operations and service provision while achieving reliability, availability, fault isolation, service restoration, and survivability objectives.

As an example of an advanced IM&C capability, consider today's software defined or virtual private telecommunications networks (SDN/VPNs), in which traffic is routed through networks under the control of computers residing in network control points or operations centers (NCP/NOCs). These computers are connected to remote stored program-controlled switching and multiplexing equipment using common-channel signaling (CCS) networks. The computers, and associated databases containing a subscriber's unique VPN information, screen every call and apply call-processing control in accordance with customer-defined requirements.

The IM&C capabilities implemented in an NCP/NOC not only control normal call-processing and routing, but they monitor and manage virtually every aspect of a network. Of particular interest to WMD operations, NOCs are the management and control means by which the extraordinary survivability features of SDH/SONET bidirectional line-switched rings (BLSRs) are realized.

Highly survivable operations, if needed for some WMD missions, can be realized through the combination of fiber-optic and other media Information Communications functional area capabilities; flexible and programmable switching and multiplexing Information Exchange functional area capabilities; and importantly, computer, database, and software IM&C functional area capabilities. Thus, commercial hardware and software product technologies implementing IM&C capabilities can be central to any proliferant's successful adaptation of commercial public telephone networks for WMD military purposes.

The increasing importance of IM&C to telecommunications and other complex Information Systems is due to many worldwide trends. In the past, data processing was usually accomplished within mainframes in a relatively small number of large, centralized processing sites. In the telecommunications arena, networks supported limited sets of services derived from a relatively small set of basic technologies, using equipment from only a few vendors. Today, divestiture, deregulation, privatization (overseas), and rapid technological expansion and competition has resulted in significant growth in the number of private and public telecommunications networks. These networks support numerous services and are derived from a wide variety of network elements (NEs) with equipment supplied by hundreds of manufacturers.

To cope with added functional complexity and reduce manpower requirements, network operators are placing more processors in voice communications networks (VCNs). Analogously, advances in microprocessors technology and the corresponding trend away from centralized-mainframe designs has spawned a large number of data communications networks (DCNs) now connecting distributed processors in client/server configurations. In both cases, the result is that networks are more complex and more software driven than ever.

Not surprisingly, as information systems proliferate, add more components, more functions and more users, IS management itself becomes more difficult and complex, yet increasingly crucial. The fast growing cellular telephone industry adds new dimensions to telecommunications management, particularly for roaming applications where one carriers' subscribers must be recognized and served by other carrier's networks.

In the United States, divestiture has meant that many end-to-end connections require services and/or facilities from two different local exchange carriers (LECs), one or more interexchange carriers (IXCs) or backbone networks, and often two local area networks comprising customer premises equipment (CPE) from a variety of manufacturers.

Overseas, similar situations exist among interconnected pan-European national networks and within countries where privatization has given rise to a variety of alternative service providers. Effective, integrated IM&C in this environment is difficult to achieve, but may be far simpler in third-world countries, where rebuilding homogeneous nationwide networks from the ground up may be feasible.

Since the IS product environment worldwide is heterogeneous, practical, long-term, and end-to-end (e.g., systems including customer-owned and carrier or other service provider-based, common-user information systems), effective IM&C approaches must be based on standards and a common, evolving agent process/manager process paradigm. Relevant standards include the International Telecommunications Union (ITU), Telecommunications System Sector (TSS) M30X0 Telecommunications Management Network series; the International Standards Organization (ISO) Common Management Information Protocol (CMIP) and several subsidiary standards; the Internet Activities Board, Simple Management Network Protocol (SMNP); and the Institute of Electronics Engineers (IEEE) local and metropolitan area network standard entitled LAN/MAN Management.

To achieve the rapid fault isolation and service restoration leading to ultra-high availability and militarily acceptable levels of survivability, standards must be implemented in appropriate network elements and arranged in architectures with designed-in performance monitoring; fault isolation; and excess traffic, processing, storage capacity, and disaster recovery back-up resources that can be quickly reallocated to compensate for intentional, man-made, or naturally occurring damage or failure.

In public networks, this means stored program central office, tandem and digital cross-connect switching, multiplexing, router and server equipment; telecommunication management networks (TMNs, i.e., data communication networks designed to exchange management information but logically separate from "managed networks"); broadband fiber-optic Synchronous Digital Hierarchy/SONET (SDH/SONET)-based backbone transmission; and alternate multimedia communications (e.g., broadband satellite and satellite or terrestrial based mobile communications). An advanced signaling system such as the ITU-TSS Signaling System # 7 (SS # 7—AT&T and Bellcore versions are commonly referred to as CCS 7 and SS 7, respectively) plays an important role in normal and degraded-mode military operations of advanced telecommunications system. For example, during the Cold War era, COCOM permitted the export of SS # 7-capable switching hardware, but restricted export of SS # 7 itself.

Figure 2.5-1 summarizes IM&C dimensions, i.e., the functions, managed entities, and domains implied in the above discussion. In the figure, IM&C functions are divided into "technical" and "business/government/military" categories, with only key subfunctions illustrated. Managed entities are grouped under "IS Services," "IS Networks," and "IS Elements" categories, again with only partial subcategory illustrations. Finally, the dedicated-facilities and common user management domains are shown.

RATIONALE

Figure 2.5-1 graphically demonstrates the challenges involved in creating either end-to-end integrated management and control systems or achieving the goal of "open IM&C systems." However, as noted, in third-world countries where upgrading essentially allows designers to start with a "clean slate," military information systems can be built upon homogeneous or even single-vendor common-user commercial systems. These systems can easily be more survivable than dedicated, special purpose alternatives built from equipment made to military specifications.

The reason is twofold. First, civil information systems generate revenue only when operational. As a consequence, the profit motivation for high availability, minimum downtime, and immunity to failures and accidental cable cuts is paramount.

Second, although it is possible to design excess capacity into military systems to account for losses in warfare, capacity requirements sufficient to handle peacetime civilian requirements are generally orders of magnitude larger than any justifiable military overbuild design requirements.

To illustrate these advantages, consider the Autovon military network. It was once regarded as the preeminent, survivable voice network with 55 U.S. switch centers. Today civil requirements have resulted in switch numbers and capacities dwarfing old Autovon military requirements. As a consequence, the most survivable military IS designs are those based on the ability to make optimal use of civil systems by placing them at the disposal of military users. This is especially true of commercial technologies embodying the most effective IM&C mechanisms to circumvent outages caused by natural disasters and irreducible component failures. Tables 2.5-1 and 2.5-2 illustrate specific technology capabilities with WMD significance.

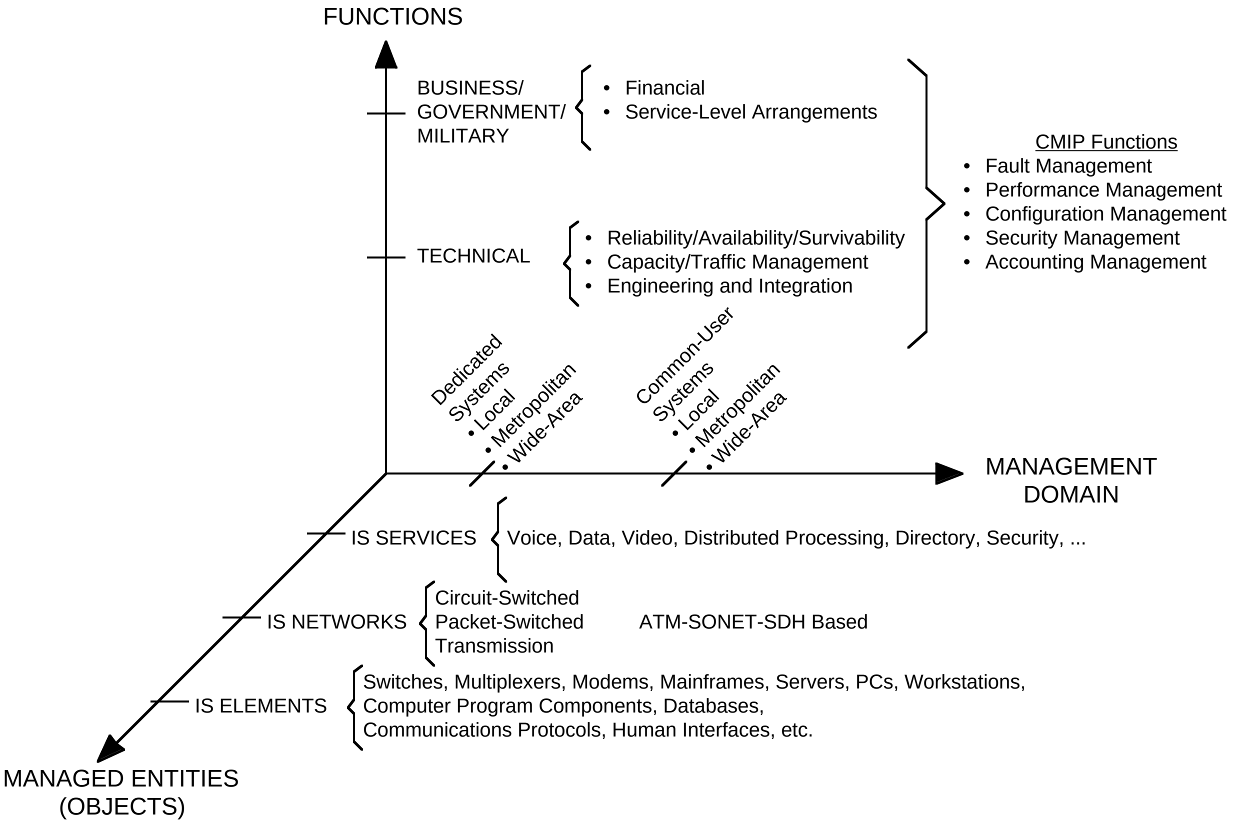

Figure 2.5-1. Information Systems Management and Control

FOREIGN TECHNOLOGY ASSESSMENT

The Information Systems Management and Control (IM&C) column in Figure 2.0-2 shows the comparative IM&C capabilities of 32 countries and a representative assessment for subnational groups. Only one-third of those listed have all IM&C Functional Area capabilities because this is a large, complex, functional area consisting of 11 elements that include the capability for planning, organizing, designing, optimizing, engineering, implementing, provisioning, monitoring, directing, controlling (operations, maintenance, configuration and change management), and accounting for IM&C activities and resources. Countries with strong capabilities in all IM&C technologies are the world Information Systems leaders (or host divisions of multinational companies), which have installed much of the world's information systems telecommunications base. The world's IM&C leaders are Canada, France, the UK, and the United States. In contrast, Iran, Iraq, Libya, North Korea, and the subnationals are among those countries that have only limited, if any, IM&C capabilities. An ambitious WMD proliferator would need strong capabilities in all IM&C technologies to rapidly convert civilian telecommunications and the other complex information systems functional area technologies to military use and take advantage of the extraordinary survivability modern systems could provide for WMD operations. A minimal proliferator that does not intend to conduct sustained or sophisticated WMD operations might not benefit from the possession of IM&C technologies.

Table 2.5-1. Information Systems Management and Control Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Logically and/or physically separate signaling and Telecommunications Management Network (TMN)	Encrypted networks that support normal network operations and service offerings; specially designed to implement real-time management via ATM; dynamic autonomous reconfigurability at all levels of service (intelligent fault recovery); seamless support to broadcast and multilevel, multi-user point-to-point data communications services; hybrid real-time/ non-real-time distributed computing environments incorporating mobile assets; automated data distribution and control from multiple sources. Can monitor and manage virtually every aspect of the network during normal and degraded conditions.	WA Cat. 5A, P2; CCL Cat. 5A, P2	None Identified	Specially designed, commercially available management systems that allow for self test.	Operating systems and network management software incorporating hierarchical, multilevel security; intelligent agents for distributed computing environment monitoring, work load allocation, and dynamic configuration management.
Combined network control point/operations center (NCP/NOC)	Programmable, computer-based facilities for managing and controlling switching, multiplexing, communications, and other network operations.	WA Cat. 5A, P1; CCL Cat. 5A, P1	None Identified	None Identified	Vendor-specific NCP/NOC software
Automated system management system (SMS) hardware and software	Monitors performance, detecting, isolating, and diagnosing failures, rapidly accomplishing restoration and reprovisioning.	CCL EAR 99	None Identified	None Identified	Vendor-specific SMS software

(cont'd)

Table 2.5-1. Information Systems Management and Control Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
SMS and network element hardware and software	Implementing evolving TMN and CMIP/SNMP manager process/agent process paradigm-based protocols and object-oriented, management information base (MIB) architectures, models, standards and interfaces.	CCL EAR 99	None Identified	None Identified	Operating system and network management software incorporating hierarchical, multi-level security; intelligent agents for distributed computing environment monitoring, work load allocation, and dynamic configuration management.
Customer or integrated network management systems (CNM/INMS)	Providing end-to-end, global, unified network management of an entire enterprise network.	CCL EAR 99	None Identified	None Identified	Evolving network management software incorporating html/ browser technology
Signaling System (SS) 7	Implementing SS # 7-based encrypted common channel signaling.	WA Cat. 5A, P2; CCL Cat. 5A, P2	None Identified	None Identified	SMS proprietary software to implement SS # 7.

Table 2.5-2. Information Systems Management and Control Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Logically and/or physically separate signaling and Telecommunications Management Network (TMN)	Proprietary products are available within so-called Intelligent Networks but not implemented to the same extent by all commercial telephone companies or PTTs. While the TMN model enjoys nearly universal endorsement, telco carriers and equipment are only making slow progress towards adopting and implementing national or world-wide standards.	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.
Combined network control point/ operations center (NCP/NOC)	Proprietary products are implemented in modern telephone companies and used to render their "flagship" software defined/virtual private network (SDN/ VPN) service offerings.	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.
Automated system management system (SMS) hardware and software	Proprietary products for failure detection and recovery.	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.
SMS and network element hardware and software	Proprietary products are available and used separately in local and long-distance exchange carrier and customer-owned network domains.	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.
Customer or integrated network management systems (CNM/INMS)	Proprietary products are available and used separately in local and long-distance exchange carrier and customer-owned network domains. An SMNP open systems based industry consensus is emerging.	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.
Signaling System 7	None	Highly efficient, highly survivable, rapidly reconfigurable and reconstitutable C^2I information systems operations.	Earlier generation hardware and software.

SECTION 2.6—INFORMATION SYSTEMS FACILITIES

OVERVIEW

Information Systems Facilities is the Functional Area encompassing any or all of the following capabilities: exterior physical shelter and interior room; equipment and other IS support structures; prime power generation and/or co-generation; power conditioning; environmental heating, ventilation and air-conditioning (HVAC); chemical and biological filtration and protection; electromagnetic pulse protection; tempest shielding; radiation protection; and human habitation and life-support accommodations.

Clearly, not all of these capabilities are required for every instance of military operations. Physical shelters may be fixed, or transportable in ground mobile, airborne or shipborne configurations. They may support manned command, control and intelligence centers, manned information processing or communications centers, or unattended IS resources.

Civil IS shelters typically may not involve sleeping quarters or other overnight accommodations, but instead merely provide facilities housing IS equipment and personnel in common office work environments.

Where nuclear weapons are involved, the Cold War era taught that under determined attack, there is no such thing as a survivable, fixed command center or IS operations building. Not even so-called deep underground command centers, regardless of cost, could be certified as survivable. As a consequence, in military WMD scenarios in which long-term survivability is mandatory, mobile facilities are the only viable option. From a U.S. perspective, preparation for global nuclear warfare, beginning with the World-Wide Military Command and Control System (WWMCCS) program in the 1970's, led to the investment of billions of dollars in military, mobile command, surveillance, and IS center technology. The airborne command center, the Airborne Warning and Command System (AWACs), and the Ground Mobile Command Center (GMCC) are illustrative developments. For tactical scenarios, the Tri-Tac program developed a wide variety of mobile/transportable voice and data switching, communications satellite and terrestrial terminals, and various IS processing center products to support moving battlefield theater locations. In Europe, the Deutsche-Bundespost placed cable hocks within civilian telecommunications networks, permitting mobile switching and multiplexing gear to be connected with surviving transmission media to restore service interrupted by intentional or collateral wartime damage.

By the late 1980's, enormous advances in microprocessor-based computer power, coupled with dramatic reductions in space, weight, and prime power consumption, made possible installation in a single rack those IS capabilities which previously required an 18-wheel tractor-trailer.

Highlights

- Older military or commercial high technology, highly survivable transportable/mobile information systems facility capabilities are readily available to proliferants.
- Advances in processing power, coupled with dramatic reductions in space, weight, and power consumption, allow information systems capabilities to be packaged in much smaller volumes.
- In many cases, the total cost per transportable information systems facility may be an order of magnitude less than the cost of a single precision-guided conventional weapon.

Due to these advances, the trend towards transportable IS facilities accelerated in the 1990's. Today, satellite terminals able to operate in military or civilian bands are encased in suitcases. COTS "office in suitcase" products incorporate multimedia telecommunications, position location, and rich varieties of distributed computing environment data processing functions.

Worldwide, many commercial telecommunications carriers inventory central office, tandem, and dual-function switches; cellular/PCS base-station; digital loop carrier (DLC); and other capabilities in transportable/mobile configurations. Alternatively, with broadband, fiber-optic transmission, traffic can be affordability back-hauled great distances to remotely restore damaged or otherwise failed switching, multiplexing, DLC, or other functions.

Because so many commercial enterprises now literally depend upon continuous telecommunications and data processing operations, and because downtimes of even 15 minutes can have catastrophic revenue and profit consequences, many businesses have elaborate internal or third-party, contract-based, disaster recovery IS capabilities.

All of the above IS technology capabilities are known to potential WMD proliferants and available on world markets. Thus, the possibility that WMD proliferants will be able to use transportable or mobile IS facilities to mount highly survivable offensives must be fully accounted for in planning by U.S. or allied forces.

RATIONALE

The relevance of older military or commercial, high-technology, highly survivable IS facility capabilities in WMD warfare is evident from the above discussion.

Should a WMD proliferator possess only fixed IS and support facilities, U.S. and allied precision-guided and other conventional weapons can be effective. In future WMD and other conflicts, we may find that adversaries have deployed, or can deploy, transportable or mobile IS facilities. Ominously, in many cases the total cost per transportable IS facility may be an order of magnitude less than the costs of a single precision-guided conventional weapon needed to target and destroy such a facility.

Clearly, the wartime utility of high-technology, high-survivability IS Facility capabilities by WMD users must be fully understood by U.S. strategists and planners if effective countermeasures and counter-strike alternatives are to be available.

See Tables 2.6-1 and 2.6-2 for specific examples of pertinent IS Facility capabilities. Sections 3 (Biological Weapons Technology), 4 (Chemical Weapons Technology), and 5 (Nuclear Weapons Technology) present specific technologies that provide personal and shelter-based protection from chemical, biological and nuclear weapons effects, respectively. Note that survivable IS facilities are not required by proliferators with minimal WMD weapon inventories and capabilities, or those that perhaps would launch isolated WMD attacks.

FOREIGN TECHNOLOGY ASSESSMENT

The last column in Figure 2.0-2 contains a foreign technology assessment by country and for subnational groups in the IS Facilities Functional Area. Countries with advanced Information Systems, and especially those defending against or planning large-scale, sustained WMD operations, need all of the IS Facilities Functional Area capabilities. Only nine of the 32 countries listed have capabilities in all of the technologies in this functional area.

Like the IM&C technologies, the IS Facilities Functional Area technologies are found among the world leaders in Information Systems: Canada, France, Germany, Japan, the UK, and the United States. Denmark, Norway, Russia, and Sweden also have all IS Facilities Functional Area technologies. Several countries have limited IS Facilities Functional Area technologies: Iran, North Korea, and Poland. Iraq, Libya, Vietnam, and the subnationals also have limited capabilities in these technologies.

Proliferants committed to conducting large-scale and sustained WMD warfare need substantial IS Facilities Functional Area capabilities, particularly for operations requiring highly survivable transportable and mobile IS capabilities.

Table 2.6-1. Information Systems Facilities Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Transportable command and force shelters	High mobility and WMD weapon effects protection incorporating closed-cycle or specialized air-decontamination capabilities and radiation-hardened to protect/limit exposure of internal components to a total dose* of 5×10^3 Gy(SI) or a transient dose of 5×10^6 Gy(SI)/sec.	WA ML 13; USML XXI	None Identified	EMI/EMP testing	None Identified
Specially designed tractor-trailer rigs for telecommunications restoration	Equipped with central office and dual function switches, multiplexing and media termination equipment, incorporating closed-cycle or specialized air-decontamination capabilities and radiation-hardened to protect/limit exposure of internal components to a total dose of 5×10^3 (Gy)(SI) or a transient dose of 5×10^6 Gy(SI)/sec, able to restore transmission and call center service and rapidly deployable via road, rail, or air shipment.	WA ML 13; USML VII	None Identified	None Identified	None Identified
Transportable base stations	Provides and with the ability to rapidly deploy or restore terrestrial cellular, PCS, or SMR service. Incorporating closed-cycle or specialized air-decontamination capabilities and radiation-hardened to protect/limit exposure of internal components to a total dose of 5×10^3 Gy(SI) or a transient dose of 5×10^6 Gy(SI)/sec.	WA ML 13; USML XXI	None Identified	None Identified	None Identified

* The dose rates are expressed in *Système Internationale d'Unités* (SI) metric units of radiation. The gray (Gy) is a unit of absorbed dose of ionizing radiation; one Gy is an absorbed dose of ionizing radiation equal to one joule per kilogram of absorber. The gray replaces the rad. One rad = 0.01 Gy.

Table 2.6-2. Information Systems Facilities Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Transportable command and force shelters	Degree of ability to withstand bombs, missiles, or WMD weapons effects	Highly survivable C^2I and trans-attack conflict execution operations	Use other fixed and mobile assets as available
Specially designed tractor-trailer rigs for telecommunications restoration	Deployment and activation rates under military conflict situations	Highly survivable switching, multiplexing and multimedia communications capabilities	Use other fixed and mobile assets as available
Transportable base stations	Requires combined use with survivable wireline telco service items to reap maximum benefits	Survivable home-country and theater of operations communications (see additional citations above)	Use other fixed and mobile assets as available

SECTION III

BIOLOGICAL WEAPONS TECHNOLOGY

SECTION 3—BIOLOGICAL WEAPONS TECHNOLOGY

Scope

Highlights

- Biological weapons are unique because they are made up of pathogenic organisms that can reproduce and cause infection (and death) in a large number of hosts.
- It takes hours to days for symptoms of exposure to appear.
- Biological weapons are relatively inexpensive to produce.
- All of the equipment used to produce biological agents is dual use, with applications in the pharmaceutical, food, cosmetic, and pesticide industries.
- Dissemination and dispersion are key to the effective employment of biological weapons.
- Many toxic organisms are subject to destruction by external forces (e.g., sunlight, explosives).

BACKGROUND

Biological agents are naturally occurring microorganisms (bacteria, viruses, fungi) or toxins that can cause disease and death in a target population. They can also attack the food supply and/or materiel of a nation. Biological weapons (BW) which project, disperse, or disseminate biological agents have two characteristics that enhance their effectiveness as weapons: (1) biological agents, other than toxins, reproduce and, therefore, a small amount of infectious agent can cause disease; (2) biological agents, other than toxins, usually require an incubation period of hours to days to manifest signs of exposure so the affected soldier is not certain whether a biological agent attack has occurred until illness sets in. The uncertainty can compromise unit cohesion and weaken U.S. force superiority.

The United States has forsworn the use of biological weapons and has developed a strategy of offensive strike power by other means, coupled with biological defense capability, as a suitable deterrent to potential adversaries. A nation, subnational group, or organization, or even an individual, determined to construct a biological weapon and release the agent can, with minimal financial resources and infrastructure, produce an effective weapon. Small amounts of biological material are sufficient because of the reproductive nature of microorganisms. The availability of small amounts of biological organisms, including those listed by the Australia Group (AG), in culture collections provides a major resource for such determined entities. All of these stocks are also available from natural sources, such as soil samples and infected rodents. In addition to naturally occurring organisms, genetically modified organisms may be used as biological agents. Some organisms exist primarily in repositories and may be used as biological agents (Variola Virus). It is estimated that between 10 and 10,000 virulent organisms of the AG agents are sufficient to cause illness in one individual. The number of organisms required is a function of the specific agent and the means of delivery. The delivery of a limited amount of a biological agent might be militarily significant if the agent is released in a contained environment (e.g., a closed building, submarine, or surface vessel).

There are aspects that make biological weapons agents unique and different from all other weapon systems. Whereas a subnational group would be required to have a significant infrastructure to develop nuclear devices, it would be less complicated to make biological agents. Moreover, the biological agent could be a strategic and disorganizing threat because of its ability to reproduce and the delayed manifestation of symptoms. Those delivering BW could be protected by active or passive immunization or by well-designed protective masks to protect the respiratory system from aerosols, the primary delivery mechanism.

An additional concern is the relative low cost required for the production and the ease of deployment of biological agents by subnational groups and organizations for biomedical, pharmaceutical, and food production. All of the equipment used to produce biological agents is dual use.

Because biological agents reproduce, only small amounts of a starter organism are needed. The use of appropriate growth media or nutrients in a cell culture system of 100 liters, or of four passes through a 25-liter system, can generate sufficient agent to infect numerous targets in a contained area (e.g., subway, contained office building). Other weapons of mass destruction (WMD) require the purchase of large amounts of precursor or of fissile material to achieve threat capability. The self-generation of the biological agent is a unique element of this WMD.

Biologically derived toxins also present a threat. The recent apprehension in the United States of an individual citizen who produced large quantities of the toxin ricin is an example of the danger related to the production of toxin WMDs by small groups. As with other chemical agents, the toxins do not reproduce and, therefore, represent a threat that differs quantitatively from biological agents.

1. History of Biological Weapons

Crude forms of biological warfare have been employed since 300 B.C., when the decaying corpses of animals and humans were placed near water and food supplies of adversaries. Over the years, different diseases, including plague and smallpox, were used as the agent. Catapults were one vehicle for introduction of the infected tissue. Other vehicles, including blankets, have been employed to transmit smallpox to a target population.

World War I saw the development of biological warfare strategies. Cholera and plague were thought to be used in Italy and Russia while anthrax was presumably used to infect animals in Romania. A consequence of such events was the 1925 Protocol for the Prohibition of the Use in War of Asphyxiating, Poisonous, or Other Gases, and of Bacteriological Methods of Warfare—known as the Geneva Protocol. This protocol banned the use of biological agents in warfare but not research, development, production, or stockpiling of such agents.

With the advent of World War II, rapid developments occurred in biological warfare capability in the United States and other nations. In February 1942, the U.S. National Academy of Sciences established a Biological Warfare Committee, chaired by Edwin B. Fred of the University of Wisconsin. The administration of the biological warfare effort was placed under civilian supervision: Dr. George Merck directed the advisory group, and Ira Baldwin of the University of Wisconsin became the scientific director. In 1943, Fort Detrick, Maryland, became the site of these activities, as Camp Detrick. In Canada, Sir Fredrick Banting, Dr. J.R. Collys, and Dr. Charles Best led the biological warfare capability effort.

The technologies examined at Fort Detrick included pathogen identification, modes of transmission, infection, detection, public health measures, containment, rapid drying of organisms, and packing for delivery. In 1969, President Nixon stated that the U.S. unilaterally renounced biological warfare. Biological weapon stockpiles and their associated munitions were destroyed following the preparation of an environmental impact statement and review by both federal and state authorities and the public. Low targeting capability, the potential for catastrophic outcome on civilian populations, and public antipathy to biological weaponry were factors in the renunciation of biological warfare. In 1972, there was international agreement to the Convention of the Prohibition of the Development, Production, and Stockpiling of Bacteriological and Toxin Weapons and their Destruction [Biological Weapons Convention (BWC)]. Concern over USSR compliance with the Convention arose with the sudden outbreak of anthrax cases in Sverdlovsk (now Ekaterinenberg) in 1979.

The early 1980's saw renewed discussion of the utility of biological weapons as strategic weapons. For example, information became publicly available concerning studies of biological agents in Japan and the studies on the effects of infectious agents on human subjects in Harbin, Manchuria, during World War II. The number of infectious agents used on human populations was about 25 (e.g., plague, typhus, smallpox, tularemia, gas gangrene, tetanus, cholera, anthrax, tick encephalitis). In 1941, the Japanese deployed plague-infected fleas in Hunan Province, resulting in the death of several hundred persons. The difficulty encountered by the Japanese was the development of an effective delivery system.

In recent years, newly emerging infectious diseases have complicated the picture. They include AIDS, prion disorders, and several hemorrhagic fevers such as Ebola. These diseases and the possible reduction in immunocompetence have fostered an increased role of the United States and international agencies in monitoring disease outbreaks. Several federal agencies in the United States are responsible for the health and protection of the population, including military personnel, from infectious diseases. The civilian agencies include the National Institutes entities that address health care issues of primary importance to the defense community: Walter Reed Army Institute of Research, United States Army Medical Research Institute of Infectious Diseases (USAMRIID), and the Naval Medical Research Units.

2. Recent Developments Affecting Biological Warfare Capability

The introduction of modern biotechnology during the past 25 years has markedly changed the qualitative and quantitative impact that biological warfare, or the threat of such warfare, can have on military forces and urban communities. This new technology provides the potential capability of (1) developing biological agents that have increased virulence and stability after deployment; (2) targeting the delivery of organisms to populations; (3) protecting personnel against biological agents; (4) producing, by genetic modification, pathogenic organisms from non-pathogenic strains to complicate detection of a biological agent; (5) modifying the immune response system of the target population to increase or decrease susceptibility to pathogens; and (6) producing sensors based on the detection of unique signature molecules on the surface of biological agents or on the interaction of the genetic materials in such organisms with gene probes. The specific technologies used in realizing these capabilities include (1) cell culture or fermentation; (2) organism selection; (3) encapsulation and coating with straight or crosslinked biopolymers; (4) genetic engineering; (5) active or passive immunization or treatment with biological response modifiers; (6) monoclonal antibody production; (7) genome data bases, polymerase chain reaction equipment, DNA sequencers, and the rapid production of gene probes; and (8) the capability of linking gene probes and monoclonal antibodies on addressable sites in a reproducible manner.

New technologies related to biological warfare are emerging rapidly. The technology of monoclonal antibody production has existed only since 1975, while the technology of genetic engineering has existed since the 1980's. Technology for sequencing the genomes of organisms has changed so dramatically that the rate of sequencing has increased by several orders of magnitude since 1994. All of these reflect the enormous change in information databases and in technology including biotechnology, computer equipment, processes, and networking of research teams. Information that will emerge from the human genome effort is likely to increase our understanding of the susceptibilities of different populations to disease and stresses of various sources. Such information may increase the proliferation of BW agents, particularly in areas with active ethnic rivalries, and lead to a new variant of ethnic cleansing.

The rapid rate of development reflects to some degree the national and international investment in this technology. The level of federal spending in the United States in the entire biotechnology area during 1994 approximated 4 billion dollars. The private sector invested approximately 7 billion dollars during the same year. This investment and the rate of information accrual indicates that biological technology that can be used for peaceful and military purposes is increasing in capability at a rate exceeding most other technologies. The pharmaceutical industry is relying on biotechnology for new therapeutic products to improve prophylaxis and therapy for many different diseases and is concerned that these new technologies not fall into the hands of potential adversaries.

Figure 3.0-1 portrays graphically the explosive growth of applicable biotechnologies. The illustration was prepared from a broad field of knowledge and applications, which, in aggregate, are doubling every 18 months. Examples of sustained geometric growth include monoclonal antibodies, combinatorial chemistry, and gene probes, which are explained below.

- Monoclonal Antibodies - In the early 1970's, Kohler and Milstein developed a procedure to produce antibodies for a single antigenic epitope. An epitope is the region of a molecule that initiates the production of a single antibody species. The dimensions of an epitope approximate a surface area 50 × 50 Angstroms. These antibodies are called monoclonal antibodies. With quality control, these antibodies can be produced in gram quantities in a highly reproducible manner, and therefore, they are suited for industrial uses. The industries currently using monoclonal antibodies include medical diagnostics, food, environmental protection, and cosmetics.

- Combinatorial Chemistry - This is a technique for rapidly synthesizing large numbers of peptides, polynucleotides, or other low molecular weight materials. These materials are synthesized on a solid-state matrix and in an addressable form so that materials of known sequence can be accessed readily. The materials can function as receptors, pharmaceuticals, or sensor elements. The technique, developed by Merrifield in the 1970's, has been essential for the growth of combinatorial chemistry.

- Gene Probes - These are polynucleotides that are 20–30 units bend, under stringent conditions, complementory nucleic acid fragments characteristic of biological agents. These units provide the basis of rapid detection and identification.

OVERVIEW

This section of the MCTL is concerned with technologies related to the development, integration and deployment of biological weapons . The infectious organisms discussed are those identified by the AG (see Figure 3.0-2). The AG list does not include every known organism that could be used in a biological weapon. Toxins will be considered in the biological weapons section consistent with the AG and the BWC of 1972. Several aspects of biological warfare will be covered: (1) the identity of the biological organism or toxins; (2) equipment and materials necessary for the production, containment, purification, quality control, and stabilization of these agents; (3) the technologies for the dissemination and dispersion of biological agents; (4) equipment for detection, warning, and identification of biological agents; and (5) individual and collective biological defense systems.

RATIONALE

Biological weapons are unique because the effects from pathogenic organisms, except toxins, are not seen for hours to days after dissemination. If adequate detection devices are not available, the first indication of a biological weapon attack could be symptoms in target personnel. At this point, treatment propylaxis and therapy is often ineffective. In addition, incapacitated troops require tremendous logistical support (four or five medical corpsmen and associated personnel for each ill person); thus, incapacitants may be preferable to lethal agents. Also, besides deaths caused by infectious agents, the psychophysical damage suffered by troops who believe they have been exposed to a biological attack could markedly impair combat functions. The perception is almost as significant as the reality. The affected soldier is not certain whether a biological attack has occurred and could be psychologically, if not physically, impaired.

The biological technology industry is information intensive rather than capital intensive. Data on technologies involved in biological production are widely available in the published literature. These technologies are dual use, with applications in the pharmaceutical, food, cosmetic, and pesticide industries. New technologies, such as genetic engineering, are more likely to affect fabrication, weaponization, or difficulty of detection than to produce a “supergerm” of significantly increased pathogenicity.

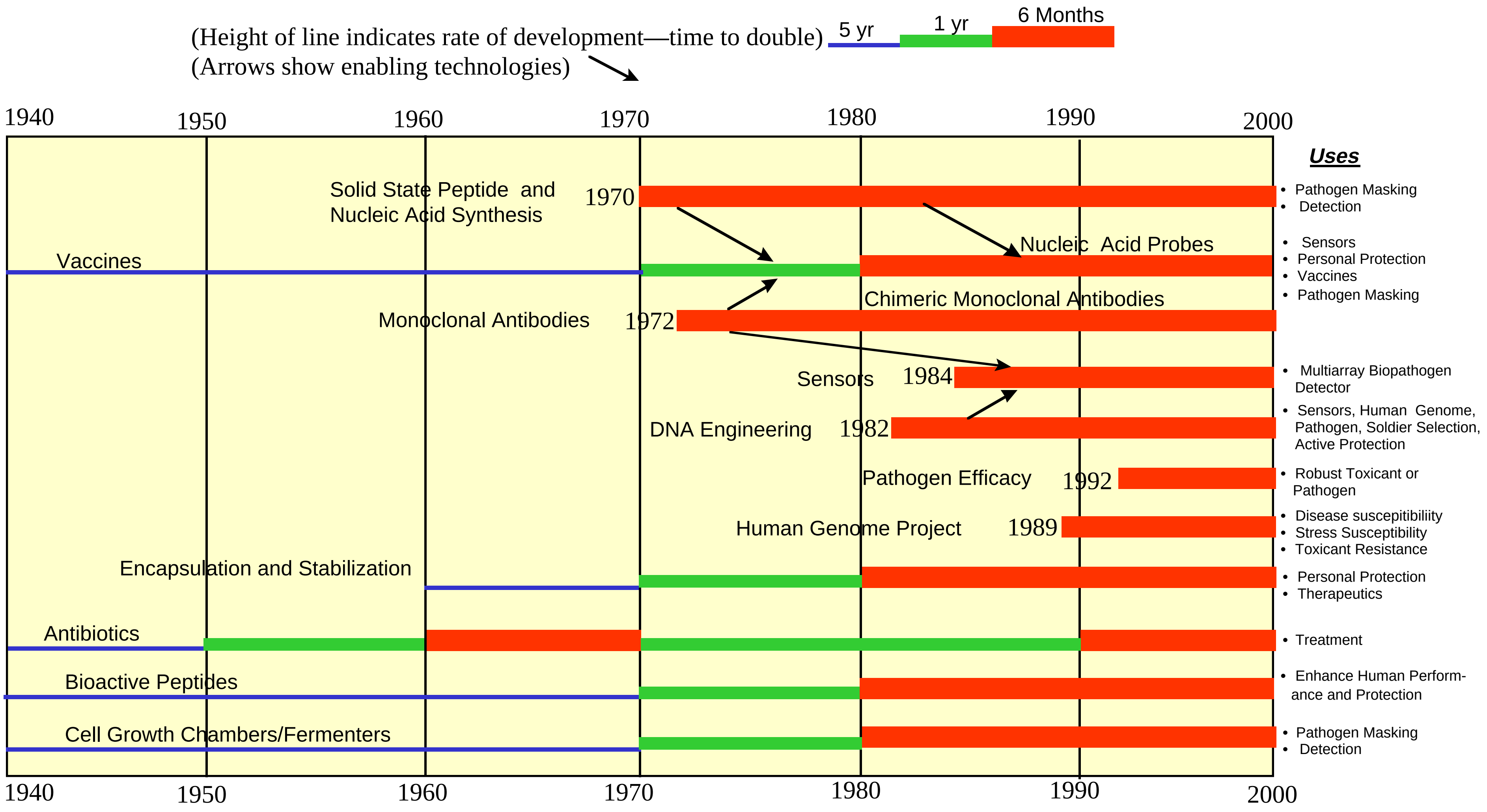

Figure 3.0-1. Progress in Applicable Biotechnologies

Viruses

V1. Chikungunya virus
V2. Congo-Crimean haemorrhagic fever virus
V3. Dengue fever virus
V4. Eastern equine encephalitis virus
V5. Ebola virus
V6. Hantaan virus
V7. Junin virus
V8. Lassa fever virus
V9. Lymphocytic choriomeningitis virus
V10. Machupo virus
V11. Marburg virus
V12. Monkey pox virus
V13. Rift Valley fever virus
V14. Tick-borne encephalitis virus (Russian spring-summer encephalitis virus)
V15. Variola virus
V16. Venezuelan equine encephalitis virus
V17. Western equine encephalitis virus
V18. White pox
V19. Yellow fever virus
V20. Japanese encephalitis virus

Rickettsiae

R1. Coxiella burnetti
R2. Bartonella quintana (Rochlimea quintana, Rickettsia quintana)
R3. Rickettsia prowasecki
R4. Rickettsia rickettsii

Bacteria

B1. Bacillus anthracis
B2. Brucella abortus
B3. Brucella melitensis
B4. Brucella suis
B5. Chlamydia psittaci
B6. Clostridium botulinum
B7. Francisella tularensis
B8. Burkholderia mallei (pseudomonas mallei)
B9. Burkholderia pseudomallei (pseudomonas pseudomallei)
B10. Salmonella typhi
B11. Shigella dysenteriae
B11. Vibrio cholerae
B13. Yersinia pestis

Genetically Modified Microorganisms

G1. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences associated with pathogenicity and are derived from organisms in the core list.
G2. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences coding for any of the toxins in the core list or their subunits.

Toxins

T1. Botulinum toxins
T2. Clostridium perfringens toxins
T3. Conotoxin
T4. Ricin
T5. Saxitoxin
T6. Shiga toxin
T7. Staphylococcus aureus toxins
T8. Tetrodotoxin
T9. Verotoxin
T10. Microcystin (Cyanginosin)
T11. Aflatoxins

Viruses (Warning List)

WV1. Kyasanur Forest virus
WV2. Louping ill virus
WV3. Murray Valley encephalitis virus
WV4. Omsk haemorrhagic fever virus
WV5. Oropouche virus
WV6. Powassan virus
WV7. Rocio virus
WV8. St Louis encephalitis virus

Bacteria (Warning List)

WB1. Clostridium perfringens
WB2. Clostridium tetani
WB3. Enterohaemorrhagic Escherichia coli, serotype 0157 and other verotoxin-producing serotypes
WB4. Legionella pneumophila
WB5. Yersinia pseudotuberculosis

(cont'd)

Figure 3.0-2. Australia Group Biological Agents

Genetically Modified Microorganisms

WG1. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences associated with pathogenicity and are derived from organisms in the warning list.
WG2. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences coding for any of the toxins in the warning list or their subunits.

Toxins (Warning List)

WT1. Abrin
WT2. Cholera toxin
WT3. Tetanus toxin
WT4. Trichothecene mycotoxins
WT5. Modecin
WT6. Volkensin
WT7. Viscum Album Lectin 1 (Viscumin)

Animal Pathogens

Viruses:
AV1. African swine fever virus
AV2. Avian influenza virus
AV3. Bluetongue virus
AV4. Foot and mouth disease virus
AV5. Goat pox virus
AV6. Herpes virus (Aujeszky’s disease)
AV7. Hog cholera virus (synonym: Swine fever virus)
AV8. Lyssa virus
AV9. Newcastle disease virus
AV10. Peste des petits ruminants virus

Animal Pathogens (cont’d)

Viruses (cont’d):
AV11. Porcine enterovirus type 9 (synonym: Swine vesicular disease virus)
AV12. Rinderpest virus
AV13. Sheep pox virus
AV14. Teschen disease virus
AV15. Vesicular stomatitis virus

Bacteria:
AB3. Mycoplasma mycoides

Genetically Modified Microorganisms:
AG1. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences associated with pathogenicity and are derived from animal pathogens on the list.

Plant Pathogens

Bacteria:
PB1. Xanthomonas albilineans
PB2. Xanthomonas campestris pv. citri

Fungi:
PF1. Colletotrichum coffeanum var. virulans (Colletotrichum kanawae)
PF2. Cochliobolus miyabeanus (Helminthosporium oryzae)
PF3. Microcyclus ulei (syn. Dothidella ulei)
PF4. Puccinia graminis (syn. Puccinnia graminis f. sp. tritici)

Plant Pathogens (cont’d)

Fungi (cont’d):
PF5. Puccinia striiformis (syn. Pucciniaglumarum)
PF6. Pyricularia grisea/Pyricularia oryzae

Genetically Modified Microorganisms:
PG1. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences associated with pathogenicity derived from the plant pathogens on the list.

Awareness Raising Guidelines

Bacteria:
PWB1. Xanthomonas campestris pv. oryzae
PWB2. Xylella fastidiosa

Fungi:
PWF1. Deuterophoma tracheiphila (syn. Phoma tracheiphila)
PWF2. Monilia rorei (syn. Moniliophthora rorei)

Viruses:
PWV1. Banana bunchy top virus

Genetically Modified Microorganisms:
PWG1. Genetically modified microorganisms or genetic elements that contain nucleic acid sequences associated with pathogenicity derived from the plant pathogens identified on the awareness raising list.

Figure 3.0-2. Australia Group Biological Agents (cont’d)

While laboratory-scale capability for production of biological agents is sufficient for achieving most terrorist purposes, large-scale production for military purposes can be achieved easily in dual-use facilities. All of the equipment needed for large-scale production of offensive biological agents is dual use and available on the international market. Although a typical vaccine plant costs in excess of $50 million, a less elaborate fermentation plant that could produce biological agents could be built for less than $10 million.

If disseminated properly, only a small amount of biological agent is needed to infect numerous people. Proper dissemination, however, is a non-trivial problem because the agent must be dispersed in 1 to 10 micron particles and be inhaled by the target population. Symptoms normally take hours to days to appear. Detection is key to implementation of protective measures. Since biological organisms are living, they have the potential to reproduce. They can continue to affect people for extended periods of time. However, they are subject to being negated by sunlight and the environment, but most can be effectively stabilized against adverse environmental effects. Stress from explosive dissemination and/or missile firing can reduce efficiency to about the 5-percent level, which is why aerosol dissemination by pressurized gases was adopted by munition designers in the old U.S. program. Dissemination efficiencies of up to 70 percent were achieved, with 30 to 50 percent being produced routinely. Vaccines can be produced to defend against biological agent use; however, to produce the vaccine, the organism being employed by an adversary must be known.

Although some of the proliferation concerns for biological weapons are similar to those for other WMD, some concerns are unique. The unique features include containment of the agent during production, stabilization and dispersion of the agents, detection, identification, and warning. All these aspects are important because biological agents are relatively easy to hide. The diffusion of information, technologies, and raw materials associated with biological and pharmaceutical processing are almost always dual use and, therefore, raise non-proliferation issues.

Because of the low financial costs of acquiring equipment for biological agent production, the implications for the proliferation of production and dispersion are clear: developing nations can attack targets effectively with biological agents. Defensive technologies are of interest because changes in vaccine production or other self-protection measures could presage an offensive attack. Stabilization and dispersion are proliferation concerns because these technologies increase the efficacy of biological agents. Detection, identification, and warning technologies can be used to support efforts to mask the presence of biological agents even though these technologies do not pose a direct threat.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 3.0-3)

Most industrialized nations manufacture equipment and materials that can be used for the production, containment, purification, quality control, and stabilization of biological agents and for their dissemination and dispersion. Most developed nations manufacture the equipment for identifying these agents, but the means for detection and warning are less readily available. All these technologies are dual use, with applications in the pharmaceutical, food, cosmetic, and pesticide industries. The AG group of biological agents are readily available in the natural environment and from culture collections in the industrialized and in some developing nations. The recent outbreaks of Ebola in Africa and Hanta (Hantaan) virus infections in Asia and North and South America are evidence of occurrence in the natural environment. In addition, these organisms can be obtained from national collections [e.g., American Type Culture Collection (ATCC) and European collection]. The ATCC and European collections do not necessarily share information.

Many collections of organisms recognized as potential biological agents and included in the AG list exist throughout the world and are made available with minimal monitoring of use or transport. This is particularly the case in the open societies of the United States, Europe, and Japan, as was documented in 1995 by a case occurring in Ohio. The nutrients, growth media, and small-size fermenters are readily available.

Country	Sec 3.1 Biological Material Production	Sec 3.2 Stabilization, Dispersion and Weapons Testing	Sec 3.3 Detection, Warning, and Identification	Sec 3.4 Biological Defense Systems
Australia[1]	♦♦	♦♦	♦♦	♦♦♦
Austria[1]	♦	♦♦	♦♦♦	♦♦♦
Belgium[1]	♦♦	♦♦	♦♦	♦♦
Brazil	♦♦	♦♦	♦	♦
Bulgaria	♦	♦♦	♦♦	♦♦♦
Canada[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
China	♦♦♦	♦♦♦	♦♦♦	♦♦♦
Cuba	♦♦	♦♦	♦♦	♦
Czech Republic[1]	♦♦	♦♦♦	♦♦♦	♦♦♦♦
Denmark[1]	♦♦	♦♦	♦	♦♦
Egypt	♦	♦♦	♦	♦♦
Finland[1]	♦♦♦	♦♦♦	♦♦♦	♦♦♦
France[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Greece[1]	♦	♦	♦	♦♦
Hungary[1]	♦♦♦	♦♦	♦♦♦	♦♦♦♦
India	♦♦♦	♦♦♦	♦♦	♦♦
Iran	♦♦	♦♦	♦	♦♦
Iraq	♦♦♦	♦♦	♦	♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy[1]	♦♦♦	♦♦	♦♦	♦♦
Japan[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Korea (North)	♦♦	♦♦	♦	♦♦♦
Korea (South)[1]	♦♦♦	♦♦	♦♦	♦♦♦
Libya	♦♦	♦	♦	♦
Netherlands[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Norway[1]	♦♦♦	♦♦♦	♦♦	♦♦
Pakistan	♦♦	♦♦	♦♦	♦♦♦
Poland[1]	♦♦	♦♦	♦♦	♦♦♦
Romania[1]	♦♦	♦	♦♦	♦♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Slovak Republic[1]	♦♦	♦♦	♦♦♦	♦♦♦
South Africa	♦♦	♦♦	♦♦♦	♦♦♦
Spain[1]	♦♦	♦	♦	♦
Sweden[1]	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
Switzerland[1]	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦
Syria	♦♦	♦♦	♦	♦
Turkey	♦♦	♦♦		
Ukraine	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦
United Kingdom[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States[1]	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

[1] Indicates that the nation is a member of the Australia Group (AG).

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 3.0-3. Biological Weapons Foreign Technology Assessment Summary

SECTION 3.1—BIOLOGICAL MATERIAL PRODUCTION

OVERVIEW

The previous section addressed the various organisms that might be selected for production (The AG Biological Agents). This section addresses the production of the organisms, including procedures such as culture, fermentation, viral reproduction, etc.; the stabilization of the organisms; and specific equipment used in the manufacturing process.

The stages involved in the production of biological agents include selection of the organisms, large-scale production of organisms from small starter cultures, and stabilization of the organisms. The list of biological organisms and toxin products that are of concern as biological agents is derived from the AG consensus.

The design of a production facility provides important information regarding whether the facility is intended to produce pharmaceutical grade products or biological weapon grade materials. Relevant design elements include containment, purification equipment, sterilization equipment, and ventilation and filtration systems.

The design of a biochemical processing plant is an important signal of covert biological agent production. Containment of the biological material during processing is of special interest. There is a clear distinction between processing materials for biological or toxin agent weaponization and processing protective agents to be used for countermeasures or personnel performance enhancement. For the production of biological agents for offensive military activities, the processing containment requirement is to protect the environment from the agent because of its infectious nature. For the production of biomaterials, such as vaccines, biological response modifiers, antibiotics, and anti viral agents, for defensive military activities, the containment requirement is to protect the processed biomaterial from contaminating materials in the environment. Effectiveness of countermeasures is enhanced by achieving high levels of purity and cleanliness in the product before it is administered to friendly personnel. By contrast, an unpurified biological agent that will be used in BW is generally more stable than the purified agent that is needed to produce vaccines and biological response modifiers (BRMs). Consequently, a proliferant does not require a high level of purity if production is for BW use only.

Generation of biological agents requires fermenters or single cell production capabilities with operational conditions identified in the MCTL, including smooth, highly polished stainless steel surfaces, self-containment capability, and negative pressure conditions. The primary difference between the production requirements for biological weapons and non-military commercial purposes lies in containment and contamination. During biological agent production, efforts are generally made to avoid contaminating the environment with the organism. Less concern arises about the contamination of the product. Conversely, the pharmaceutical, brewing, and biotechnology industries are most concerned about protecting the purity and quality of the product. This concern is reflected in the nature of the sealing joints, positive or negative pressure chambers, and containment of venting systems.

Highlights

- Biological weapon production is similar to commercial production of biological materials.
- With the exception of toxins, biological organisms can multiply.
- Containment of the organisms is critical.
- Design of the plant can indicate covert biological agent production.

Utilities involving clean steam, sterile air, and inert gas supply are most critical for containment in the processing of biologically based materials for human use, which must meet good manufacturing practices (GMP). Clean steam, generated from a purified water supply, must be supplied to all processing equipment having direct contact with the product to ensure sterility and prevent the influx of environmental contaminants. Steam sterilization is accomplished before product processing by direct supply to the equipment. Steam is supplied to the equipment seals (e.g., sample ports, agitator shafts, raw material addition ports) during processing as a primary barrier. Equally important is the removal of collapsed steam or condensate formed on the equipment. This prevents the formation of pockets of standing water, which promote bacterial growth, and maintains the high temperature necessary for sterilization. The collected contaminated condensate can be channeled to an area for final sterilization or inactivation before it is released into the environment. Efficient steam supply and condensate removal requires pressure regulators, pressure relief devices, venting, and the capability for free draining of all lines.

Supplying sterile, inert gases to processing equipment is a method of containment. This can protect oxygen-sensitive biomaterials and prevent aerosol generation of toxic products. Inert gases, such as nitrogen, helium, and argon, are usually supplied directly to processing equipment through sterile, in-line filters, maintaining a pressurized system or providing an inert blanket over the product in processing vessels.

To attain a higher level of containment, many bioprocessing industries have employed greater degrees of automation. Potential contamination of purified product, human exposure to toxic products or constituents, and the risk of human error are minimized. Processing facilities make use of state-of-the-art computerized distributed control systems (ABB, Modicon, Allen Bradley Corp.), which allow automatic control, control from remote locations, and automatic data logging and trending.

Another component in bioprocessing is the design of ventilation within the primary and secondary barriers of a process area. Ventilation at primary barriers (i.e., barriers separating product from equipment operators and the rest of the processing area) is accomplished with dedicated, in-line air/gas membrane filters. Ventilation across secondary barriers requires more complicated air handling system design to allow for the maintenance of clean areas (rated by the number of particles per volume of air) and maintenance of positive or negative pressure between the processing area and the outside environment or between different processing areas in the same facility. Equipment used in these designs includes high efficiency fans and high efficiency particulate air (HEPA) filters.

The procedure used for the actual replication of an organism is a function of the organism itself. Tables 3.1-1 and 3.1-2 include several techniques, including cell culture, fermentation, viral replication, recombinant DNA, and powdering and milling. Cell culture is necessary for the reproduction of pathogenic viruses and Rickettsiae since they will not reproduce outside a living cell (e.g., chick embryo or tissue cultures). Single cell growth chambers, including fermentation, are used for the production of bacteria and bacterial toxins, although some bacteria (e.g., plague bacteria) can also be cultivated in living animals. Recombinant DNA techniques are a preferred method to produce rare animal toxins. Because of the complexity of this technique, the capability is not as widespread as the others. Powdering and milling is the technique generally used to produce BW and toxin weapons (TW) agent particles having diameters less than or equal to 10 μm, the size most effective for respiratory delivery.

RATIONALE

Figure 3.0-2 lists the naturally occurring pathogens and toxins potentially used as BW agents. Whereas the majority of these agents have no current dual-use applications, a small number do have biomedical roles other than those in vaccine production. The highly toxic botulinal toxin A, produced by Clostridium botulinum, shows medicinal promise in blocking involuntary muscle spasms or weakening a muscle for therapeutic purposes. Five medical uses of toxins that might be used in BW have been approved by the Food and Drug Administration. Immune protection against these agents is important because they occur naturally in some regions of the world. Toxins and pathogens that affect animals, such as anthrax, brucella, plague, and tularemia, are widespread. Vaccines are widely produced and administered. The issue of the need for the same toxic agent for either BW/TW production or countermeasure vaccine production emphasizes the dual-use nature of the technologies. Indeed, initial processing of agents and processing of their associated vaccines only differ by a few steps (e.g., the degree of purification and the type of containment used).

The qualitative and quantitative impact of biological warfare, or the threat of such warfare, on military forces and urban communities has changed markedly in the past 20 years. The production techniques described in this section have resulted in more virulent strains of organisms and the genetic modification of non-pathogenic organisms to pathogenic strains with virulent characteristics. The implications of genetic engineering for chemical and biological warfare are far-reaching. Genetic engineering provides the potential for improved virulence by the incorporation of genes (i.e., specific strands of DNA) permitting increased production of a pathogen or toxin. Thus, as much as 100 times more pathogen or toxin could be produced per cell than that which could be produced by naturally occurring strains. Cells that normally do not produce toxins may be altered to produce toxins for biological weapon development. Conversely, known pathogens or toxins may be genetically inactivated for vaccine countermeasure development. Cells can also be modified to produce antibodies directly for passive immunization against specific infectious agents. As with the human immune system, many current biowarfare detection kits depend on antibodies reacting with the antigenic surface coatings of pathogenic bacteria or viruses. Thus, modified non-pathogens can be used to mask the agent from the immune-based detector and, potentially, from the human immune system itself to increase the agent's effectiveness.

General robustness or survivability of a pathogen under the environmental stresses of temperature, ultraviolet (UV) radiation, and desiccation (drying) can also be genetically improved to promote stability during dissemination; nutrient additives are used to enhance survival of selected biological agents in aerosols. Controlled persistence of a pathogen to permit survivability under specified environmental conditions may eventually be possible. The potential also exists for the development of so-called "conditional suicide genes," which could program an organism to die off following a predetermined number of replications in the environment. Thus, an affected area may be safely reoccupied after a predetermined period of time.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 3.0-2)

Seed stocks of the AG group of biological agents are readily available in the natural environment and from culture collections in the industrialized and in some developing nations. The recent outbreaks of Ebola in Africa and Hanta virus infections in Asia and North and South America are evidence of this. In addition, these organisms may be obtained from national collections (e.g., American Type Culture Collection [ATCC] and European collections).

Most industrialized nations manufacture equipment and materials necessary for the production, containment, purification, and quality control of these materials. Canada, France, Germany, Israel, Japan, the Netherlands, Russia, Sweden, Switzerland, the Ukraine, the UK, and the United States are the most advanced countries in the techniques of manufacturing large quantities of biological agents and protective vaccines and materials required for prophylaxis and therapy.

Table 3.1-1. Biological Material Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
HUMAN PATHOGENS See Figure 3.0-2					
Viruses	Any quantity is a concern. Less than 20 pounds can incapacitate humans in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Cell culture apparatus; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Bacteria	Any quantity is a concern. Less than 220 pounds can incapacitate humans in a 100-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Fermenters; cell cultures; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Toxins	Any quantity is a concern. Less than 600 pounds can incapacitate humans in a 100-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Fermenters; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Rickettsiae	Any quantity is a concern. Less than 100 pounds can incapacitate humans in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Cell culture apparatus; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Genetically Modified Microorganisms	Any quantity is a concern.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Infectivity of cultured organisms plus items in four entries above.	Not applicable
ANIMAL PATHOGENS See Figure 3.0-2					
Viruses	Any quantity is a concern. Less than 20 pounds can incapacitate animals in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Cell culture apparatus; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Bacteria	Any quantity is a concern. Less than 220 pounds can incapacitate animals in a 100-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Fermenters; cell cultures; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Genetically Modified Microorganisms	Any quantity is a concern.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Infectivity of cultured organisms plus items in two entries above	Not applicable

(cont'd)

Table 3.1-1. Biological Material Production Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
PLANT PATHOGENS **See Figure 3.0-2**					
Viruses	Any quantity is a concern. Less than 30 pounds can affect plants in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Cell culture apparatus; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Bacteria	Any quantity is a concern. Less than 30 pounds can affect plants in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Fermenters; cell cultures; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Fungi	Any quantity is a concern. Less than 50 pounds can affect plants in a 10-km^2 area.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Fermenters; cell cultures; laminar flow facilities; containment equipment; biological agent detectors	Not applicable
Genetically Modified Microorganisms	Any quantity is a concern.	AG List; WA ML 7; CCL Cat 1C; USML XIV	Not applicable	Infectivity of cultured organisms plus items in three entries above**.**	Not applicable
EQUIPMENT					
Containment Facilities	Equipment having three or more physical barriers between the agent and the employee.	AG List; CCL Cat 2B	HEPA filters	Toxic agent detectors	Not applicable
Fermenters	Having: a capacity > 100 liters; multiple sealing joints; capable of *in situ* sterilization in a closed state.	AG List; CCL Cat 2B	Stainless steel; titanium; glass	Toxic agent detectors	Not applicable
Centrifugal Separators	Capable of processing 5-liter batches	AG List; CCL Cat 2B	Smooth surface; Aerosol containment	Toxic agent detectors	Not applicable
Cross-flow Filtration Equipment	Capable of processing 20-liter batches	AG List; CCL Cat 2B	Smooth surface; Aerosol containment	Toxic agent detectors	Not applicable

Table 3.1-2. Biological Material Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
HUMAN PATHOGENS **See Figure 3.0-2**			
Viruses	Containment and dissemination	Biological agents in biological weapons	Not applicable
Bacteria	Containment and dissemination	Biological agents in biological weapons	Not applicable
Toxins	Containment and dissemination	Biological agents in biological weapons	Not applicable
Rickettsiae	Containment and dissemination	Biological agents in biological weapons	Not applicable
Genetically Modified Micro-organisms	Containment and dissemination	Biological agents in biological weapons	Not applicable
ANIMAL PATHOGENS **See Figure 3.0-2**			
Viruses	Containment and dissemination	Biological agents in biological weapons	Not applicable
Bacteria	Containment and dissemination	Biological agents in biological weapons	Not applicable
Genetically Modified Micro-organisms	Containment and dissemination	Biological agents in biological weapons	Not applicable
PLANT PATHOGENS **See Figure 3.0-2**			
Bacteria	Containment and dissemination	Biological agents in biological weapons	Not applicable
Fungi	Containment and dissemination	Biological agents in biological weapons	Not applicable
Genetically Modified Micro-organisms	Containment and dissemination	Biological agents in biological weapons	Not applicable

Note: The United States has forsworn the use of biological weapons; however, to perfect defensive procedures, it is necessary to understand the organisms.

(cont'd)

Table 3.1-2. Biological Material Production Reference Data (cont'd)

EQUIPMENT			
Containment Facilities	Protection of the environment and the employee.	Containment, isolation, and production of biological agents	Programs to automate process, allowing automatic control, control from remote locations, and automatic data logging
Fermenters	Cleanliness of facilities and contamination of the agent	Containment, isolation, and production of biological agents	Programs to automate process, allowing automatic control, control from remote locations, and automatic data logging
Centrifugal Separators	Cleanliness of facilities and contamination of the agent	Containment, isolation, and production of biological agents	Programs to automate process, allowing automatic control, control from remote locations, and automatic data logging
Cross-flow Filtration Equipment	Quality of the filters and amount of air-flow	Containment, isolation, and production of biological agents	None identified

Note: The United States has forsworn the use of biological weapons; however, to perfect defensive procedures and intelligence-gathering procedures, it is necessary to understand the manufacturing procedures for these organisms.

SECTION 3.2—STABILIZATION, DISSEMINATION, AND DISPERSION

OVERVIEW

Biological weapons production can be divided into three distinct phases: biological agent production (see Section 3.1), stabilization, and dissemination/dispersion. This section discusses the latter two parts. Stabilization and dissemination/dispersion are important issues because of the susceptibility of the biological agents to environmental degradation, not only in storage but also in application. This is a problem whether the end use is for biological weapons, pharmaceutics, cosmetics, pesticides, or food-related purposes and is related to the susceptibility of the organisms to inactivation of the biochemical compound by the environment. This loss of bioactivity can result from exposure to high physical and chemical stress environments, such as high surface area at air-water interfaces (frothing), extreme temperatures or pressures, high salt concentrations, dilution, or exposure to specific inactivating agents.

This section discusses various techniques of stabilization, such as freeze drying and ultra freezing, and various techniques of dissemination/dispersion, such as spray devices, cluster bombs, etc. Section 1 of this document discusses modes of delivery, such as cruise missiles, airplanes, and artillery shells .

The primary means of stabilization for storage or packaging are initial concentration; direct freeze drying (lyophilization); direct spray drying; formulation into a special stabilizing solid, liquid, or sometimes gaseous solution; and deep freezing. Methods of concentration include vacuum filtration, ultrafiltration, precipitation, and centrifugation. Freeze drying is the preferred method for long-term storage of bacterial cultures because freeze-dried cultures can be easily rehydrated and cultured via conventional means. Many freeze-dried cultures have remained viable for 30 years or more.

Deep or ultra freezing of biological products is another long-term storage technique for species and materials not amenable to freeze drying. The method involves storage of the contained products in liquid nitrogen refrigerators (–196° Celsius) or ultra-low temperature mechanical freezers (–70° Celsius). Mechanical freezing systems should include precautionary back-up freezers and electrical generators. Cryoprotective agents, such as dimethyl sulfoxide (DMSO), glycerol, sucrose, lactose, glucose, mannitol, sorbitol, dextran, polyvinylpyrollidone, and polyglycol, are required to ensure cell viability during storage. A toxin agent is most effective when prepared as a freeze-dried powder and encapsulated. Such encapsulation, however, is not necessary for weaponization. Infectious biological agents are generally stabilized and then spray dried.

Effective delivery of these agents must also consider the environmental effects on the agent (inactivation). Dissemination (delivery) of biological agents in biological warfare has been traditionally accomplished by aerosol dispersal using either spray devices or through incorporation of the agents with *explosive devices* (cluster bombs, missile warheads with submunitions designed for extended biological agent dispersal). The latter, however, must be approached with caution since explosive, heat-generating entities can inactivate the organisms/toxins. The preferred approach is dispersion via the use of a pressurized gas in a submunition. Other preferred platforms from an efficiency standpoint include small rotary-wing vehicles, fixed-wing aircraft fitted with spray tanks, drones, bomblets, cruise missiles, and high-speed missiles with bomblet warheads. Fixed-wing aircraft and ground vehicles with aerosol generators also make excellent delivery systems.

Aerosolization of biological agents using spray devices is the method of choice since the extreme physical conditions associated with explosive dissemination can completely inactivate the biological agent. (Aerosol dispersal allows for control of particle size and density to maximize protection from environmental degradation and uptake of the enclosed biological agents in the lungs of targeted populations.) Aerosol particles with a diameter of 1–15 µm mass median diameter (MMD) are readily absorbed by lung cells following inhalation, the primary mode of infection by most biological agents. Some agents can also act following ingestion of contaminated food or water. However, infectious agents generally do not penetrate intact skin. Equipment used with aerosol dispersal of biological agents includes spray nozzles or aerosol delivery systems capable of dispersing particles or droplets and compressors for initial weaponization by agent integration with compressed gas (air). For subnational or terrorist groups, the biological agents can be dispersed by manual aerosol generators. The availability of vaccines against selected biological agents may render the user immune to the effects of the agent although a suffcient dose of agent may overwhelm the vaccine’s protective effect.

Dissemination efficiency rates of aerosol delivery systems are in the range of 40–60 percent. Cruise missiles, aircraft carrying gravity bombs or spray attachments,

Highlights

- Stabilization is critical to effective dissemination.
- The environment can affect the survival of the organism.
- Explosive delivery means can result in inactivation of the organism.

and fixed-wing or rotor craft with attached sprayers are all vehicles for delivery of biological agents. The delivery of biological agents by explosive devices is much less efficient (~1–5 percent).

In a theater environment, the effective use of BW agents requires analysis of meteorological conditions and the mapping of the target.

RATIONALE

Biological agents have some unique characteristics that make weaponizing them attractive. Most biological weapons consist of living organisms (toxins are the exception) and, thus, can replicate once disseminated. A relatively small group of persons, using single individuals deployed in a military staging area, could bring about the infection of a large percentage of targeted persons. The clinical illness could develop within a day of dispersal and last for as long as 2–3 weeks. The mission and political impact of such a strike on a combat or constabulary force of 10,000 soldiers may compromise operations. In a civil situation, major subway systems in a densely populated urban area could be targeted for biological agent strike, resulting in massive political and social disorganization. Approximately 10 grams of anthrax spores can kill as many persons as a ton of sarin. Under appropriate meteorological conditions and with an aerosol generator delivering 1–10 micron particle-size droplets, a single aircraft can disperse 100 kg of anthrax over a 300 km^2 area and theoretically cause 3 million deaths in a population density of 10,000 people per km^2. The mean lethal inhalator dosage is 10 nanograms.

On the other hand, some biological agent characteristics can severely limit the effectiveness of BW, which consist of living organisms. A technique to stabilize (protect) the organisms from adverse environments is essential if the weapons are to maintain their effectiveness over some period of time. This requirement of stabilization also extends to the methods of delivery since the organisms are very susceptible to degradation in the environments associated with delivery systems.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 3.0-3)

Any country having pharmaceutical, cosmetic, or advanced food storage industries will have stabilization facilities similar to those that could be used for biological weapons. The ability to disseminate the biological agent over a wide area would be limited to those countries having cruise missiles or advanced aircraft. Even the smallest country or a terrorist group, however, has the capability to deliver small quantities of BW agent to a specific target. Canada, France, Germany, Israel, Japan, the Netherlands, Russia, the UK, and the United States have the most advanced techniques of manufacturing large quantities of biological agent and are also the most apt to have the capability to disseminate the biological agent over large areas.

Table 3.2-1. Stabilization, Dissemination, and Dispersion Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Freeze-drying Equipment	Having: steam sterilizable; a condensor capacity > 25 kg in 24 hours and < 400 kg in 24 hours	AGList; CCL Cat 2B	Stainless steel; titanium; glass	Toxic agent detectors	None identified
Aerosol Inhalation Chambers	Designed for aerosol challenge testing having a capacity > 0.5 cubic meter	AGList; CCL Cat 2B	High efficiency filter that passes particles 0.1 to 10 µm in diameter	Toxic agent detectors	None identified
Delivery systems and spray tanks to allow bomblet dissemination	Any capability is a concern	WA ML 4, 7; USML IV, XIV	None identified	Spin flow and flow-forming machines	None identified
Warheads for missiles	Any capability is a concern	WA ML 4; USML IV, XIV	None identified	Spin flow and flow-forming machines	None identified
Development and use of accurate, short-term weather prediction	Any capability is a concern	CCL EAR 99	None identified	None identified	Validated software to predict short-term weather patterns

Table 3.2-2. Stabilization, Dissemination, and Dispersion Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Freeze-drying Equipment	Maintaining low temperature	Stabilize biological agents for use in BW or for storage	None identified
Aerosol Inhalation Chambers	Filters that pass 0.1–10 µm particles and remove large quantities of debris (>20 µm diameter)	Testing aerosols for BW use	Detonation-induced release of particles having uncontrolled sizes
Delivery systems and spray tanks to allow bomblet dissemination	Delivery range, accuracy, and effect on contained organisms	Delivery of both conventional weapons and WMD	Detonation-induced release of particles having uncontrolled sizes
Warheads for missiles	Delivery range, accuracy, and effect on contained organisms	Delivery of both conventional weapons and WMD	Balloon-floated devices; non-fixed-wing vehicles
Development and use of accurate, short-term weather prediction	Dissemination of biological weapon	Predict dispersion patterns of disseminated biological weapons to maximize the effect on hostile troops and, at the same time, minimize the effect on friendly troops	On-site determination of wind pattern and wind flow

SECTION 3.3—DETECTION, WARNING, AND IDENTIFICATION

OVERVIEW

Detection, warning, and identification involve sensors and transduction of a detected signal to a transponder. Standoff detectors provide early, wide-area spectroscope and warning of biological agent attack. Stand-off detectors are spectroscope-based monitors of materials containing nucleic acid/protein with absorbance in the 230–285 nanometer range. They can be confounded by biological material or pollen of size similar to that of the biological agent. Point detectors are used at designated locations. Most detection and warning systems are based on physical or chemical properties of biological agents. The point detectors include dipstick kits selective for some but not all AG agents (see Table 3.0-2) or multiarray sensors using antibodies generated against AG agents or gene sequences complementary to AG agents. Identification systems, which are critical to medical response, use immunochemical or gene probe techniques or mass spectral analysis. No single sensor detects all agents of interest. Detectors for biological agents must have a short response time (less than 30 minutes for biological agents) with a low false alarm rate. Detection equipment must be integrated with a command and control system to ensure an alarm is raised. Early warning is essential to avoid contamination. Agent location, intensity, and duration are crucial parameters for command decisions.

Sensor systems based on physical or chemical properties of biological agents include high-performance liquid and gas chromotography, mass spectrometry, scattering Light Detection and Ranging (LIDAR), and ion mobility spectrometry (IMS). The basic recognition component of the sensor designed for a specific agent is generally a large molecule that binds selectively to the target agent. The recognition molecules are physically bound to a supporting surface that generates a signal (transduction) when the recognition molecule binds the biological agent. The methods for transduction include (1) changes in absorption of light at specific wavelengths; (2) changes in resonating frequency of a piezoelectrically active surface caused by mass effects; (3) changes in pathways of light movement at an interface of target agent and recognition molecules; and (4) switching of a light-conducting pathway resulting from interaction of recognition molecule with the biological agent. Recognition molecules are antibodies (association constants of 10^{-6} to 10^{-8}), receptors (dissociation constant, KD, KD = $<10^{-14}$), or DNA sequences complementary to genetic material encoded by the biological agent.

Highlights

- Reliable, quick-response sensor systems are essential for detection and warning.
- Identification is critical to medical response.
- Various physical phenomena are used to convert sensor signals to useful detection and identification information.
- Underlying sensor technology exists in many countries.

Biodetection systems providing limited warning and identification functions currently exist. Systems in the inventory or in the advanced stages of development warn that a biological attack has occurred and collect samples for subsequent laboratory analysis. However, no real-time, on-site detection systems are available today. The rapid growth in biotechnology is assisting in the area of improved biological defense technologies, although many of the same advances can also be used to improve biological agents.

RATIONALE

Early detection and warning is the first line of defense against biological agents. Detection and identification of biological agents allow commanders to take steps to avoid contamination, to determine the appropriate protection for continued operations, and to initiate proper prophylaxis and therapy to minimize casualties and performance degradation.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 3.0-3)

Besides the United States, several countries have a significant capability in the sensor technology that underlies detection and identification of biological agents: Canada, France, Germany, Israel, Japan, The Netherlands, Russia, Sweden, and the UK. Several other countries are just a step behind: Austria, China, Czech Republic, Finland, Hungary, Slovak Republic, South Africa, Switzerland, and the Ukraine. The worldwide efforts to develop improved biological agent detectors are extensive.

Table 3.3-1. Detection, Warning, and Identification Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Immuno-based detectors	Capability of detecting organisms of AG agents	WA ML 7; WA IL Cat 1A; USML XIV	Antibodies directed against AG list agents	Antibody development	None identified
Gene-based probe	Capability of detecting organisms of AG agents	WA ML 7; WA IL Cat 1A; USML XIV	Polynucleotides complementary to AG gene sequences; polymers	Gene sequence data	None identified
Molecular recognition (e.g., antigens, antibodies, enzymes, nucleic acids, oligomers, lectins, whole cells, receptors, organelles)	Capability of detecting organisms of AG agents. Can recognize weapons grade agent, by-products of its preparation or manufacturing signatures; does not recognize normally occurring environmental materials.	WA ML 7; WA IL Cat 1A; USML XIV	Antibodies directed against AG List agents or polynucleotides complementary to AG gene sequence	Coatings, films, or fibers of biopolymers or chemical polymers that bind BW agents (binding Kd less than 1 x 10^{-8})	Molecular modeling (e.g., protein and DNA sequencing)
Mass Spectrometry	Capable of scanning samples of 10,000 daltons or less in 30 minutes or less	WA ML 7; WA IL Cat 1A; USML XIV	None identified	Database development; portable, field-rugged mass spectroscope	Spectrum recognition algorithms
IMS	Detecting hundreds of organisms	WA ML 7; WA IL Cat 1A; USML XIV; CCL Cat 6	None identified	Database development; ion source; spectroscope capable of concentrating and analyzing 1,000 organisms	Spectrum recognition algorithms
Scattering LIDAR	Detect agent (liquids and aerosols) at any distance	WA ML 7; WA IL Cat 1A; USML XIV	None identified	None identified	Spectrum and background recognition algorithms
Transducers [e.g., optical, electrochemical, acoustic, piezoelectric, calorimetric, Surface Acoustic Wave (SAW); fiber-optic wave guide]	Converts recognition of agents to an optical or electrical signal; low hysteresis; optical/ electronic component processing within 30 minutes	WA ML 7; WA Cat 3A; USML XIV; CCL Cat 3A	None identified	Production equipment configured for the detection of biological agents	Spectrum recognition algorithms

(cont'd)

Table 3.3-1. Detection, Warning, and Identification Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Sample Collection (e.g., air, liquid, dust, soil sampling)	Collects and concentrates <10 µm particles into liquid medium	WA ML 7; USML XIV	None identified	Aerosol samplers able to collect ≤10 µm diameter particles into a liquid	None identified
Sample Processing (e.g., cell disruption, concentration, purification, or stabilization)	Completion within 30 minutes	WA ML 7; USML XIV	None identified	Neg. pressure orifice devices for rupturing cell membranes or wall/ retention of nucleic acids; impact collectors; ion trap mass spectrometers capable of scanning samples below 10,000 daltons in 5 minutes or less; pyrolyzers	Spectrum recognition algorithm
Development and use of sensor models	Specific performance of military sensors	USML XIII	Software/technical data for military systems on control lists	None identified	None identified

Table 3.3-2. Detection, Warning, and Identification Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Immuno-based detectors	Low cross-reaction of antibodies with non-pathogenic organisms	Confirmation and All Clear device; screening device	Light scattering (e.g., LIDAR) not specific for agent; culture and morphological characterization of the agent
Gene-based probe	Obtaining the sufficient length of nucleic acid sequence (approx. 30 to 40 polynucleotides) to define the pathogen	Characterization and identification of AG agents; enables the conversion of pathogenic to non-pathogenic organisms and vice-versa	Light scattering (e.g., LIDAR) not specific for agent; culture and morphological characterization of the agent
Molecular recognition (e.g., antigens, antibodies, enzymes, nucleic acids, oligomers, lectins, whole cells, receptors, organelles)	Identifying specific epitopes or genetic sequences characteristic of threat agents; designing probes that are specific for the epitopes or sequences that are stable under the conditions of use and can be incorporated into the sensor	Contamination avoidance; biological agent detection; process and quality control in biological agent manufacturing	Light scattering (e.g., LIDAR) not specific for agent; culture and morphological characterization of the agent
Mass Spectrometry	Requires sophisticated software; must know what you are looking for; extremely powerful analytical tool; training/maintenance requirements higher; requires significant power; size and weight problems	Identification of agents	Stand-off technologies including light scattering (e.g., LIDAR) not specific for agent; culture and morphological characterization of the agent
IMS	Detect broad range of biological materials, including agents; short response time; semi-quantitative	Alarm with potential for individual application, monitoring; early warning	Immuno-based detectors, gene-based probes, and molecular recognition; culture and morphological characterization of the agent
Scattering LIDAR	Background varies widely; size, power and weight requirements; need frequency agile laser	Early interrogation of suspect aerosol clouds	Immuno-based detectors, gene-based probes, and molecular recognition; culture and morphological characterization of the agent
Transducers (e.g., optical, electrochemical, acoustic, piezoelectric, calorimetric, SAW; fiber optical wave guide)	Miniaturization, stability to environment and exposure to samples; reproducibility, calibration; simplicity of use	Contamination avoidance; biological, chemical agent detection	Culture and morphological characterization of the agent
Sample Collection (e.g., air, liquid, dust, soil sampling)	100–1,000 liters of air per minute; sample preparation; separation and concentration of biological agent	Contamination avoidance; biological agent detection; process and quality control.	Appearance of illness in exposed personnel
Sample Processing (e.g., cell disruption, concentration, purification, or stablization)	Sample processing while maintaining integrity of agent; automation and miniaturization; amplification techniques	Contamination avoidance; biological agent detection; process and quality control in biological/toxin agent manufacturing.	Appearance of illness in exposed personnel
Development and use of sensor models	Clutter characteristics; specific sensor techniques for clutter rejection/ sub-clutter target detection/identification	C3I; mission rehearsal	Appearance of illness in exposed personnel

SECTION 3.4—BIOLOGICAL DEFENSE SYSTEMS

OVERVIEW

This section covers measures that can be taken to protect forces in a biological weapons environment. The protection and countermeasures issues related to biological warfare and defense concern the individual soldier and the unit.

The individual soldier can be protected by providing prophylactic treatment before deployment into a risk area, by providing full respiratory protection during time periods of potential exposure [Mission-Oriented Protection Posture (MOPP) gear] to the biological agent, or by using pharmacological, physical, or biomedical antidotes to threat agents shortly after exposure. Prophylaxis of the individual is generally accomplished by immunization, using the attenuated or dead biological agent, which serves as an immunogen. More recently, it has become possible to provide protection by immunizing personnel against a fragment of the toxin/biological agent. Initiating the immunization process to achieving protection usually involves a period of weeks. Multivalent vaccines and DNA vaccines are in development to enhance countermeasures against biological agents.

Protection measures for a unit or group primarily rely on weather monitoring, remote probe monitoring for biological agents, and central command data acquisition, transfer, and analysis. Large-scale decontamination measures for barracks, vehicles, and other equipment are also considered unit protection.

Individuals can be protected from exposure to biological weapons agents by active or passive immunization against the agents. Figure 3.0-2 has identified many of the agents of concern. A nation's capability to use a biological agent should be limited by its ability to provide protection against the agent for its forces and civilian population. A proliferant may not recognize such a limit. In addition, administering biological response modifiers (BRMs) to personnel at the appropriate time can mobilize the immune system in a normal individual. This will reduce the likelihood that exposure to a biological or toxin agent will degrade the individual's function or result in disease or death. These performance enhancers (BRMs) are discussed in detail below.

BRMs or immunomodulators are biomolecules with the ability to enhance or diminish the immune response of the body. During the last decade, several BRMs (e.g., interferons, interleukins) have been identified. When injected, they enhance the immune response of the human subject to a given antigen (virus or bacterium). Derivatives of these immune enhancing agents can be administered to personnel to improve performance efficiency.

Several naturally occurring proteins, including interferons and interleukins, function as immunostimulating BRMs. In addition to naturally occurring BRMs such as interferons and interleukins, immuno-enhancing drugs, such as arsphenamine and cefodizime, act to stimulate natural immune response. These drugs are used widely in medicine following chemotherapy and for treatment of various autoimmune diseases. Growth factors for cells of the hematopoetic immune system have been found useful for ameliorating immunosuppression conditions. BRMs can be administered via conventional methods, using encapsulation technology for mass treatment through aerosols or using controlled release systems for long-term internal treatment. Although the immune system enhancers are of potential benefit, they may have undesired side effects, such as fever and malaise, that can degrade combat performance.

Highlights

- A proliferant would require some type of BW defensive capability for protection during employment and defense against a counterattack.
- Vaccines are possible but the agent must be known (requires lead time for full protection).
- Detection and identification are key to determine appropriate defensive measures to take after an attack.
- A mask is sufficient to prevent a majority of biological agents from infecting personnel.
- Biotechnology offers potential for enhanced protection in the future.

Anti-idiotype antibodies can be used to initiate immunization in forces against toxic biological agents. Immunization with the anti-idiotype can induce production of antibodies that recognize and bind the biological agent specifically and selectively. In the most favorable scenario, the human subject would be completely protected immunologically and yet never be exposed to attenuated biological or toxin agent.

Immunosuppressants are one class of BRMs that show promise in offensive biological warfare. These are substances that cause subjects to become "immunocompromised" or more susceptible to infection and, therefore, can be used directly or in concert with other encapsulated chemical or biochemical weapons for diminishing an adversary's capabilities. These substances include pharmaceuticals, such as cyclosporin, rapamycin, and FK506, which are useful in chemotherapy treatments for various cancers and in the prevention of organ, bone marrow, or skin graft rejection.

Biological agent protection requires only respiratory and eye protection rather than the complete MOPP gear required for chemical protection. The protective garment requirements include resistance to the penetration of biological weapon or toxin materials, filtration of inflow air to remove particles containing the agents, and cooling of the interior compartment.

Current clothing and mask systems used for protection against biological agents act as a barrier between the agent and the respiratory system or mucosal tissues of the target. They do not inactivate the agent. For biological protection, such clothing is sufficient but is not comfortable. Visual field of view is decreased and the head mask results in discomfort because of temperature increase and fogging.

RATIONALE

Biological defense systems technologies have been included for two reasons. First, an aggressor can be expected to have some standard of protection for the force employing BW. Standards of protection could vary from minimal to sophisticated, but all should be considered, especially those that allow a proliferant to feel secure in offensive operations. Secondly, an attacker would have to be prepared for a counterattack in kind (depending on the opponent).

Self-protection defensive measures would be easiest to take in an offensive attack mode. The attacker would know in advance what biological weapon(s) would be employed and could immunize those that might come in contact with the organism(s). Protective masks could be worn to provide additional protection.

When being attacked, a country would encounter problems similar to those faced by the United States: unknown agents being used at an unspecified place for an undetermined duration. Immunization requirements would have to be determined by intelligence reports of enemy capabilities. Some type of detection (see Section 3.3) would be needed to alert forces to take protective measures.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 3.0-3)

Vaccines can be produced by any country with a pharmaceutical industry. Equipment can be purchased on the open market since it is all dual use. Protective masks are made in many countries. A simple dust mask could provide significant protection as long as it was worn when being exposed to the biological agent.

Table 3.4-1. Biological Defense Systems Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Production and design technology for protective masks	Any capability	WA ML 7; WA Cat 1A; USML X	Butyl rubber; silicone rubber	Simulated agents; leakage testers; mannequin-face model for mask and suit design; particle-size analysis equipment	Software for generating facial contours
Production and design technology for collective protection	Any capability	WA ML 7; USML X	Teflon/Kevlar laminate for biological resistance, decontaminability and environmental durability	Simulated agents	None identified
Decontamination	Any capability	WA ML 7; USML XIV	Hypochlorite or similar bleach compound or autoclaving for sterility	None identified	None identified
Vaccines	Any capability	CCL EAR 99	Target strains	None identified	None identified
BRMs	Any capability	CCL EAR 99	None identified	None identified	None identified
Regenerative collective protection - Membrane filtration	Any capability	WA ML 7; USML XIV	Filter system to remove 0.1- to 15-micron particles by sieve action	Simulated agents; particle-size analysis equipment	None identified
Regenerative collective protection - Plasma destruction	Any capability	WA ML 7; USML XIV	Portable plasma generator	Simulated agents; recovery of infectious agent	None identified
Encapsulation: liposomes; polymer entrapment; micelles; emulsions; immobilization of biopolymers	Any capability	CCL EAR 99	None identified	None identified	None identified
Antibiotics	Any capability	CCL EAR 99	None identified	None identified	None identified

Table 3.4-2. Biological Defense Systems Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Production and design technology for protective masks	Communications (microphone pass-through); respiration (air management); eye protection; composite eye lens retention system; anthropometrics; performance degradation; ability to consume fluids	Protective masks that are suitable in removing aerosol dispersed biological agents	Avoid contamination
Production and design technology for collective protection	Affordable; deployable; adaptable to structure	Continue to operate without degradation	Individual protection
Decontamination	Volume of agent; time required; adaptability to unknown agents; environmentally sound; identification of what needs to be decontaminated; identification of decrease of toxicity to allowable level	Reduce contamination to allow military operations	Oxidizing or chlorinating chemical treatment; heat at 120 °C with pressure
Vaccines	Efficacy of vaccine; efficacy of prophylaxis; pre- vs. post-exposure treatment	Minimize BW casualties; reconstitute forces; maintain performance standards	Preclude viral or bacterial entry or maturation in target tissue
BRMS	Efficacy of prophylaxis; pre- vs. post-exposure treatment	Minimize casualties after BW attack; reconstitute forces; maintain performance standards	Enhance immune response
Regenerative collective protection - Membrane filtration	Remove particles having average diameter of 0.1–15 µm, and allow rapid flow of air	Reduction of logistics burden; preclude inhalation of aerosolized biological agent	Standard filters
Regenerative collective protection - Plasma destruction	Production of lightweight plasma generators (e.g., ozone that is bactericidal or inactivates viruses)	Reduction of logistics burden; inactivate aerosolized biological agent	Standard filters
Encapsulation; liposomes; polymer entrapment; micelles; emulsions; immobilization of biopolymers	Ensure release of prophylaxis and therapeutics shortly after contact with plant/animal/human tissues	Individual protection; decontamination; performance retention	None identified
Antibiotics	Inhibit cysteine proteases or cellular transport	Minimize casualties after BW attack; reconstitute forces; maintain performance standards	Preclude viral or bacterial entry or maturation in target tissue

SECTION IV

CHEMICAL WEAPONS TECHNOLOGY

SECTION 4—CHEMICAL WEAPONS TECHNOLOGY

Scope

Highlights

- Chemical weapons (CW) are relatively inexpensive to produce.
- CW can affect opposing forces without damaging infrastructure.
- CW can be psychologically devastating.
- Blister agents create casualties requiring attention and inhibiting force efficiency.
- Defensive measures can be taken to negate the effect of CW.
- Donning of protective gear reduces combat efficiency of troops.
- Key to employment is dissemination and dispersion of agents.
- CW are highly susceptible to environmental effects (temperature, winds).
- Offensive use of CW complicates command and control and logistics problems.

BACKGROUND

Chemical weapons are defined as weapons using the toxic properties of chemical substances rather than their explosive properties to produce physical or physiological effects on an enemy. Although instances of what might be styled as chemical weapons date to antiquity, much of the lore of chemical weapons as viewed today has its origins in World War I. During that conflict "gas" (actually an aerosol or vapor) was used effectively on numerous occasions by both sides to alter the outcome of battles. A significant number of battlefield casualties were sustained. The Geneva Protocol, prohibiting use of chemical weapons in warfare, was signed in 1925. Several nations, the United States included, signed with a reservation forswearing only the first use of the weapons and reserved the right to retaliate in kind if chemical weapons were used against them. (Note: the United States did not ratify the Protocol until 1975). Chemical weapons were employed in the intervening period by Italy (in Ethiopia) and Japan (in Manchuria and China). Both nations were signatories to the Geneva Convention. Chemical weapons were never deliberately employed by the Allies or the Axis during World War II, despite the accumulation of enormous stockpiles by both sides. Instances of employment of chemical weapons in the local wars since then are arguable, although they were definitely used in the Iran-Iraq conflict of 1982–87. In January of 1993, a lengthy and detailed Chemical Weapons Convention (CWC) was signed in Paris by many countries. Unlike the Geneva Convention's single paragraph prohibition, the CWC attempts to define the prohibited substances, including their effects, and to establish enforcement mechanisms. In addition to banning CW use, the CWC bans the development, production, stockpiling, and transfer of chemical weapons.

The CWC obliges a state party to destroy chemical weapons under its possession, jurisdiction, and control; to destroy all CW it abandoned in the territory of another state party; and to destroy CW production facilities under its jurisdiction or control. On April 29, 1997, the CWC entered into force, thereby putting in place a detailed and intrusive declaration and verification regime. Russia possesses the largest acknowledged stockpile of chemical weapons and may have difficulty adhering to the CWC's destruction reuirements because of economic difficulties.

Development of chemical weapons in World War I was predominantly the adaptation of a chemical "fill" to a standard munition. The chemicals were commercial chemicals or variants. Their properties were, for the most part, well known. The Germans simply opened canisters of chlorine and let the prevailing winds do the dissemination. Shortly thereafter the French put phosgene in a projectile and this method became the principal means of delivery. In July 1917, the Germans employed mustard shells for the first time and simultaneously attempted to use a solid particulate emetic, diphenyl chloroarsine, as a mask breaker. Mustard, an insidious material, penetrates leather and fabrics and inflicts painful burns on the skin. These two themes, along with significant increases in toxicity, represent a large segment of the research and development of chemical weapons that nations have pursued over the years. There is first the concept of agents that attack the body through the skin, preferably also through clothing, and more preferably through protective clothing. Along with that concept is the idea of penetrating or "breaking" the protective mask so that it no longer offers protection for the respiratory system. Increasing the toxicity of the chemical agent used would theoretically lower the amounts required to produce a battlefield effect. Unless this increase is significant, however, it can be masked by the inefficiencies of disseminating the agent. Consequently, later development has focused on the methods for delivering the agent efficiently to the target.

The chemicals employed before World War II can be styled as the **"classic" chemical weapons**. They are relatively simple substances, most of which were either common industrial chemicals or their derivatives. An example is phosgene, a *choking agent* (irritates the eyes and respiratory tract). Phosgene is important in industry as a chlorinating material. A second example is hydrogen cyanide, a so-called *blood agent* (prevents transfer of oxygen to the tissues), now used worldwide in the manufacture of acrylic polymers. The industrial application of many of the classic chemical agents is recognized by the CWC and they are included on a schedule wherein few restrictions apply. They would be only marginally useful in modern warfare and generally only against an unsophisticated opponent. Moreover, large quantities would be required to produce militarily significant effects, thus complicating logistics.

Blister agents or **vesicants** are an exception to the limited utility of classic agents. Although these materials have a relatively low lethality, they are effective casualty agents that inflict painful burns and blisters requiring medical attention even at low doses. The classic mustard is the most popular among proliferant nations since it is relatively easy to make. Mustard is generally referred to as the "king" of agents because of its ease of production, low cost, predictable properties, persistence, and ability to cause resource-devouring casualties rather than fatalities. Its insidious nature is both an advantage and a disadvantage. Mustard on the skin causes no immediate sensation and symptoms normally do not appear until several hours after exposure. At incapacitating levels this may be as long as 12 hours. (Contrary to the normal expectation, horrible fatalities occurred in the Iran-Iraq War because Iranian soldiers, feeling no effects, continued to wear mustard soaked clothing and inhale its fumes.)

To produce immediate effects, an arsenical vesicant known as lewisite was developed in the United States. Much of the former Soviet Union vesicant stocks were mixtures of lewisite and sulfur mustard.

Between the world wars the development of chemical weapons included adaptation to aircraft delivery (bombs) and exploitation of lewisite, since the more potent mustard was, from a battlefield perspective, slow in producing casualties. Independent experiments in several countries led them to consider/adopt mixtures of mustard and lewisite as fills for chemical munitions.

Nerve gases, or anticholinesterase agents, were discovered by the Germans in the 1930's and developed during World War II. In 1936 during studies of possible pesticides, the German chemist Gerhard Schrader discovered what he called "tabun" or GA. Two years later Schrader discovered the even more toxic "sarin" or GB. These compounds are orders of magnitude more toxic than those used in World War I and thus represent the significant toxicity increase that changed the concept of employment. Fortunately for the Allies, the Germans never exploited their technological advantage, although they did produce a large number of tabun-filled munitions.

Nerve gases are liquids, not gases, which block an enzyme (acetylcholinesterase) that is necessary for functions of the central nervous system. Similar in action to many pesticides, they are lethal in much lower quantities than classic agents. The nerve gases are effective when inhaled or when absorbed by the skin (percutaneous), or both, although there are differences in effectiveness. In general, the lower the material's volatility (and hence its inhalation threat) the greater its percutaneous toxicity. Nerve agents are generally divided rather arbitrarily into G- and V-agents, although there are numerous structural variants that are potent cholinesterase inhibitors. Nerve agents known to date to have been produced for chemical warfare purposes are all organophosphorus compounds and are liquids at room temperature.

The Italians, Hungarians, Japanese, French, English, Russians, and Americans, as well as the Germans, all perfected mustard, phosgene, and similar agents during World War II. Although never used in the conflict, these nations amassed such huge quantities of chemical munitions that their disposal presented a practical problem, one that would be virtually insurmountable in today's more environmentally conscious world. In those more naive times, however, the munitions simply found their way to the bottoms of almost all the world's oceans in the holds of expendable ships.

After World War II the victors took an interest in exploiting the potential of the remarkably potent "nerve" agents. The British, in particular, had captured small stocks of sarin (GB) and set about investigating its potential. The Soviets removed the Germans' GB production plant to the Soviet Union. GB turned out to be perhaps the best of the respiratory agents, being volatile as well as exceedingly toxic. The United States designed a cluster bomb to exploit the characteristics of GB and followed this with a litany of adaptations of munitions. Artillery rockets were produced as were bombs, projectiles, and spray tanks. Many of these used the basic design of high-explosive weapons and simply changed the fill to GB. In the instance of the spray tank, it was necessary to use a polymeric thickening material so that the liquid would form large droplets and not evaporate before it reached the ground. The French, British, and Canadians all built small-scale facilities to produce the GB for testing. The United States, however, entered into full-scale production of GB, as did the Russians just a little later. The Russians also produced soman (GD), an agent the U.S. developers had decided to forswear because of its properties of being refractory to treatment above a single lethal dose.

In the late 1950's, UK scientists discovered another category of nerve agents, the V-agents. These were particularly interesting in that most of them were very effective percutaneously and represented an effective way to circumvent the ubiquitous gas mask. The United States and the UK pursued a form of V-agent called VX, although they produced it by entirely different processes. The Russians exploited another structural analog that proved more adaptable to their industrial processes.

The 1960's saw continued development in nonlethal agents, or riot control agents, first used in World War I. These materials, most notably CS, are strong irritants of the mucous membranes with very high safety ratios. The letters "CS" are code letters for a solid powder classified as a riot-control agent (O-chlorobenzylmalonitrile). This compound is a highly effective irritant of the mucous membranes with an exceedingly high safety ratio (~63,000). The purpose of CS and similar materials is temporary incapacitation without permanent harm. CS was developed and first used by the UK. It was quickly adopted and used extensively by the United States and since has been produced and employed by many nations. CS is a solid at room temperature and presents a problem for effective dissemination in useful particle sizes. Particulate CS, like most solids, tends to develop an electrostatic charge which causes the particles to agglomerate into larger particles. Much development effort during the 1960's was spent on finding effective dissemination techniques.

The work on particulate CS could be extrapolated to another type of chemical agent that was of extreme interest in the 1960's: **incapacitating agents**. These were initially seen by some as a panacea to make warfare safe and humane. Thousands of potential compounds were screened, obtained from government sources in the United States and from commercial pharmaceutical companies around the world. Although there were several promising materials, primarily mental incapacitants, only BZ was ever standardized.

The problem of incapacitants, or incapacitating agents, is complex. The use of incapacitants in warfare is considered to be prohibited by the Chemical Weapons Convention even though only a single agent, BZ (3-Quinuclidinyl benzilate), and its immediate precursors are included as listed compounds (Schedule 2) in that Treaty. In retrospect, while BZ was the only incapacitating agent formally accepted (i.e., type classified) by the United States, it was a poor choice and is now obsolete. It remained in U.S. stocks for only a short period of time. The substance is a mental rather than a physical incapacitant with long-onset time and unpredictable symptoms. The victim becomes confused and is likely to be incapable of acting decisively. The confusion, however, may not be readily apparent. The duration of action is long, about 48 hours, making prisoner management difficult. There are, moreover, hundreds of compounds more potent, faster acting, and with shorter duration of effect. Mental incapacitants are predominantly glycolates, whereas some of the more potent candidates for physical incapacitants have come from research on improved anesthetics. Indeed, almost all potential incapacitants are byproducts of the pharmaceutical industry and have legitimate pharmaceutical uses. The defining technologies for such incapacitating weapons, then, are the production of a physiologically effective compound in greater than practical pharmaceutical quantities and incorporation of the material in weapons. It is probable that the physical state of an incapacitant will be a particulate solid and that the practical route for effective use is by inhalation.

Binary chemical weapons use toxic chemicals produced by mixing two compounds immediately before or during use. Binary weapons do not necessarily employ new toxic chemicals. In U.S. parlance, relatively innocuous precursors were stored separately and reacted to form the toxic chemical agent en route to the target. In principle, the binary concept could also be used to produce highly lethal but unstable compounds or mixtures of compounds unsuitable for long-term storage. The U.S. type classified and produced a GB (sarin) binary nerve agent weapon, the M687 projectile (a 155-mm artillery shell), and was in the late stages of development of two other binary weapons when its offensive CW program was terminated. The Russians have been publicly accused by dissidents within their own agencies of developing new binary agents, and the Iraqis are known to have constructed binary bombs and missile warheads, albeit with crude manual mixing of the reactants.

Other possibilities for chemical agents include toxins and allergens which also have been, at times, considered biological agents. Although not living organisms themselves, these materials are usually products of living organisms with complex molecular structures. A wide variety of toxins with an equally broad spectrum of chemical, physical, and physiological properties exists. The CWC attempts to avoid the complexity by listing only two toxins in its list of substances for verification. They are ricin, a byproduct of castor bean extraction, and saxitoxin, a shellfish poison. Given the large number of potential toxins, these would appear to be place holders to permit the inclusion of any toxin if deemed necessary at a future date.

Until the recent attempts at terrorism by the Japanese cult Aum Shinrikyo, virtually all uses of chemical weapons have been as tactical weapons by nations. These have ranged from attempts to break the stalemate in World War I to the recent use by Iraq to blunt Iranian human wave attacks in the Iran-Iraq War (1982–87). Chemical weapons were not employed by the major protagonists in World War II. Between World Wars I and II, two signatories of the Geneva Protocol (Italy and Japan) employed chemical weapons. Typically, nations have employed them against unprotected targets and not against an equally well-armed nation; chemical weapons are therefore arguably an example of mutual deterrence. Although there have been charges of chemical weapon use in virtually every conflict in recent decades, most have not been substantiated by clinical or physical evidence.

The growth of chemical agent technology development that spurred production is illustrated in Figure 4.0-1. Chemical agents used initially in World War I were industrial compounds adapted for weapons use. As the war continued, more compounds were screened and specialized agents, particularly sulfur mustard, came to the fore. After the war, research continued at a slow but steady pace, with the major breakthrough being the German discovery of the nerve gases in the mid 1930's. Agent technology accelerated again in the 1950's with the British discovery of the V-agents. The 1960's featured extensive work and discovery in incapacitants and riot control agents as well as the early work on binary agents. If the dissidents of the Russian chemical program are to be believed, major advances are continuing.

In the lethal chemical arena a development effort that spread out over three decades was the concept of binary agent employment. This concept entailed the creation of highly efficient yet simple reaction schemes that could be used to create toxic agents from non-toxic ingredients in the weapon en route to the target. The United States developed three different binary munitions, a GB projectile (a 155-mm artillery shell), an aerial bomb producing VX, and a medium-range missile warhead (for the MLRS) containing an intermediate volatility agent. Iraq made a crude attempt to exploit binary systems in the Gulf War, but none were actually deployed.

The Russian Army apparently quashed early attempts to develop binary agents by its technicians, although public revelations in 1995 by scientist Vil Mirzayanov and in 1996 by a former head of the Russian demilitarization program indicate recent Russian development of binary systems for new and novel classes of nerve agents.

An historical perspective of the growth of dissemination technology in comparison to agent technology also can be seen in Figure 4.0-1. Dissemination technology into the 1950's consisted mainly of the use of an explosive burster in adapted shells and iron bombs. During that time the concept of submunitions for better agent dispersal (e.g., missile warheads such as the Sergeant) and spray tanks (e.g., the Aero 14B) evolved and led to more uniform dissemination. These were followed in the mid-1960's and 1970's by concepts of thermal dissemination and aerodynamic breakup, as well as rheological techniques of particle size control in the 1990's.

Despite the importance of detection, the major technological advances for detection, identification, and warning are relatively recent. Initially, detectors were papers impregnated with a dye that underwent a color change when exposed to a chemical agent. By World War II, air-sampling tubes filled with liquids that changed color on exposure were available, as well as rather crude wet chemical point detectors. The advent of the nerve gases after World War II led to the development of sensitive enzyme detection techniques and point detection alarms. The latter were based on wet chemistry and required extensive servicing. The recent advances in microprocessing and fieldable instrumentation techniques have made remote and area sensing of chemical agents feasible.

A major advance in individual physical protection occurred very early with the development of the activated charcoal filtered gas mask. Many incremental improvements to aid in effectiveness against particular agents and to add to communication and creature comforts followed. Impregnated clothing for protection against percutaneous poisoning was another rather early development which continues to be improved incrementally by increasing protection factors and wearability.

OVERVIEW

This section addresses technologies that would enable a country to develop both offensive and defensive chemical weapons capability. The United States has forsworn the offensive use of chemical weapons and is a party to the Chemical Weapons Convention. Therefore, technologies for offensive military operations are not of interest except to maintain an appreciation for others' potential and to continue to develop a robust defense against them. References to offensive operations and technologies are included to ensure that there is an understanding of what is required to develop, integrate, and employ chemical weapons.

There are a number of reasons for a country to pursue the development of chemical weapons. Chemical weapons are relatively inexpensive to produce. Many standard munitions can be modified and filled with toxic chemicals. A chemical attack (or even a credible threat of a chemical offensive) can reduce the efficiency of an opposing force by making it take precautionary steps (donning protective suits, entering shelters, etc.) or diverting its attention to defensive measures. Casualties incurred can burden a country's medical resources. Unlike conventional weapons, chemical munitions, for the most part, injure or kill people while leaving the surrounding infrastructure intact. Moreover, because of their unconventional nature, chemical weapons can be psychologically devastating for a force being attacked.

Military forces that contemplate CW employment have many things to consider. The use of chemical weapons runs counter to the global norm and is apt to engender strong denunciation by third parties and retaliation by the nation attacked. There are significant operational hurdles. Logistics, training, and command and control are complicated by the possible employment of chemical munitions. Care must be taken to prevent one's own force from bearing the brunt of an attack. A properly defended force might be slowed but will not be stopped. Although the "cost" of CW employment could be high in terms of the above factors, the "benefit" of degrading an adversary's performance and the psychological affect might be deemed sufficient to offset the cost.

This section on **Chemical Weapons Technologies** contains four subsections. **Chemical Material Production** addresses technologies for producing toxic chemical agents that could be used in chemical weapons. Those that require special expertise are covered in more detail than those available through standard industrial processes. **Dissemination, Dispersion, and Weapons Testing** addresses those technologies that a proliferant could use to disperse toxic chemicals and ensure the viability of its dissemination systems. Also addressed are **Detection, Warning, and Identification** technologies that enable forces to detect and identify toxic agents and provide warning to minimize the threat. The last subsection, **Chemical Defense Systems,** discusses those systems that provide protection from the effects of chemical weapons.

RATIONALE

A number of technologies are required to develop, integrate, and employ chemical weapons. Although many of these technologies are old and available in the open literature, successful employment entails more than simply producing toxic chemicals. Technologies used for dissemination and dispersion are perhaps the most important. The myriad technologies for offensive use are included in this section to provide the reader an appreciation of the requirements to develop chemical weapons and an understanding of where offensive breakthroughs might occur, even though the United States has renounced the capability. Technologies needed to detect the use of toxic chemicals and provide protection are essential to all countries. Even proliferants that employ chemical weapons require some type of detection and protection capability.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 4.0-2)

Starting in World War I, a number of countries have employed chemical weapons. After false starts by others, the Germans finally employed chlorine successfully at Ypres, Belgium, in 1915. Other WWI use included phosgene and chloropicrin in 1916 by the British, and mustard in 1917 by Germany. Lewisite was developed in 1918, too late to be used in WWI.

Between the world wars, Japan began research on chemical weapons and began production in the late 1920's. The Italians used mustard in Ethiopia in 1935–36. Although Allied and Axis nations produced and stockpiled chemical weapons, they were not used during World War II. Egypt employed mustard and probably G-agent in Yemen in the 1960's. Both sides relied on CW during the Iran-Iraq conflict. The Iraqis used mustard, tabun, and sarin from 1982–87 and were prepared to do so in the Gulf War. Libya dropped chemical agents from a transport aircraft against Chadian Troops in 1987.

Many nations have become States Parties to the CWC and can be expected to adhere to their commitments not to develop chemical weapons. Others will not sign or may abrogate their commitments. Any nation with a sophisticated chemical industry has the potential to produce chemical weapons, although nerve agents require a greater amount of expertise than classical agents and vesicants. Having the potential, however, does not indicate intent.

Subnational groups, both independent and state-sponsored, could produce or purchase toxic chemicals or possibly chemical warfare agents to threaten a civilian populace. Since civilians are poorly prepared for attacks by toxic materials, consequences of a successful attack could be severe. Governments are increasingly concerned about the use of toxic chemicals in light of the Aum Shinrikyo attack in Tokyo but thus far have been unable to come to grips with the complexity of the problem. The armed forces of many nations have some type of detection equipment and protection gear, although there are wide variations in their quantity and capability.

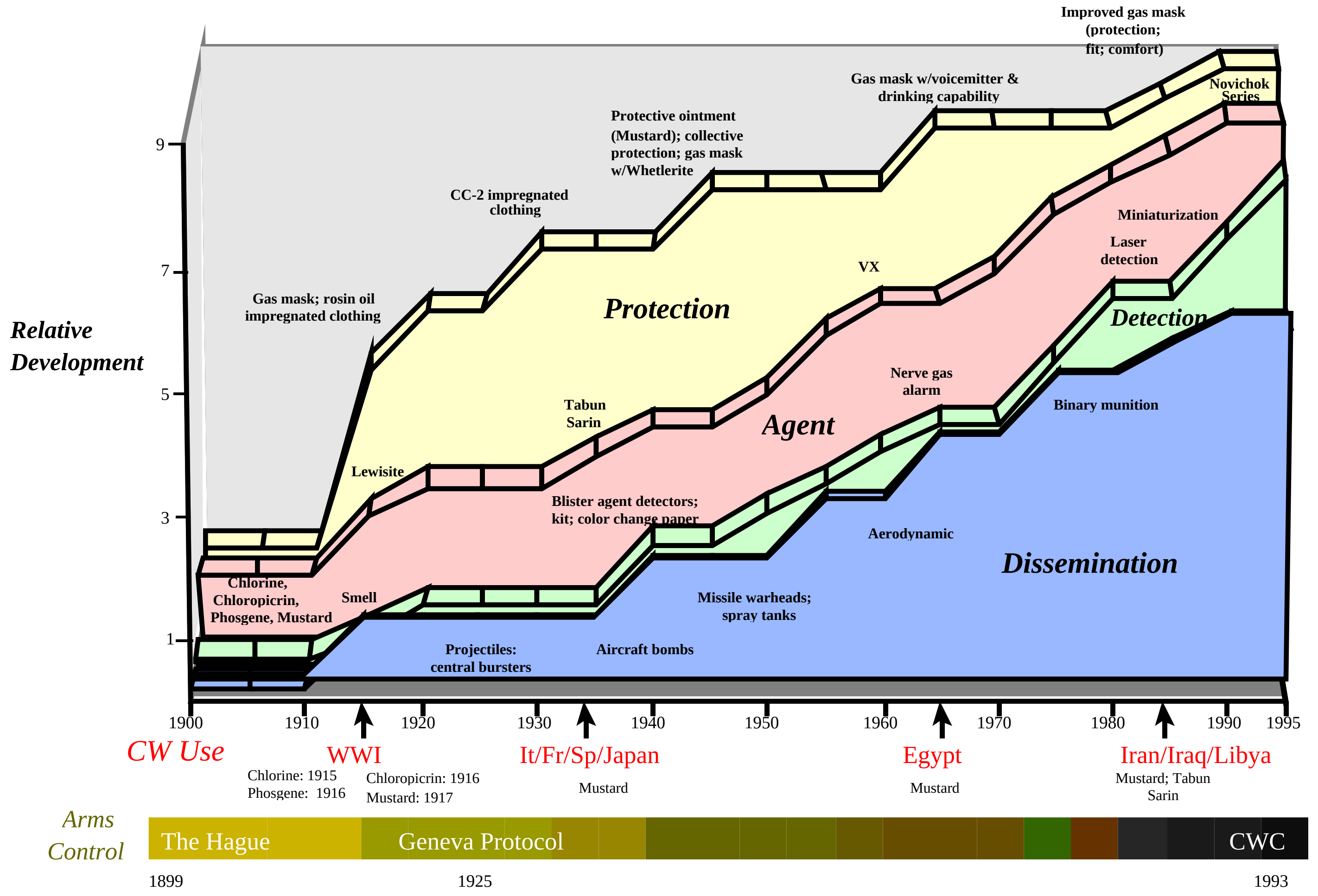

Figure 4.0-1. Relative Development of Chemical Weapons Technologies

Country*	Sec 4.1 Chemical Material Production	Sec 4.2 Dissemination, Dispersion and Weapons Testing	Sec 4.3 Detection, Warning and Identification	Sec 4.4 Chemical Defense Systems
Australia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Bulgaria	♦♦♦	♦♦	♦♦	♦♦
Canada	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
China	♦♦♦♦	♦♦♦♦	♦♦	♦♦
Czech Republic	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Denmark	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Egypt	♦♦♦♦	♦♦♦	♦♦	♦♦
Finland	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Hungary	♦♦♦♦	♦♦	♦♦♦	♦♦♦
India	♦♦♦♦	♦♦	♦♦	♦♦
Iran	♦♦♦♦	♦♦♦	♦♦	♦♦
Iraq	♦♦♦♦	♦♦♦♦	♦♦	♦♦
Israel	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Italy	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Japan	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦
Libya	♦♦♦♦	♦♦♦	♦♦	♦♦
Netherlands	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
North Korea	♦♦♦♦	♦♦	♦♦	♦♦♦
Norway	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Pakistan	♦♦♦	♦♦	♦♦	♦♦
Poland	♦♦♦	♦♦	♦♦	♦♦
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Slovak Republic	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
South Korea	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Spain	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Sweden	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Switzerland	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Syria	♦♦♦	♦♦♦	♦♦	♦♦
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Viet Nam	♦♦♦	♦♦	♦♦	♦♦
Subnationals	♦♦♦	♦	♦♦	♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 4.0-2. Chemical Weapons Foreign Technology Assessment Summary

SECTION 4.1—CHEMICAL MATERIAL PRODUCTION

OVERVIEW

This subsection contains information on a number of the toxic chemicals and their most important precursors. Included are nerve agents (e.g., sarin, soman, tabun, VX), vesicants (e.g., sulfur mustards, lewisites, nitrogen mustards), and "classic" chemical agents (phosgene, cyanogen chloride, hydrogen cyanide). Important precursors are also listed. These include DF, DC, and QL, all used in producing nerve agents.

There are thousands of toxic chemicals that could be used in chemical weapons. Those listed have been stockpiled and/or used by a number of countries. The CWC Schedules of Chemicals (Figure 4.1-1) and the Australia Group (AG) list of precursors (Figure 4.1-2) are also provided to ensure recognition of those being considered either for verification provisions of the CWC or for export control. It should be remembered that the CWC schedules and the AG list do not include all of the known chemicals that have been or could be used to produce toxic agents.

Depending on the type of agent to be produced, there can be technical hurdles that must be overcome. "Classic" agents can be manufactured using existing chemical infrastructure, and most have legitimate commercial uses. Likewise, vesicants are not technologically complicated. The production of the nerve agents, however, requires significantly more sophisticated chemical processing. Some production processes require strict temperature control. Containment of toxic substances and gases can pose problems. Depending on the immediacy of use, purity of product can add a difficult dimension to production. In some cases, special equipment or handling is required to prevent corrosion of equipment and/or rapid deterioration of the product.

These hurdles can be overcome. If sufficient purity cannot be attained, an agent can be manufactured and used immediately. This presupposes the capability to manufacture a sufficient quantity in the time allotted. If special, corrosive-resistant equipment cannot be obtained, corroded equipment can be replaced when necessary or only a limited amount can be produced. If nerve agent production is technologically infeasible for a proliferant, a simpler agent (vesicant or classic agent) can be produced. Alternatives can entail increased costs, increased munition requirements, or reduced CW capability.

Some of the simpler **classic chemical agents** can be manufactured using existing chemical infrastructure. For example, phosgene is manufactured internally within chemical plants throughout the world for use as a chlorinating agent. Chlorination is the most common of chemical intermediate reactions in the chemical process industry. A reasonable size phosgene facility could be purchased with an investment of $10–$14 million. Similarly, hydrogen cyanide is currently manufactured worldwide as an intermediate in the manufacture of acrylic polymers and could be diverted for other uses or separately manufactured with about the same investment. In either instance the technologies are simple, well known, and require no specialized equipment. These CW agents require high munitions expenditures and are easily defeated by a gas mask, so that use would most likely be against unprotected populations and/or poorly equipped combatants.

Almost all proliferant states since World War I have manufactured **vesicants**, principally sulfur mustard, bis(2-chloroethyl) sulfide. There are several routes to this compound, none of which require sophisticated technology and/or special materials. The earlier producers favored the Levinstein Process, which consists of bubbling dry ethylene through sulfur monochloride, allowing the mixture to settle and (usually) distilling the remaining material. More recent production has involved chlorination of thiodiglycol, a relatively common material with a dual use as an ingredient in some inks. This method does not result in the solid byproducts of the Levinstein Process and can be more easily distilled. Drums of thiodiglycol, produced in the United States and illegally diverted from their intended recipients, were found by international inspectors after the Gulf War at Iraqi CW production sites. The principal problem experienced by initial manufacturers of sulfur mustard has been the insidious nature of this material. Virtually all those producing mustard have experienced a large number of industrial accidents resulting in casualties from mustard burns. Nitrogen mustards have been synthesized only in pilot plant quantities, but did not require any unusual processes or materials. Lewisite was produced by both the United States and the Soviet Union during World War II. The plants were quite small and unsophisticated by

Highlights

- There are many routes to produce most toxic chemicals.
- Thousands of chemicals exist that could be considered for chemical weapons.
- If corrosive-resistant equipment cannot be procured (for corrosive reactants and products), standard equipment can be used and replaced or discarded.
- Many CW precursors are common industrial chemicals. Some have been used in the past as agents in CW.
- Most technologies associated with CW production are old and available in the open literature.

today's standards. Lewisite is an arsenical and as such would require unusually large amounts of arsenates in its production.

Production of the **nerve agents** requires significantly more sophisticated chemical processing. In a majority of these materials, there are corrosive chemicals in the process that require specialized corrosion-resistant construction materials . With the exception of GA (tabun), manufactured by the Germans in World War II and the Iraqis during the Iran-Iraq war, G-agent production involves both chlorination and fluorination steps. Both of these steps require special and expensive construction materials. Reactors, degassers, distillation columns, and ancillary equipment made of high nickel alloys or precious metals are needed to contain the corrosive products and by products. Only the last step of the process involves the highly toxic material, so that special air handling equipment would be needed for only a small portion of the facility.

There are many process routes for producing the G- and V-agents; the majority involve the synthesis of methylphosphonic dichloride (DC) at some stage. The United States designed and built plants for four different processes for producing DC. Two were used in the stockpile production of GB (sarin), a third represented an upgrade of the stockpile production process to minimize waste, and the fourth represented a newer method used in producing material for binary weapons. The Soviet Union used a still different process to make DC and Iraq one similar to the last U.S. process. DC is a relatively easy material to store and to ship and need not be produced at the same site as the final product. It is very stable and has been stored for over 30 years with little deterioration. The size of the facility required to produce DC in militarily significant quantities ranges from very large down to room sized. A facility to produce DC with ancillary support would cost approximately $25 million not including pollution and environmental controls and waste treatment. Modern waste treatment and pollution abatement to U.S. standards would more than double the cost, although it is doubtful that a proliferant would build to these standards. The various DC production processes require some special corrosion-resistant equipment, generally glass-lined reactors and storage tanks, although not the ultra-expensive equipment required for later stages. DC has limited commercial use.

In the actual production of G-agents, the partially fluorinated DC (now a transient mixture called Di-Di) is reacted with an alcohol or alcohols and the product degassed and usually distilled. As noted previously, this is the toxic step of the reaction which requires air handling and filtering and also part of the highly corrosive portion that requires high nickel alloy (such as Hastelloy C) equipment and piping or precious metals (such as silver). The U.S. stockpile of GB was produced in this fashion and the former Soviet Union stockpiles of GB and GD (soman) by a variation of that process. The Iraqis used a somewhat over-fluorinated DC and mixed alcohols to produce a GB/GF mixture which was inherently unstable. Most of the alcohols involved in producing G-agents have large-scale commercial use. An exception is the alcohol for producing GD, pinacolyl alcohol, which has very limited pharmaceutical use.

Two principal general methods have been employed for V-agent production. The process used in the United States was called the Transester Process. It entails a rather difficult step in which phosphorus trichloride is methylated to produce methyl phosphonous dichloride. The material is reacted in turn with ethanol to form a diester and this material then transesterified to produce the immediate precursor of VX. The product is reacted with sulfur to form V-agent. This process has the advantage of being straightforward and producing high quality product. Conversely, it has the disadvantage of some difficult chemical engineering steps. The V-agent formed exclusively in the United States was VX. The former Soviet Union, the only other known producer of significant quantities of V-agent, did not produce VX per se, but rather a structurally different variant with the same molecular weight. The Soviets designed their process to make maximum use of production capability already available. The DC of the G-agent process was used in an Amiton process conducted in solution. The technique has the advantage of producing a single intermediate (DC). Disadvantages include the need to recover a highly toxic material from solution and to handle large quantities of contaminated solvent. In general, the V-agents are not easily distilled, and it is unlikely that a final purification process can be developed.

Incapacitating agent production is similar in many ways to the manufacture of pharmaceuticals, since these compounds are normally variations or derivatives of compounds used or postulated for use as pharmaceuticals. Since most pharmaceuticals are produced in relatively small quantities, production would entail a scale-up to an unusual process size for the type of reactions entailed. Moreover, virtually all candidate incapacitating agents are solids at room temperature and would require drying and grinding to an inhalable particulate. Given the tendency of many compounds to acquire a static charge and agglomerate, the grinding is a nontrivial manufacturing problem. The problems associated with manufacture (and use) of solid lethal agents (such as carbamates) are analogous to those experienced with incapacitants.

As a consequence of the diversity and complexity involved, it is difficult to provide any generic insights to **toxin** production. The only toxin to exist naturally in large quantities is ricin. It is a byproduct of castor oil production. Production of ricin is a physical separation. There are weak parallels with plutonium extraction or uranium isotope enrichment in nuclear processing. Toxin separation is much easier, less expensive, and requires smaller equipment. These advantages might make a toxin attractive to a poor, proliferating country. Most other toxins must be laboriously extracted in small quantities from the organism that secretes them. While synthetic toxins are possible, they are complex molecules, the synthesis of which in any significant amount would be difficult. Biotechnology may enhance the ability to produce toxins that were previously difficult to obtain in significant quantity.

Production of chemical agents in the past has anticipated their long-term storage since (in the instance of United States at least) they were viewed as deterrent weapons and by policy would not have been employed except in response to aggressor use.

This also meant that the agents and/or their weapons of employment might be stored for extensive periods of time. The life span of chemical weapons was first expected to be a decade. The requirement was later increased to 20 years when it became clear that munitions were likely to be stored at least that long. Chemical agents can either be stored in bulk quantities or loaded into munitions. With the nerve agents in particular, the quality of the initial material must be excellent and they must be stored under inert conditions with the absolute exclusion of oxygen and moisture. Generally an overlay of dry helium was employed to leak check munitions. A small amount of stabilizer (2–4 percent) was also used to extend agent life span. The United States stored agent in both bulk containers and in munitions. In the latter instance, the munitions were normally stored in revetted bunkers. This was particularly true when explosives and propellants were uploaded in the munitions. Storage of agents in explosive, uploaded munitions has both advantages and disadvantages. The principal advantage is speed of use when the munition is needed. There is no labor-intensive or time-consuming uploading process, and most munitions can be handled and shipped as if they were conventional munitions. The principal disadvantage is that explosives and propellants become part of the “system,” and their storage and deterioration may complicate the handling of the chemical weapons. An illustrative case is seen in the 115-mm M55 rockets where burster, fuse, and rocket propellant cannot be easily and/or safely separated from the agent warhead before demilitarization. As a consequence, demilitarization is far more complicated and costly than it would be otherwise.

Agents stored in bulk in the United States are now stored entirely in large cylindrical “ton” containers similar to those used to store and ship many commercial chemicals. The procedure for the former Soviet Union’s stockpile appears to have been to upload their stocks of nerve agent into munitions when produced, but to store them without the bursters or fuses. These munitions were then themselves stored in more conventional warehouse-like structures. Conversely, the older stocks of vesicants (i.e., mustard, lewisite and mustard-lewisite mixtures) are stored in bulk, apparently intended to be filled in munitions a short time before use. Bulk storage of the vesicants by the Russians is in large railroad-car-size tanks again located in warehouse-like structures. When the Iraqis produced chemical munitions they appeared to adhere to a “make and use” regimen. Judging by the information Iraq gave the United Nations, later verified by on-site inspections, Iraq had poor product quality for their nerve agents. This low quality was likely due to a lack of purification. They had to get the agent to the front promptly or have it degrade in the munition. This problem would have been less severe in their mustard rounds because of less aggressive impurities. The problem of degradation inhibited their ability to deploy and employ nerve weapons but probably did not have a great effect on their use of mustard. Using their weapons soon after production probably worked well in the Iran-Iraq War, where the skies over Iraq were controlled by the Iraqis. Unfortunately for the Iraqis, loss of air control in the Gulf meant the weapons could never reach the front. The chemical munitions found in Iraq after the Gulf War contained badly deteriorated agents and a significant proportion were visibly leaking.

Binary munitions were once intended by the United States as a means of retaining a retaliatory capability without the necessity of an agent stockpile. The relatively nontoxic intermediates could be stored separately and not placed in proximity to one another until just before use. This requires some human engineering to ensure the munitions designs permit simple, rapid mating of the ingredient containers and production of the lethal agent en route to the target. The binary system was envisioned almost exclusively for application to the standard nerve agents. Although at least three types of binary munitions were planned, only one (155-mm artillery shell) was in production when the United States ended CW production. The Russians claim to have considered binary munitions but not produced any. The Iraqis had a small number of bastardized binary munitions in which some unfortunate individual was to pour one ingredient into the other from a Jerry can prior to use.

Release of agent by enemy action during shipment is a disadvantage of unitary chemical munitions. The sinking of the U.S. cargo ship John Harvey in the harbor at Bari, Italy, during World War II and the subsequent unwitting release of a large quantity of mustard gas is a case in point. Mustard escaped from damaged munitions contaminating those escaping the sinking ship and civilians on shore.

RATIONALE (See Table 4.1-1)

Since there are so many toxic chemicals that could be used in chemical weapons, only those agents of major significance and their precursors have been included. These toxic chemicals have been designated of most concern by the world community. The majority of nerve agents, sulfur mustards, lewisites, and some of the nitrogen mustards are listed in the CWC schedules of chemicals (Figure 4.1-1). Each nerve agent is representative of a family (hundreds to thousands) of chemicals. Those specifically included have been produced and stockpiled by a number of countries. The precursor DC is the fundamental building block for a significant portion of G- and V-agents. The classic chemicals (phosgene, cyanogen chloride, and hydrogen cyanide) have been included since they are so readily available that a proliferant could obtain them easily. Although these chemical agents would require high munitions expenditures and are easily defeated by a gas mask, they could be used effectively against unprotected populations and/or poorly equipped combatants.

Toxins have not been included in this subsection but can be found in Section 3, Biological Weapons Technologies. Although toxins are not living organisms, they are made by living organisms. They are listed in Schedule 1A of the CWC and the biological agent part of the Australia Group list.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 4.0-2)

Any country with a chemical industry has the capability, if not the intent, to produce toxic chemicals. Most of the technologies are old and described in the open literature. The countries listed in Figure 4.0-2 have the capability or have used chemical weapons in the past and therefore are technically capable of producing chemical weapons. The assessment is not an indication of current intent. Many of these countries have signed/ratified the CWC.

There have been numerous press reports of toxic chemicals produced in Russia that are not covered in the CWC schedules. Vil Mirzayanov, a chemist and former high-ranking scientist in the former Soviet Union's chemical weapons program, published an article in *Kuranty* in 1991 (and co-authored another article in 1992 in the *Moscow News*) in which he claimed that Russia had developed new kinds of chemical weapons. Substances like Novichok (A-230, A-232, and A-234) are chemical agents that the Russians are said to have developed in spite of agreement to halt production of chemical weapons. These statements were repeated by a former head of the Russian demilitarization program.

There has been press coverage of a large, underground facility being built at Tarhunah in Libya that the United States claims is designed as a chemical production facility. Libya dropped chemical agents obtained from Iran from a transport aircraft against Chadian troops in 1987. Late in 1988, Libya completed a chemical agent facility at Rabta as part of its drive to develop an indigenous CW capability. When the United States brought international attention to the plant, Libya responded by fabricating a fire to make it appear that the facility had been seriously damaged. This plant was closed in 1990, but the Libyans announced its reopening in September 1995 as a pharmaceutical facility. The Rabta facility is still capable of producing chemical agents.

Since the late 1980's, North Korea has expanded its chemical warfare program. Today it can produce large quantities of blister, blood, choking, and possibly nerve agents. It also maintains a number of facilities involved in producing or storing precursors for toxic chemicals, the agents themselves, and weapons. As mentioned previously, Iran delivered limited quantities of blister and blood agents against Iraqi soldiers late in the Iran-Iraq War. Iran has increased its rate of production since 1984 and has produced at least several hundred tons of blister, blood, and choking agents. Some of these agents have been weaponized to support ground combat operations.

Before the Gulf War, Iraq had become nearly self-sufficient in producing many precursors and had developed a variety of chemical weapons on its own. The chief inspector of the UN Special Commission chemical destruction group said that all known chemical munitions, agents, and precursors in Iraq had been eliminated by May 1994. Many think that Iraq can revive its CW capability in a matter of months in the absence of UN monitoring or import controls.

On the Asian subcontinent, India and Pakistan are capable of developing chemical weapons. India has a large chemical industry that produces numerous dual-use chemicals that are potential precursors. In June 1997, India submitted CW declarations to the CWC governing body in The Hague. This was the first time the Indians publicly acknowledged a CW program. Pakistan has procured dual-use precursors from foreign sources and is moving slowly toward the capability of producing precursors.

The Aum Shinrikyo cult in Japan proved that subnational groups can obtain the expertise and ingredients to threaten society with chemical agents. A Senate Permanent Subcommittee on Investigations study indicated that the cult had produced the nerve agents sarin, soman, tabun, and VX, as well as phosgene and sodium cyanide. Toxic chemicals were used at least twice, including the Tokyo subway attack that left 12 dead and more than 5,000 injured.

The following Schedules list toxic chemicals and their precursors. For the purposes of implementing this Convention, these Schedules identify chemicals for the application of verification measures according to the provisions of the Verification Annex. Pursuant to Article II, subparagraph 1(a), these Schedules do not constitute a definition of chemical weapons.

(Whenever reference is made to groups of dialkylated chemicals, followed by a list of alkyl groups in parentheses, all chemicals possible by all possible combinations of alkyl groups listed in the parentheses are considered as listed in the respective Schedule as long as they are not explicitly exempted. A chemical marked "*" on Schedule 2, part A, is subject to special thresholds for declaration and verification, as specified in Part VII of the Verification Annex.)

<u>Schedule 1</u> (CAS registry number)
A. Toxic chemicals:
(1) O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) alkyl
(Me, Et, n-Pr or i-Pr)-phosphonofluoridates,
e.g., sarin: O-Isopropyl methylphosphonofluoridate (107-44-8)
soman: O-Pinacolyl methylphosphonofluoridate (96-64-0)
(2) O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) N,N-dialkyl
(Me, Et, n-Pr or i-Pr) phosphoramidocyanidates,
e.g., tabun: O-Ethyl N,N-dimethyl phosphoramidocyanidate (77-81-6)
(3) O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) S-2-dialkyl
(Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr)
phosphonothiolates and corresponding alkylated or protonated salts,
e.g., VX: O-Ethyl S-2-diisopropylaminoethyl methyl phosphonothiolate (50782-69-9)
(4) Sulfur mustards:
2-Chloroethylchloromethylsulfide (2625-76-5)
Mustard gas: Bis(2-chloroethyl)sulfide (505-60-2)
Bis(2-chloroethylthio)methane (63869-13-6)
Sesquimustard: 1,2-Bis(2-chloroethylthio)ethane (3563-36-8)
1,3-Bis(2-chloroethylthio)-n-propane (63905-10-2)
1,4-Bis(2-chloroethylthio)-n-butane (142868-93-7)
1,5-Bis(2-chloroethylthio)-n-pentane (142868-94-8)
Bis(2-chloroethylthiomethyl)ether (63918-90-1)
O-Mustard: bis(2-chloroethylthioethyl)ether (63918-89-8)
(5) Lewisites:
Lewisite 1: 2-Chlorovinyldichloroarsine (541-25-3)
Lewisite 2: Bis(2-chlorovinyl)chloroarsine (40334-69-8)
Lewisite 3: Tris(2-chlorovinyl)arsine (40334-70-1)
(6) Nitrogen mustards:
HN1: Bis(2-chloroethyl)ethylamine (538-07-8)
HN2: Bis(2-chloroethyl)methylamine (51-75-2)
HN3: Tris(2-chloroethyl)amine (555-77-1)
(7) Saxitoxin (35523-89-8)
(8) Ricin (9009-86-3)

B. Precursors:
(9) Alkyl (Me, Et, n-Pr or i-Pr) phosphonyldifluorides
e.g. DF: Methylphosphonyldifluoride (676-99-3)
(10) O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) O-2-dialkyl
(Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr)
phosphonites and corresponding alkylated or protonated salts e.g. QL:
O-Ethyl O-2-diisopropylaminoethyl methylphosphonite (57856-11-8)
(11) Chlorosarin: O-Isopropyl methylphosphonochloridate (1445-76-7)
(12) Chlorosoman: O-Pinacolyl methylphosphonochloridate (7040-57-5)

(cont'd)

Figure 4.1-1. Chemical Weapons Convention Schedules of Chemicals

Schedule 2

A. Toxic chemicals:

(1) Amiton: O,O-Diethyl S-[2-(diethylamino)ethyl] phosphorothiolate (78-53-5) and corresponding alkylated and protonated salts
(2) PFIB: 1,1,3,3,3-Pentafluoro-2-(trifluoromethyl)-1-propene (382-21-8)
(3) BZ: 3-Quinuclidinyl benzilate (*) (6581-06-2)

B. Precursors:

(4) Chemicals, except for those listed in Schedule 1, containing a phosphorus atom to which is bonded one methyl, ethyl, or propyl (normal or iso) group but not further carbon atoms, e.g.,
    Methylphosphonyl dichloride (676-97-1)
    Dimethyl methylphosphonate (756-79-6)
    Exemption: Fonofos: O-Ethyl S-phenyl ethylphosphonothiolothionate (944-22-9)
(5) N,N-Dialkyl (Me, Et, n-Pr or i-Pr) phosphoramidic dihalides
(6) Dialkyl (Me, Et, n-Pr or i-Pr) N,N-dialkyl (Me, Et, n-Pr or i-Pr)-phosphoramidates
(7) Arsenic trichloride (7784-34-1)
(8) 2,2-Diphenyl-2-hydroxyacetic acid (76-93-7)
(9) Quinuclidine-3-ol (1619-34-7)
(10) N,N-Dialkyl (Me, Et, n-Pr or i-Pr) aminoethyl-2-chlorides and corresponding protonated salts
(11) N,N-Dialkyl (Me, Et, n-Pr or i-Pr) aminoethane-2-ols and corresponding protonated salts
    Exemptions: N,N-Dimethylaminoethanol (108-01-0) and corresponding protonated salts
    N,N-Diethylaminoethanol (100-37-8) and corresponding protonated salts
(12) N,N-Dialkyl (Me, Et, n-Pr or i-Pr) aminoethane-2-thiols and corresponding protonated salts
(13) Thiodiglycol: Bis(2-hydroxyethyl)sulfide (111-48-8)
(14) Pinacolyl alcohol: 3,3-Dimethylbutane-2-ol (464-07-3)

Schedule 3

A. Toxic chemicals:

(1) Phosgene: carbonyl dichloride (75-44-5)
(2) Cyanogen chloride (506-77-4)
(3) Hydrogen cyanide (74-90-8)
(4) Chloropicrin: Trichloronitromethane (76-06-2)

B. Precursors:

(5) Phosphorus oxychloride (10025-87-3)
(6) Phosphorus trichloride (7719-12-2)
(7) Phosphorus pentachloride (10026-13-8)
(8) Trimethyl phosphite (121-45-9)
(9) Triethyl phosphite (122-52-1)
(10) Dimethyl phosphite (868-85-9)
(11) Diethyl phosphite (762-04-9)
(12) Sulfur monochloride(10025-67-9)
(13) Sulfur dichloride (10545-99-0)
(14) Thionyl chloride (7719-09-7)
(15) Ethyldiethanolamine (139-87-7)
(16) Methyldiethanolamine (105-59-9)
(17) Triethanolamine (102-71-6)

Source: *The Chemical Weapons Convention,* “Annex on Chemicals,” Part B.

Figure 4.1-1. Chemical Weapons Convention Schedules of Chemicals (cont’d)

Chemical	C.A.S. #
1. Thiodiglycol	111-48-8
2. Phosphorus Oxychloride	10025-87-3
3. Dimethyl Methylphosphonate	756-79-6
4. Methyl Phosphonyl Difluoride	676-99-3
5. Methyl Phosphonyl Dichloride	676-97-1
6. Dimethyl Phosphite	868-85-9
7. Phosphorus Trichloride	7719-12-2
8. Trimethyl Phosphite	121-45-9
9. Thionyl Chloride	7719-09-7
10. 3-Hydroxy-1-methylpiperidine	3554-74-3
11. N,N-Diisopropyl-ß-Aminoethyl Chloride	96-79-7
12. N,N-Diisopropyl-ß-Aminoethane Thiol	5842-07-9
13. 3-Quinuclidinol	1619-34-7
14. Potassium Fluoride	7789-23-3
15. 2-Chloroethanol	107-07-3
16. Dimethylamine	124-40-3
17. Diethyl Ethylphosphonate	78-38-6
18. Diethyl N,N-Dimethylphosphoramidate	2404-03-7
19. Diethyl Phosphite	762-04-9
20. Dimethylamine Hydrochloride	506-59-2
21. Ethyl Phosphinyl Dichloride	1498-40-4
22. Ethyl Phosphonyl Dichloride	1066-50-8
23. Ethyl Phosphonyl Difluoride	753-98-0
24. Hydrogen Fluoride	7664-39-3
25. Methyl Benzilate	76-89-1
26. Methyl Phosphinyl Dichloride	676-83-5
27. N,N-Diisopropyl-ß-Amino-Ethanol	96-80-0
28. Pinacolyl Alcohol	464-07-3
29. O-Ethyl 2-Diisopropylaminoethyl Methylphosphonite	57856-11-8

Chemical	C.A.S. #
30. Triethyl Phosphite	122-52-1
31. Arsenic Trichloride	7784-34-1
32. Benzilic Acid	76-93-7
33. Diethyl Methylphosphonite	15715-41-0
34. Dimethyl Ethylphosphonate	6163-75-3
35. Ethyl Phosphinyl Difluoride	430-78-4
36. Methyl Phosphinyl Difluoride	753-59-3
37. 3-Quinuclidone	3731-38-2
38. Phosphorus Pentachloride	10026-13-8
39. Pinacolone	75-97-8
40. Potassium Cyanide	151-50-8
41. Potassium Bifluoride	7789-29-9
42. Ammonium Bifluoride	1341-49-7
43. Sodium Bifluoride	1333-83-1
44. Sodium Fluoride	7681-49-4
45. Sodium Cyanide	143-33-9
46. Tri-ethanolamine	102-71-6
47. Phosphorus Pentasulphide	1314-80-3
48. Di-isopropylamine	108-18-9
49. Diethylaminoethanol	100-37-8
50. Sodium Sulphide	1313-82-2
51. Sulphur Monochloride	10025-67-9
52. Sulphur Dichloride	10545-99-0
53. Triethanolamine Hydrochloride	637-39-8
54. N,N-Diisopropyl-2-Aminoethyl Chloride Hydrochloride	4261-68-1

Source: ACDA Fact Sheet on Australia Group Export Controls, November 7, 1995 (current as of September 6, 1997).

Figure 4.1-2. Australia Group Chemicals

Table 4.1-1. Chemical Material Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Manufacturing processes for O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) alkyl (Me, Et, n-Pr or i-Pr)-phosphonofluoridates, e.g., **sarin (GB)**: O-Isopropyl methylphosphonofluoridate (CAS: 107-44-8)	Sovereign States: capable of annual production of approx. 100 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	Phosphorus trichloride; DF; DC; hydrogen fluoride; isopropanol	Needs expensive corrosive-resistant equipment such as hastelloy or silver	None identified
Manufacturing processes for O-Alkyl (≤C10, incl. cycloalkyl) alkyl (Me, Et, n-Pr or i-Pr)-phosphonofluoridates, e.g., **soman (GD)**: O-Pinacolyl methylphosphonofluoridate (CAS: 96-64-0)	Sovereign States: capable of annual production of approx. 100 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	Phosphorus trichloride; DC; hydrogen fluoride; pinacolyl alcohol	Needs expensive corrosive-resistant equipment such as hastelloy or silver	None identified
Manufacturing processes for O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) N,N-dialkyl (Me, Et, n-Pr or i-Pr) phosphoramidocyanidates, e.g., **tabun (GA)**: O-Ethyl N,N-dimethylphosphoramidocyanidate (CAS: 77-81-6)	Sovereign States: capable of annual production of approx. 200 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	Phosphorus oxychloride or phosphorus trichloride; sodium cyanide; dimethlyamine; ethyl alcohol	None identified	None identified
Manufacturing processes for O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr) phosphonothiolates and corresponding alkylated or protonated salts, e.g., **VX** (CAS: 50782-69-9)	Sovereign States: capable of annual production of approx. 200 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	QL; sulfur or DC if Amiton-like process is used	Inert atmosphere High-temperature methylation equipment (QL process)	None identified
Manufacturing processes for Phosphonochloridates, e.g., **chlorosarin**: O-Isopropyl methylphosphonochloridate (CAS: 1445-76-7)	Sovereign States: capable of annual production of approx. 300 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	DC	Glass-lined reactors	None identified

(cont'd)

Table 4.1-1. Chemical Material Production Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Manufacturing processes for Sulfur mustards: (see Figure 4.1-1 for names) - CAS: 2625-76-5 - CAS: 505-60-2 - CAS: 63869-13-6 - CAS: 3563-36-8 - CAS: 63905-10-2 - CAS: 142868-93-7 - CAS: 142868-94-8 - CAS: 63918-90-1 - CAS: 63918-89-8	Sovereign States: capable of annual production of approx. 500 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	Sulfur monochloride or sulfur dichloride or Thiodiglycol	None identified	None identified
Manufacturing processes for lewisites: - Lewisite 1: 2-Chloro-vinyldichloroarsine (CAS: 541-25-3) - Lewisite 2: Bis(2-chlorovinyl)chloro-arsine (CAS: 40334-69-8) - Lewisite 3: Tris(2-chlorovinyl)arsine (CAS: 40334-70-1)	Sovereign States: capable of annual production of approx. 500 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	Arsenic trichloride	None identified	None identified
Manufacturing processes for Nitrogen mustards: - HN1: Bis(2-chloro-ethyl)ethylamine (CAS: 538-07-8) - HN2: Bis(2-chloro-ethyl)methylamine (CAS: 51-75-2) - HN3: Tris(2-chloro-ethyl)amine (CAS: 555-77-1)	Sovereign States: capable of annual production of approx. 500 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	HN 1: ethyl diethanolamine HN 2: methyl diethanolamine HN 3: triethanolamine	Glass- or enamel-lined equipment	None identified

(cont'd)

Table 4.1-1. Chemical Material Production Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Manufacturing processes for Amiton: O,O-Diethyl S-[2-(diethylamino)ethyl] phosphorothiolate and corresponding alkylated or protonated salts (CAS: 78-53-5)	Sovereign States: capable of annual production of approx. 500 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	None	Normally made in solution, extraction equipment	None identified
Manufacturing processes for PFIB: 1,1,3,3,3-Pentafluoro-2-(trifluoromethyl)-1-propene (CAS: 382-21-8)	Sovereign States: capable of annual production of approx. 2,000 tons Subnational: capable of producing any amount	CWC; WA ML 7; USML XIV	None	Needs expensive corrosion resistant equipment such as Hastelloy or silver	None identified
Manufacturing processes for Phosgene: carbonyl dichloride (CAS: 75-44-5)	Sovereign States: capable of annual production of approx. 2,000 tons Subnational: capable of producing any amount	CWC (exempted from WA ML); USML XIV	None	Corrosion resistant equipment	None identified
Manufacturing processes for Cyanogen chloride (CAS: 506-77-4)	Sovereign States: capable of annual production of approx. 2,000 tons Subnational: capable of producing any amount	CWC (exempted from WA ML); USML XIV	None	None identified	None identified
Manufacturing processes for Hydrogen cyanide (CAS: 74-90-8)	Sovereign States: capable of annual production of approx. 5,000 tons Subnational: capable of producing any amount	CWC (exempted from WA ML); USML XIV	None	None identified	None identified
Manufacturing processes for Alkyl (Me, Et, n-Pr or i-Pr) phosphonyldifluorides, e.g., **DF:** Methyl-phosphonyldifluoride (CAS: 676-99-3)	Sovereign States: capable of annual production of approx. 200 tons Subnational: capable of producing any amount	CWC; AG List; WA ML-7; CCL Cat 1E	DC; hydrogen fluoride	Production equipment made of Hastelloy or other high nickel alloys; silver	None identified

(cont'd)

Table 4.1-1. Chemical Material Production Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Manufacturing processes for Alkyl (Me, Et, n-Pr or i-Pr) phosphonylchlorides, e.g., **DC**: Methyl-phosphonyl dichloride (CAS: 676-97-1) Note: This material, rather than DF, is the fundamental building block of a significant portion of G and V agents.	Sovereign States: capable of annual production of approx. 400 tons Subnational: capable of producing any amount	CWC; AG List; WA ML-7; CCL Cat IE	Thionyl chloride or phosgene or phosphorous pentachloride. Dimethylmethylphosphonate (DMMP) (many production processes available).	Glass-lined vessels Glass-lined distillation columns	None identified
Manufacturing processes for O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) O-2-dialkyl (Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr) phosphonites and corresponding alkylated or protonated salts, e.g., **QL** (CAS: 57856-11-8)	Sovereign States: capable of annual production of approx. 200 tons Subnational: capable of producing any amount	CWC; AG List; WA ML 7; CCL Cat 1E	TR (diethyl methylphosphonite) KB (2-(N-N-diethylamino) ethanol). Similar esters and amino alcohols.	Waste treatment incinerators Distillation columns High-temperature methylation equipment	None identified

Table 4.1-2. Chemical Material Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Manufacturing processes for O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) alkyl (Me, Et, n-Pr or i-Pr)-phosphono–fluoridates, e.g., **sarin (GB)**: O-Isopropyl methylphosphonofluoridate (CAS: 107-44-8)	Oxidation; alkylation; fluorination; esterification. Large power needs. Must be distilled and stabilized unless manufactured for immediate use.	Troop concentrations, sabotage.	A number of production processes have been documented
Manufacturing processes for O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) alkyl (Me, Et, n-Pr or i-Pr)-phosphonofluoridates, e.g., **soman (GD)**: –O-Pinacolyl methylphosphonofluoridate (CAS: 96-64-0)	Oxidation; alkylation; fluorination; esterification. Large power needs. Must be distilled and stabilized unless manufactured for immediate use.	Troop concentrations, sabotage.	A number of production processes have been documented
Manufacturing processes for O-Alkyl ($\leq C_{10}$, incl. cycloalkyl) N,N-dialkyl (Me, Et, n-Pr or i-Pr) phosphoramidocyanidates, e.g., **tabun (GA)**: O-Ethyl N,N-dimethyl phosphoramido-cyanidate (CAS: 77-81-6)	Cyanation reaction	Troop concentrations, sabotage.	A number of production processes have been documented
Manufacturing processes for O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr) phosphonothiolates and corresponding alkylated or protonated salts, e.g., **VX** (CAS: 50782-69-9)	Alkylation reaction or use of Amiton-like process. Product should be stabilized.	Troop concentrations, sabotage, terrain denial	A number of production processes have been documented
Manufacturing processes for Phosphonochloridates, e.g., **chlorosarin**: O-Isopropyl methylphosphonochloridate (CAS: 1445-76-7)	No fluorinated reactor involved; therefore, do not need Hastelloy although glass-lined vessel required. Easier to produce, but far less toxic.	Sabotage (more applicable to subnational)	A number of production processes have been documented

(cont'd)

Table 4.1-2. Chemical Material Production Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Manufacturing processes for **Sulfur mustards**: (see Figure 4.1-1 for names) - CAS: 2625-76-5 - CAS: 505-60-2 - CAS: 63869-13-6 - CAS: 3563-36-8 - CAS: 63905-10-2 - CAS: 142868-93-7 - CAS: 142868-94-8 - CAS: 63918-90-1 - CAS: 63918-89-8	Ventilation; filtration	Troop concentrations, sabotage, terrain denial	A number of production processes have been documented
Manufacturing processes for **lewisites**: - Lewisite 1: 2-Chlorovinyl-dichloroarsine (CAS: 541-25-3) - Lewisite 2: Bis(2-chlorovinyl)-chloroarsine (CAS: 40334-69-8) - Lewisite 3: Tris(2-chlorovinyl)-arsine (CAS: 40334-70-1)	Corrosion; potential for explosive reactions	Troop concentrations, sabotage	A number of production processes have been documented
Manufacturing processes for **Nitrogen mustards**: - HN1: Bis(2-chloroethyl)-ethylamine (CAS: 538-07-8) - HN2: Bis(2-chloroethyl)-methylamine (CAS: 51-75-2) - HN3: Tris(2-chloroethyl)amine (CAS: 555-77-1)	Chlorination; neutralization	Troop concentrations, sabotage	A number of production processes have been documented including those to make other nitrogen mustards not listed on CWC schedules
Manufacturing processes for **PFIB**: 1,1,3,3,3-Pentafluoro-2-(trifluoromethyl)-1-propene (CAS: 382-21-8)	Byproduct of Teflon manufacture	Gas-mask penetrant	A number of production processes have been documented
Manufacturing processes for **Phosgene**: carbonyl dichloride (CAS: 75-44-5)	Used heavily in commercial processes	Nonpersistent gas	A number of production processes have been documented

(cont'd)

Table 4.1-2. Chemical Material Production Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Manufacturing processes for **Cyanogen chloride** (CAS: 506-77-4)	None identified	Quick-acting casualty agent Degradation of mask filters	A number of production processes have been documented
Manufacturing processes for **Hydrogen cyanide** (CAS: 74-90-8)	Used heavily in acrylic industries	Bombs, grenades	A number of production processes have been documented
Manufacturing processes for Alkyl (Me, Et, n-Pr or i-Pr) phosphonyldifluorides, e.g., **DF**: Methylphosphonyldifluoride (CAS: 676-99-3) .	Fluorination reaction; corrosion	Key component in binary G agents	A number of production processes have been documented
Manufacturing processes for Alkyl (Me, Et, n-Pr or i-Pr) phosphonylchlorides, e.g., **DC**: Methylphosphonyl dichloride (CAS: 676-97-1) Note: This material rather than DF is the fundamental building block of a significant portion of G and V agents.	Chlorination reaction	Used to make DF and Di-Di mix Also can be used in some V agent processes	A number of production processes have been documented
Manufacturing processes for O-Alkyl (H or $\leq C_{10}$, incl. cycloalkyl) O-2-dialkyl (Me, Et, n-Pr or i-Pr)-aminoethyl alkyl (Me, Et, n-Pr or i-Pr) phosphonites and corresponding alkylated or protonated salts, e.g., **QL** (CAS: 57856-11-8)	Transesterification reaction High-temperature methylation	Component of VX binary weapon; may be intermediate in VX process	A number of production processes have been documented

SECTION 4.2—DISSEMINATION, DISPERSION, AND WEAPONS TESTING

OVERVIEW

Perhaps the most important factor in the effectiveness of chemical weapons is the efficiency of dissemination. This section lists a variety of technologies that can be used to weaponize toxic chemical agents. Munitions include bombs, submunitions, projectiles, warheads, and spray tanks. Techniques of filling and storage of munitions are important. The principal method of disseminating chemical agents has been the use of explosives. (Figure 4.2-1 shows an example of a U.S. chemical bomb, the MC-1.) These usually have taken the form of central bursters expelling the agent laterally. Efficiency is not particularly high in that a good deal of the agent is lost by incineration in the initial blast and by being forced onto the ground. Particle size will vary, since explosive dissemination produces a bimodal distribution of liquid droplets of an uncontrollable size but usually having fine and coarse modes. For flammable aerosols, sometimes the cloud is totally or partially ignited (flashing) in the dissemination process. For example, explosively disseminated VX ignited roughly one third of the time it was employed. The phenomenon was never fully understood or controlled despite extensive study. A solution would represent a major technological advance.

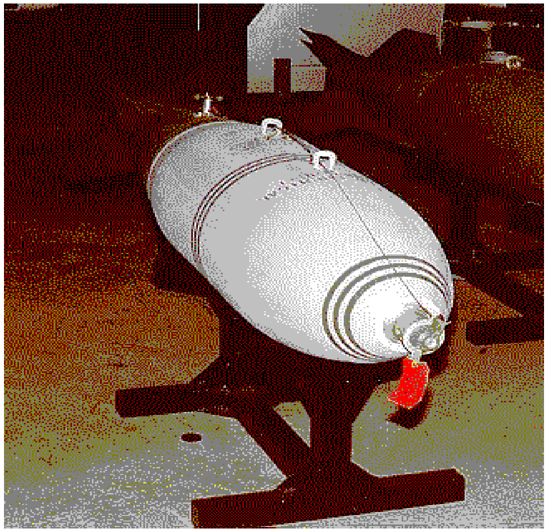

Figure 4.2-1. MC-1 Gas Bomb

Highlights

- Efficiency of dissemination is the most important factor in the effectiveness of chemical weapons.
- Much of the agent is lost in an explosive dissemination by incineration and by being forced onto the ground.
- Flammable aerosols frequently “flash” (ignite) when explosively disseminated.
- The environment (winds and temperature) are important factors in CW dissemination.

Aerodynamic dissemination technology allows nonexplosive delivery from a line source. Although this method provides a theoretical capability of controlling the size of the particle, the altitude of dissemination must be controlled and the wind direction and velocity known. Accurate weather observations can enable the attacker to predict wind direction and velocity in the target area.

An important factor in the effectiveness of chemical weapons is the efficiency of dissemination as it is tailored to the types of agent. The majority of the most potent of chemical agents are not very volatile. Indeed, the most volatile of the G-agents is GB (sarin), which has a volatility near that of water. All are nonvolatile liquids or solids at room temperature. VX is an oily liquid.

An advanced proliferant might attempt to develop on-board sensor systems for initiation and control of agent dissemination/dispersal for ballistic missiles, cruise missiles, and artillery. In these cases, the sensor (target-detection device) may employ technologies common to other electronic fuzing applications. The efficacy of explosives and pyrotechnics for dissemination is limited by the flammable nature of some agents.

In some respects, long-range strategic weapons pose a lesser problem than short-range tactical weapons that are fired over, or in the vicinity of, one’s own forces. The agent must be dispersed within the boundary layer (<200–300 ft above the ground) and yet high enough to allow effective dispersal of the agent. This poses design problems because the ground/target detection device must be substantially more sensitive than for conventional munitions. The increased sensitivity also results in increased susceptibility to false firing due to noise, mutual interference, and electronic countermeasures (ECM).

Casualties due to premature initiation of the warhead are unacceptable in tactical weapons. Accordingly, an additional function such as a simple electrical or mechanical timer may be used to arm the height-of-burst sensor.

A more recent attempt to control aerosol particle size on target has been the use of **aerodynamic dissemination** and sprays as line sources. By modification of the rheological properties of the liquid, its breakup when subjected to aerodynamic stress can theoretically be controlled and an idealized particle distribution achieved. In practice, the task is more difficult, but it represents an area where a technological advance could result in major munition performance improvements. The altitude of dissemination must be controllable and the wind direction and velocity known for a disseminated liquid of a predetermined particle size to predictably reach the ground and reliably hit a target.

Thermal dissemination, wherein pyrotechnics are used to aerosolize the agent has been used particularly to generate fine, inhalable clouds of incapacitants. Most of the more complex agent molecules, however, are sensitive to high temperatures and can deteriorate if exposure is too lengthy. Solids are a notoriously difficult problem for dissemination, since they tend to agglomerate even when pre-ground to desired sizes.

Dispersion considers the relative placement of the chemical agent munition upon or adjacent to a target immediately before dissemination so that the material is most efficiently used. For example, the artillery rockets of the 1950's and early 1960's employed a multitude of submunitions so that a large number of small agent clouds would form directly on the target with minimal dependence on meteorology. Another variation of this is multiple "free" aerial sprays such as those achieved by the BLU 80/B Bigeye weapon and the multiple launch rocket system. While somewhat wind dependent, this technique is considerably more efficient in terms of agent quantities.

Testing requirements for munitions seek to measure the efficacy of dissemination. This has been done historically on instrumented grids with samples of the disseminated material taken at known positions. The positions are assigned area values and these are integrated to determine total dosage and dose isopleths. While the technique was constantly improved, it still was crude by most standards and required numerous tests to provide useful information. Instrumental methods such as versions of light detection and ranging (LIDAR) may well be better suited to more accurate measures but without the signature of the chemical grids.

Modeling dissemination patterns for agent laydown can be an effective way to predict dispersal without physical testing. Little testing would be required given good, verified models. The problem, however, is model verification.

RATIONALE (See Table 4.2-1)

Many dissemination technologies have been included because many are available to a proliferant. In World War I, canisters of chlorine were simply opened to allow the gas to drift across enemy lines. Although this produced limited results, it is indicative of the simplicity of potential means of dispersion. Although central bursters have limitations, countries usually use this method in the early stages of CW development, although it does not have to be the first one. There is sufficient open literature describing the pros and cons of various types of dissemination to dictate the consideration of all of them by a proliferant. Most countries could develop the toxic agents and adapt their standard munitions to carry the agents. It is much more difficult, however, to achieve success in effective dispersion and dissemination. Weather observation and forecasting are essential to increase the probability of effective CW dissemination and reduce the risk of injuring friendly forces.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 4.0-2)

As stated previously, most countries have the capability to develop chemical weapons. Those with a well-developed military infrastructure could readily adapt existing munitions for chemical warfare. During the Iran-Iraq War, Iraq delivered mustard and tabun with artillery shells, aerial bombs, missiles, and rockets. Virtually any country or subnational group with significant resources has sufficient capability to attain the minimum capability that would be needed to meet terrorist aims. Any nation with substantial foreign military sales or indigenous capability in conventional weapons will have (or have ready access to) both the design know-how and components required to implement at least a moderate capability.

Table 4.2-1. Dissemination, Dispersion, and Weapons Testing Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Projectile cases for CW agents	Ability to produce fillable, fireable, and leakproof munition casings	USML II, IV; WA ML 2, 4	High fragmentation steels and corrosion/leak resistant casings	Projectile forging, casing production, high-integrity weld or ball seals, inert gas insertion, helium leak check equipment, acoustic metal flaw detection.	Liquid fill ballistic programs Dissemination prediction models
Warheads for CW missile systems	Ability to produce casings for either bulk liquid or sub-munitions capable of appropriate opening for dissemination	USML IV; WA ML 4; MTCR 4	Corrosion/leak-resistant casings	High-integrity weld or ball seals, inert gas insertion, helium leak check equipment. Ability to dynamically balance loaded warhead.	Ballistic programs able to account for effects of liquid fills Dissemination and dispersion prediction capabilities
Electronic time fuzes	Accuracy/setability to within 0.1 second	USML III; WA ML 3	Accurate electronic clock technology	Ability to test fuze accuracy and reliability.	None identified
High-explosive formulations	Precisely tailored energetic properties to prevent ignition	USML V; WA ML 8	Although standard formulations are usable, formulations to reduce potential aerosol ignition are desirable.	Measures of explosive stability, oxygen balance desirable.	Explosive dissemination pattern prediction
Energetic materials	Low-temperature burning energetic materials capable of vaporization/condensation or ablative dissemination of solid agents	USML V; WA ML 8; WA Cat 1C; CCL Cat 1C	Energetics with sufficiently low and controllable burning temperatures that do not destroy the material being disseminated.	Measurement of energetic mix burning temperatures.	Dissemination effectiveness predictive models

(cont'd)

Table 4.2-1. Dissemination, Dispersion, and Weapons Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
On-board sensors for sequencing and initiation of CW warheads	Radar or radio proximity sensors for reliable measurement of altitudes from 50 to 100 meters. Guidance integrated fuzing. Nonenergetic electromechanical mechanisms for warhead control and initiation.	USML XI, XII; WA ML 11, 15	None identified	Specially designed ground approach or terrain return simulators	HOB measurement and detection algorithms and logic algorithms for ECCM or terrain feature analysis
Aerodynamic dissemination	Nonexplosive dispersion of CW agents in a line source in the atmosphere	USML XIV; WA ML 7	Compatible thixotropic additives for control of particle size	Rheogoniometer for measurement of dynamic rheological properties of batches	Dissemination effectiveness predictive models
Submunition dispersion	Capability to produce and disperse agent filled submunitions	USML IV; WA ML 4	None identified	Corrosion/leak-resistant casings for submunitions. Sub-munition fill capability for missile warheads.	Dissemination effectiveness predictive models
Prediction/sensing of micro-meteorology	Ability to predict wind velocity and direction in a target area	CCL EAR 99; USML XIV, XXI	None identified	Deployable micrometeorological sensors	Linkage of sensor data to weapons system to control employment
De-agglomeration of particles	Ability to have majority of preground solid particles in the inhalable range	USML XIV; WA ML 7	Effective (probably item-specific) deagglomerant	Reliable particle size measurement	None identified
Dosage/Area measurement	Ability for reasonable measurement of dissemination effectiveness	USML XIV; WA ML 7	None identified	Techniques for measurement of aerosol concentrations versus time and/or ground depositions over a broad area	Software to translate data to concentration isopleths
Fuzzy logic for unmanned aircraft	Use of fuzzy logic in conjunction with on-site micrometeorological data to optimize dissemination performance	WA ML 21; USML XXI	None identified	None identified	Fuzzy programs to rapidly adjust delivery to prevailing meteorological conditions

Table 4.2-2. Dissemination, Dispersion, and Weapons Testing Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Projectile cases for CW agents	Acquiring/producing fillable/fireable and leakproof munition casings	Bombs, projectiles, submunitions, warheads	None identified
Warheads for CW missile systems	Producing casings for either bulk liquid or submunitions capable of appropriate opening for dissemination.	Missiles	None identified
Electronic time fuzes	Producibility	Conventional, biological and chemical warheads	Radar fuzes, proximity fuzes
High explosive formulations	Ability to cast stable explosives for weapon environments.	All munitions systems	None identified
Energetic materials	Low-temperature burning energetic materials capable of vaporization/ condensation or ablative dissemination of solid agents.	All munitions systems	None identified; many energetics available
On-board sensors for sequencing and initiation of CW warheads	Effects of initiation mechanism on agent	Technology common to conventional cannister weapons and strategic/ tactical nuclear weapons	Delivery from manned aircraft Surface burst/contact sensor
Aerodynamic dissemination	Nonexplosive dissemination of CW agents	Line source delivery of CW agents	Different delivery system
Submunition dispersion	Fuzing, filling	CW agent delivery	Bombs, warheads
Prediction/sensing of micro-meteorology	Data collection	Prediction of CW effects	On-site observers
De-agglomeration of particles	Keeping particles in inhalable size	Dissemination of CW agent	None identified
Dosage/Area measurement	Detection, collection	Contamination avoidance, command and control	Use animals
Fuzzy logic for unmanned aircraft	Computational ability	Delivery of CW agent	Normal logic

SECTION 4.3—DETECTION, WARNING, AND IDENTIFICATION

OVERVIEW

Because many toxic chemicals act quickly, rapid detection is needed to prevent lethal or incapacitating results from unwanted exposure. This subsection covers a variety of technologies that can be used to detect CW agents. Sample collection, sample processing, and information processing are vital to enable identification and warning of chemical exposure.

Detection can be accomplished at a designated location (point detection) or at a distance (standoff detection). No single fielded sensor detects all chemical agents of interest. Standoff detection is particularly difficult for low volatility agents (e.g., either U.S. or Russian forms of VX). Sensitivity of a detector is crucial to detecting lethal concentrations. Equipment must be reliable, provide identification quickly with a low false alarm rate and high accuracy, and be integrated into an alarm system so that warning can be distributed and proper action taken. Unknown factors can include location, persistence, and intensity of the agent. These are critical parameters for command decisions. Figure 4.3-1 shows a U.S. Chemical Agent Monitor (CAM). Detection, warning, and identification have an offensive CW component and are also necessary in a defensive context.

Figure 4.3-1. Chemical Agent Monitor (CAM)

Some amount of detection and warning capability is needed if a country is to develop and employ chemical weapons. When toxic chemicals are produced, detection and warning are necessary to the extent that the safety of workers is important. If storage sites are established, detection is needed to verify the integrity of the weapons and to ensure that the surrounding area does not become contaminated. These concerns can be mitigated if production occurs just before use. Even though soldiers and airmen employing chemical weapons might wear some type of protective clothing, detection is necessary to prevent inadvertent exposure and to minimize contamination. It should be noted that other countries have not considered safety to be as important as the U.S. did when it was involved in offensive CW preparation. Consequently, they may dispense with procedures that the U.S. deemed essential.

Highlights

- Detection requirements for a purely offensive posture are minimal.
- A prudent attacker must be prepared to defend against a counter-attack in kind if the CW threshold is crossed.
- Detection, warning, and identification of the employment of CW are key to implementing defensive measures.
- Detection of CW is a key aspect of CWC compliance.

Proliferators of chemical weapons would not need much detection equipment. The agent(s) being produced and used would be known. Point detectors would be sufficient to determine inadvertent leakage. Detection capability is required to know when the environment is safe for normal operations after CW has been employed.

Detection, warning, and identification are critical in a defensive role. Protection against chemical agents is available, but since wearing protective gear degrades military performance, units must not assume a protective posture until it is mandatory. Many prophylactic measures are most effective if implemented before exposure, and many therapeutics must be initiated soon after exposure. The sophistication needed depends on the technological capability of the enemy.

The detection and identification requirements in a defensive posture are much more difficult to meet than those required for offensive operations. Detection, warning, and identification systems are further stressed because the time, place, amount, and type of agent used are determined by the attacker. The defender must be ready for anything at any time and in any amount.

Historically, detection of ground and surface contamination has depended on a color change on special paper that was exposed to an agent. Another method was a color change that occurred when air was drawn through tubes with special dye chemicals on a substrate. Special analytical kits were used to determine the presence of chemical agents in water. Various technologies are used in automatic detectors. All of them indicate the presence of an agent in one location. A number of detectors are being developed to provide standoff capability. Figure 4.3-2 shows the U.S. Remote Sensing Chemical Agent Alarm (RSCAAL), which is designed to detect nerve and vesicant agent clouds at up to 5 km. If an agent can be detected at a sufficient distance, measures can be taken to avoid the contamination and the need to wear protective clothing.

Figure 4.3-2. RSCAAL

RATIONALE (See Table 4.3-1)

To prevent unnecessary casualties during production, transport, storage, and employment, a proliferant might need only be able to detect those agents that are being developed. A number of technologies could be used for this purpose, although only point detectors would suffice, since the location and identity would already be known. Warning would be quite simple. A prudent attacker, however, must be prepared for a retaliatory attack by an adversary. In this case, the agent to be expected might not be known. Identification and warning would be critical to taking proper defensive measures.

The ability to detect and identify toxic agents and provide warning to forces is essential for operating in a chemical environment. Early detection and warning provide situational awareness to allow military forces to avoid or reduce the threat. If exposure cannot be avoided, troops must don protective clothing. Military forces also must know when contamination has been reduced to a level that permits normal operations. Knowledge of areas of residual contamination is important as well.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 4.0-2)

A number of Western countries (Canada, France, Germany, the UK, and the United States) have significant capability in sensor technology. Russia and Israel also are well advanced in this field. At least 18 countries have some type of chemical detector in their armed forces. Countries among the 18 include China, Finland, Hungary, Iran, Iraq, Libya, the Netherlands, North Korea, the Czech Republic, and South Africa.

Table 4.3-1. Detection, Warning, and Identification Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Ion Mobility Spectrometry (IMS)	Detect level 0.05–1.0 mg/m^3 of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	Radioactive materials in some systems	None identified	Spectral data base
Mass Spectrometry-mass spectrometry (MS-MS)	Detect level 0.1–100 picograms of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B, 3A	None identified	Miniaturization and ruggedizing of current technology required	Spectral data base
Passive Infrared (IR)	Detect level @1,000 m ~100 mg/m^3 of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B, 6A	None identified	Database development	Requires data base of emission patterns
Wet chemistry	Detect >1.0 mg of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	None identified	None identified	None identified
Enzymatic reactions	Detect level <0.1 mg of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	Enzyme (aceto-cholinesterase) substrate	None identified	None identified
Gas phase ion chemistry	Detect levels <1.0 mg of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	None identified	Ion source	None identified
Gas Chromatography (GC)-IMS	Detect level 0.1–1.0 mg/m^3 of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B, 3A	Carrier gas	None identified	Spectral data base. Retention time indices.

(cont'd)

Table 4.3-1. Detection, Warning, and Identification Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
GC-Mass Spectrometry (MS)	Detect level 1–100 picograms of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B, 3A	Carrier gas	None identified	Spectral data base Retention time indices
GC-Flame Photometric Detector (FPD)-Flame Ionization Detector (FID)	Detect level 10–1,000 picograms of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	Carrier gas	None identified	Retention time indices
Transverse Field Compensation (TFC)-IMS	Detect level 0.001–0.01 mg/m^3 of CW agent	WA ML 7; WA Cat IA; AG List; USML XIV; CCL Cat 2B	Radioactive materials	None identified	Spectral data base
Surface Acoustic Wave (SAW) Crystal Arrays	Detect level 0.01–1.0 mg of CW agent	WA ML 7; WA Cat IA, 3A; AG List; USML XIV; CCL Cat 2B, 3A	Polymer coatings	None identified	Signal patterns of arrays
Absorption LIDAR	Detect levels of 1 mg/m^3 of CW agent	WA ML 7; WA Cat IA, 6A; AG List; USML XIV; CCL Cat 2B, 6A	None identified	None identified	Spectral data base
Scattering LIDAR	Detect levels above 1 mg/m^3 of CW agent	WA ML 7; WA Cat IA, 6A; AG List; USML XIV; CCL Cat 2B, 6A	None identified	None identified	Spectral data base

(cont'd)

Table 4.3-1. Detection, Warning, and Identification Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Information Processing (e.g., data reduction, information transfer, sensor multiplexing, decision making	Any capability is a concern	CCL EAR 99	None identified	Multiplexed system for detection of CW agents	Adaptations of existing systems.
Sample Processing (e.g., concentration)	Any capability is a concern	WA ML 7; WA Cat IA; AG List; USML XIV; CCL 2B	None identified	Analytical chemistry equipment	Spectral recognition algorithms
Remote liquid particulate sensing	Detect levels above 1 mg/m^3	WA ML 7; WA Cat IA; AG List; USML XIV; CCL 2B	None identified	None identified	Emission data base
Remote solid particulate sensing	Detect levels above 1 mg/m^3	WA ML 7; WA Cat IA; AG List; USML XIV; CCL 2B	None identified	Database development	Requires database of emissions

Table 4.3-2. Detection, Warning, and Identification Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Ion Mobility Spectrometry (IMS)	Replacement of radioactive elements	Point alarm	Use another detection technology
Mass Spectrometry-mass spectrometry (MS-MS)	Power requirement	Verification	Use another detection technology
Passive Infrared (IR)	Potential interference of atmospheric pollutants; identification of specific substances; limited to relatively volatile material; atmospheric transmission window; signal processor intensive	Remote detection of chemical agents	Use another detection technology
Wet chemistry	Requires significant servicing; environmental limitations on reactants	Point alarm	Use a live animal
Enzymatic reactions	Requires individual processing and interpretation; sensitivity of living substrates to environment	Point alarm	Use another detection technology
Gas phase ion chemistry	Source of ionization; analysis of products	Point alarm	Use another detection technology
Gas Chromatography (GC)-IMS	Electric requirement	Point alarm	Use another detection technology
GC-Mass Spectrometry (MS)	Electric requirement “Long” (1–20 min) response time	Point alarm	Use another detection technology
GC-Flame Photometric Detector (FPD)-Flame Ionization Detector (FID)	Electric requirement “Long” (2–10 min) response time	Point alarm	Use another detection technology
Transverse Field Compensation (TFC)-IMS	Electric requirement	Point alarm	Use another detection technology
Surface Acoustic Wave (SAW) Crystal Arrays	“Long” (0.5–5 min) response time	Point alarm	Use another detection technology
Absorption LIDAR	Substance dependent sensitivity; atmospheric transmission window	Remote sensing	Use another detection technology
Scattering LIDAR	Substance dependent sensitivity	Remote sensing	Use another detection technology
Information Processing (e.g., data reduction, information transfer, sensor multiplexing, decision making	Availability/preparation of comprehensive data base on known and potential toxic material	Areas where comparison of spectral and/or other data is required for detection/identification	Manual data analysis

(cont’d)

Table 4.3-2. Detection, Warning, and Identification Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Sample Processing (e.g., concentration)	Differentiation of samples from background	All areas of agent sensing	None identified
Remote liquid particulate sensing	Several agents (e.g., VX) are of very low volatility and provide little material for sensing	Remote sensing	None identified
Remote solid particulate sensing	Highly toxic particulates cannot be detected by current remote methods	Remote sensing	None identified

SECTION 4.4—CHEMICAL DEFENSE SYSTEMS

OVERVIEW

Chemical defense includes individual and collective protection and decontamination. The goal of individual and collective protection is to use clothing ensembles and respirators as well as collective filtration systems and shelters to insulate forces from chemical agents. Decontamination is essential to return personnel and equipment to normal operating conditions. Technologies for these types of equipment are included in this subsection.

Masks protect the respiratory system by preventing the inhalation of toxic chemical vapors and aerosols. They protect eyes and face from direct contact with chemical agents as well. Important considerations in mask design are the ability to don the mask and hood quickly, communications, respiration, performance degradation, and the ability to consume fluids while the mask is in place. Masks must be compatible with operational missions and equipment (e.g., night vision goggles). Ideally, protective clothing (garments, gloves, and boots) should provide protection from contact with chemical agents as well as flame protection, with a minimum amount of heat stress. Ensembles must be durable and able to be laundered and decontaminated. Protective equipment reduces the efficiency of the person wearing it.

Collective protection enables groups to work in a toxic-free environment in tents, vehicles, or special shelters. Efforts are aimed at making systems mobile and easy to erect. Air supplied to shelters is purified in much the same way as it is for individual masks.

Shelf life of protective equipment is a concern to all users. Periodic inspections are necessary to ensure readiness.

Decontamination removes toxic substances or renders them harmless. Individuals and equipment must be decontaminated. Depending on the particular agent, CW agents can be washed and rinsed away, evaporated, absorbed, or removed by heat treatment.

There is medical treatment available to offset the effects of chemical weapons. Atropine and 2-PAM chloride can be administered upon suspicion of exposure to a nerve agent. Atropine is an anticholinergic agent. It blocks the action of acetylcholine (a nerve transmitter substance), preventing it from stimulating nerves. 2-PAM chloride is anoxime, which increases the effectiveness of drug therapy in poisoning by some—but not all—cholinesterase inhibitors. Atropine and 2-PAM chloride only work to a limited degree with refractive nerve agents such as GD. Their administration when an exposure has not occurred can be harmful. Diazepam (more commonly known as Valium) is used as an anticonvulsant once an individual exhibits incapacitating symptoms of nerve agent exposure. The carbamate pyridostigmine, given in a dose of 30 mg every 8 hours, can be used as a pretreatment for nerve agent exposure.

Without appropriate chemical defenses, operations may have to be limited. Forces could be required to remain covered until the threat of further exposure is reduced. This could be mission threatening if persistent agents are encountered. An alternative is to avoid contamination. To do this, detection equipment must be integrated with a command and control system to ensure an alarm is disseminated.

In chemical warfare, effective chemical defense measures can greatly limit the damage inflicted by a chemical attack. In World War I the gas mask had a dramatic effect in limiting the significance of chemical weapons. Developments since then (improved masks, protective clothing, detectors, and training) have further widened the margin of protection. Collective protection takes defensive measures one step further by providing a toxic-free environment for group functions such as command centers and medical facilities. Since World War I, chemical warfare has only been used against those entirely lacking or highly deficient in protective equipment. Some suggest that chemical defense acts as a deterrent to the initiation of chemical warfare because there is less incentive to attack a well-protected force. World War II is cited as an example of this theory, since both sides were well equipped for chemical defense and neither side used chemical weapons. Others suggest that equivalent offensive capability is the real deterrent. While protective clothing can reduce the effects of CW, its use poses other problems.

Highlights

- Masks and protective clothing are needed to defend against many toxic chemicals.
- Reduction in combat efficiency from wearing protective gear is estimated to be up to 50 percent.
- Proliferators may not provide the same measure of protection that is afforded U.S. troops.
- Training and protection reduce the effectiveness of chemical weapons.

Figure 4.4-1. Joint Service Lightweight Integrated Suit Technology (JSLIST)

The wearing of individual protective equipment can hinder performance by interfering with vision, communication, and dexterity. High ambient temperatures are particularly devastating to those required to don protective clothing. With training, many of the negative effects can be minimized. Overheating, however, is difficult to overcome. In hot weather, full protective gear is very burdensome. Even the threat of agents can dictate the donning of gear. Commanders must then consider limiting the duration of operations or elect to compromise the protection afforded by individual gear. Figure 4.4-1 shows the newest U.S. protective clothing.

Although the CWC prohibits the development, production, possession, and transfer of chemical weapons, it places no restraint on chemical defensive measures. The Convention ensures the rights of parties to maintain chemical defense programs and grants parties the right to "...participate in, the fullest possible exchange of equipment, material, and scientific and technological information concerning means of protection against chemical weapons."

Chemical defense systems are needed by both an attacker and a defender. An offensive unit needs to limit the number of casualties caused by inadvertent exposure. In addition, troops must be prepared for a retaliatory strike once chemical agents have been used. Since the attacker chooses the time, place, extent, and duration of an attack, defensive measures by the attacker can be planned accordingly. The extent of defensive equipment needed by a proliferant is dictated primarily by the value the nation places on human life and well-being of its forces. Other factors include potential adversaries, extent of CW use expected, quality of munitions and sealing techniques, and proficiency of both military and civilian populations obtained through training.

RATIONALE (See Table 4.4-1)

Even proliferants must provide some amount of protection for their people if they are to prevent casualties during production, storage, transport, and employment of chemical weapons. Often rogue states include defensive training for their ground forces. That is not to say that protection must or will be supplied according to U.S. standards. In World War II, the Soviets were reported to have filled chemical shells in the open with no protection. When workers died, they were replaced.

If a defensive posture is developed, individual protection, decontamination, and collective protection could be part of the program. Military requirements are much more stringent than commercial applications which deal with known substances. Ground, air, and naval forces are all subject to attack with unknown agents and must be protected. A robust defensive capability not only protects troops but could act as a deterrent against a chemical-capable adversary.

Technologies in this section can enhance chemical protection for troops. If contamination is unavoidable, protective clothing enables an individual to continue operations in a chemical environment. Collective protection is important for providing a safe and contamination-free work area and rest/relief facilities. A key use of collective protection is in medical facilities.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 4.0-2)

Numerous countries produce chemical protective gear. Production of masks is the most common, including masks for civilians (as seen in Israel during Operation Desert Storm), although limited shelf life remains a problem. Many NATO and former Warsaw Pact countries as well as Middle East and Asian states produce protective clothing. Only a few manufacture aircraft respiratory equipment: Canada, Norway, Russia, and the UK. A number of countries have developed collective protection for shelters: Finland, France, Israel, Sweden, Switzerland, and the UK. In addition, Russia has fielded and maintains a substantial inventory of collective protection systems for a wide variety of vehicles and shelters.

Since 1990 North Korea has placed a high priority on military and civilian chemical defense readiness. Training in a chemical environment is mandatory and an integral part of armed forces training. Pyongyang is attempting to equip all forces, including its reserves, with full protective gear. In addition, it has directed that the entire population be issued gas masks. Iran has increased defensive chemical warfare training in the last few years and is making efforts to buy foreign equipment.

Table 4.4-1. Chemical Defense Systems Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Production and design technology for protective masks	Any type of vapor and aerosol protection	WA ML 7; WA Cat 1E; USML X	Butyl rubber; silicone rubber; plastics	Simulated agents; leakage testers; mannequin-face model for mask and suit design; particle-size analysis equipment.	Software for generating facial contours
Production and design technology for protective clothing	Any type of vapor and aerosol protection	WA ML 7; WA Cat 1E; USML X	Charcoal activated cloth; semipermeable membranes; polymers	Simulated agents; particle-size analysis equipment; testing methodology	None identified
Absorption technology for collective protection	Any type of vapor and aerosol protection	WA ML 7; USML XIV;	Impregnated charcoal filters; polyethylene; fluoropolymer/ aramid laminate	Simulated agents; particle-size analysis equipment	None identified
Nonaqueous decontamination technology	Ability to decontaminate to mission essential levels	USML XIV; WA ML 7	None identified	None identified	None identified
Aqueous decontamination technology	Ability to decontaminate to mission essential levels	USML XIV; WA ML 7	Sufficient water supply	None identified	None identified
Medical prophylaxis technologies	Ability to protect mission essential personnel	USML XIV; WA ML 7	None identified	None identified	None identified
Therapeutic technologies	Ability to protect mission essential personnel	USML XIV; WA ML 7	Chloromide S-330; atropine/obidoxime chloride (CAS 114-90-9)	None identified	None identified

Table 4.4-2. Chemical Defense Systems Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Production and design technology for protective masks	Communications (microphone pass-through); respiration (air management); eye protection; composite eye lens retention system; anthropometrics; performance degradation; ability to consume fluids; protect from unknowns; shelf life	Aircrew masks; protective masks	Technologies that enable contamination avoidance
Production and design technology for protective clothing	Integration with hood/mask; closure technology; performance degradation; ability to consume fluids; limited life span; protect from unknown; environmental considerations; shelf life	Individual protection	Technologies that enable contamination avoidance
Absorption technology for collective protection	Affordable; deployable; adaptable to structure; modification to deal with filter penetrants; protection from unknown; charcoal for most organic materials	Collective protection	Individual protection technologies; technologies that enable contamination avoidance
Nonaqueous decontamination technology	Volume of toxic agent; time required; adaptability to unknown agents; disposal of agent; identification of what needs to be decontaminated; identification of decrease of toxicity to allowable level; solubility of agent; corrosiveness on material; sensitivity of electrical components	Reduce contamination to allow military operations	Weather (time); aqueous decontamination; technologies that enable contamination avoidance
Aqueous decontamination technology	Volume of toxic agent; time required; adaptability to unknown agents; disposal of agent; identification of what needs to be decontaminated; identification of decrease of toxicity to allowable level; solubility of agent; corrosiveness on material; sensitivity of electrical components	Reduce contamination to allow military operations	Weather (time); nonaqueous decontamination; technologies that enable contamination avoidance
Medical prophylaxis technologies	Efficacy of prophylaxis; pre- vs. post-exposure treatment; side effects; storage; application synergism.	Reduce casualties; reconstitute forces	Therapeutics; individual and collective protection technologies; technologies that enable contamination avoidance
Therapeutic technologies	Side effects; response time	Reduce casualties; reconstitute forces	Technologies that enable contamination avoidance

SECTION V

NUCLEAR WEAPONS TECHNOLOGY

SECTION 5—NUCLEAR WEAPONS TECHNOLOGY

Scope

Highlights

- The design and production of nuclear weapons in 1997 is a far simpler process than it was during the Manhattan Project.
- Indigenous development of nuclear weapons is possible for countries with industrial bases no greater than that of Iraq in 1990. Given a source of fissile material, even terrorist groups could construct their own nuclear explosive devices.
- At least two types of nuclear weapons can be built and fielded without any kind of yield test, and the possessors could have reasonable confidence in the performance of those devices.
- The standing up of elite units to take custody of nuclear weapons or to employ them would be a useful indicator that a proliferant is approaching the completion of its first weapon.
- The acquisition of fissile material in sufficient quantity is the most formidable obstacle to the production of nuclear weapons.

BACKGROUND

General

This section examines the technologies needed to construct nuclear and radiological weapons and to employ both kinds of weapons either for military purposes or an act of terror. Since their introduction in 1945, nuclear explosives have been the most feared of the weapons of mass destruction, in part because of their ability to cause enormous instantaneous devastation and of the persistent effects of the radiation they emit, unseen and undetectable by unaided human senses. The Manhattan Project cost the United States $2 billion in 1945 spending power and required the combined efforts of a continent-spanning industrial enterprise and a pool of scientists, many of whom had already been awarded the Nobel Prize and many more who would go on to become Nobel Laureates. This array of talent was needed in 1942 if there were to be any hope of completing a weapon during the Second World War. Because nuclear fission was discovered in Germany, which remained the home of many brilliant scientists, the United States correctly perceived itself to be in a race to build an atomic bomb.

For many decades the Manhattan Project provided the paradigm against which any potential proliferator's efforts would be measured. Fifty years after the Trinity explosion, it has been recognized that the Manhattan Project is just one of a spectrum of approaches to the acquisition of a nuclear capability. At the low end of the scale, a nation may find a way to obtain a complete working nuclear bomb from a willing or unwilling supplier; at the other end, it may elect to construct a complete nuclear infrastructure including the mining of uranium, the enrichment of uranium metal in the fissile isotope ^{235}U, the production and extraction of plutonium, the production of tritium, and the separation of deuterium and ^{6}Li to build thermonuclear weapons. At an intermediate level, the Republic of South Africa constructed six quite simple nuclear devices for a total project cost of less than $1 billion (1980's purchasing power) using no more than 400 people and indigenous technology.

Although talented people are essential to the success of any nuclear weapons program, the fundamental physics, chemistry, and engineering involved are widely understood; no basic research is required to construct a nuclear weapon. Therefore, a nuclear weapons project begun in 1996 does not require the brilliant scientists who were needed for the Manhattan Project.[1]

Acquisition of a militarily significant nuclear capability involves, however, more than simply the purchase or construction of a single nuclear device or weapon. It requires attention to issues of safety and handling of the weapons, reliability and predictability of entire systems, efficient use of scarce and valuable special nuclear material (SNM) (plutonium and enriched uranium), chains of custody and procedures for authorizing the use of the weapons, and the careful training of the military personnel who will deliver weapons to their targets.

In contrast, a nuclear device used for terrorism need not be constructed to survive a complex stockpile-to-target sequence, need not have a predictable and reliable yield, and need not be efficient in its use of nuclear material. Although major acts of terrorism are often rehearsed and the terrorists trained for the operation, the level of training probably is not remotely comparable to that necessary in a military establishment entrusted with the nuclear mission.

Testing of Nuclear Weapons

The first nuclear weapon used in combat used an untested gun-assembled design, but a very simple and inefficient one. The first implosion device was tested on July 16, 1945, near Alamogordo, New Mexico, and an identical "physics package" (the portion of the weapon including fissile and fusion fuels plus high explosives) was swiftly incorporated into the bomb dropped on Nagasaki.

Nuclear weaponry has advanced considerably since 1945, as can be seen at an unclassified level by comparing the size and weight of "Fat Man" with the far smaller, lighter, and more powerful weapons carried by modern ballistic missiles.

Most nations of the world, including those of proliferation interest, have subscribed to the 1963 Limited Test Ban Treaty, which requires that nuclear explosions only take place underground. Underground testing can be detected by seismic means and by observing radioactive effluent in the atmosphere. It is probably easier to detect and identify a small nuclear test in the atmosphere than it is to detect and identify a similarly sized underground test. In either case, highly specialized instrumentation is required if a nuclear test explosion is to yield useful data to the nation carrying out the experiment. A Comprehensive Test Ban Treaty was opened for signature and signed at the United Nations on 24 September 1996 by the five declared nuclear weapon states, Israel, and several other states. By the end of February 1998, more than 140 states had signed the accord. The Treaty bans all further tests which produce nuclear yield. In all probability, most of the nations of greatest proliferation concern will be persuaded to accede to the accord, although the present government of India has refused to sign.

Rate of Change of Nuclear Weapons Technology

American nuclear technology evolved rapidly between 1944 and 1950, moving from the primitive Fat Man and Little Boy to more sophisticated, lighter, more powerful, and more efficient designs. Much design effort shifted from fission to thermonuclear weapons after President Truman decided that the United States should proceed to develop a hydrogen bomb, a task which occupied the Los Alamos Laboratory from 1950 through 1952.[2] From 1952 until the early years of the ICBM era [roughly to the development of the first multiple independently targeted reentry vehicles (MIRVs) in the late 1960's], new concepts in both fission primary and fusion secondary design were developed rapidly. However, after the introduction of the principal families of weapons in the modern stockpile (approximately the mid 1970's), the rate of design innovations and truly new concepts slowed as nuclear weapon technology became a mature science. It is believed that other nations' experiences have been roughly similar, although the United States probably has the greatest breadth of experience with innovative designs simply because of the more than 1,100 nuclear detonations it has conducted. The number of useful variations on the themes of primary and secondary design is finite, and designers' final choices are frequently constrained by considerations of weapon size, weight, safety, and the availability of special materials.

U.S. nuclear weapons technology is mature and might not have shown many more qualitative advances over the long haul, even absent a test ban. The same is roughly true for Russia, the UK, and possibly for France.

The design of the nuclear device for a specific nuclear weapon is constrained by several factors. The most important of these are the weight the delivery vehicle can carry plus the size of the space available in which to carry the weapon (e.g., the diameter and length of a nosecone or the length and width of a bomb bay). The required yield of the device is established by the target vulnerability. The possible yield is set by the state of nuclear weapon technology and by the availability of special materials. Finally, the choices of specific design details of the device are determined by the taste of its designers, who will be influenced by their experience and the traditions of their organization.

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[1] When the Manhattan Project began far less than a microgram of plutonium had been made throughout the world, and plutonium chemistry could only be guessed at; the numbers of neutrons released on average in ^{235}U and ^{239}Pu fissions were unknown; the fission cross sections (probabilities that an interaction would occur) were equally unknown, as was the neutron absorption cross section of carbon.

[2] The "Mike" test of Operation Ivy, 1 November, 1952, was the first explosion of a true two-stage thermonuclear device. The "George" shot of Operation Greenhouse (May 9, 1951) confirmed for the first time that a fission device could produce the conditions needed to ignite a thermonuclear reaction.

A Caution on the Use of "Authoritative Control Documents and Tables"

Authoritative lists of export-controlled and militarily critical equipment and materials used in the construction and testing of nuclear weapons necessarily have flaws:

- They consistently lag the technology actually available on the world market. Some items at the threshold of the Nuclear Suppliers Group (NSG) Dual-Use List restrictions may not be available as newly manufactured equipment. On the other hand, it would be improper to place the thresholds *higher*, since equipment much less sophisticated than can be bought today was used with great success in both the United States and the Former Soviet Union.
- Second, these limits do not always define the limits at which the technologies have utility to proliferators.

OVERVIEW

This section will discuss the fundamentals of nuclear weapons design, engineering, and production including the production of special nuclear materials (uranium enriched to greater than 20 percent in the isotope ^{235}U, ^{233}U, and for plutonium). It will also look at the other technologies including production of uranium and plutonium metal; manufacturing; nuclear testing; lithium production; safing, arming, fuzing, and firing (SAFF); radiological weapons; the custody, transport, and control of nuclear weapons; heavy water production; and tritium production.

It is possible to capture *schematically* the progress in nuclear weapons technology and the technologies which support nuclear weapons in the following graph (Figure 5.0-1). The X axis is time, beginning in 1942 when the Manhattan Project was fully activated. The top two lines show the development of electronics and the introduction of devices which affected the design of the non-nuclear components of the weapons. The second pair of lines shows the progress made in preparing special nuclear materials, with the processes above the dashed line referring to methods of enriching uranium and those below the dashed line referring to plutonium production and the materials for fusion weapons.

The oddly shaped heavy curve shows the *rate* at which U.S. nuclear weapons scientists made new discoveries and progress. The distance between the two curves represents the rate of progress, while the area between the curves from 1942 to any arbitrary date gives an estimate of the total knowledge acquired. The rate of progress drops almost to zero on 30 October 1958, when the Eisenhower-Khrushchev Moratorium on nuclear testing went into effect.

Superimposed on the heavy curve are events of historic importance: the first testing and use of nuclear weapons, the first Soviet test along with the dates when other nations joined the nuclear club, the evolution of hydrogen weapons and boosting, the introduction of powerful computers, computerized numerically controlled (CNC) tools, the year when the IBM PC made its appearance on desktops, tailored effects weapons such as the x-ray laser, and the end of nuclear testing. Specific U.S. achievements are also noted in the area bounded by the heavy curves. A similar chart could be made for the progress of every other nuclear weapon state, acknowledged or unacknowledged, if the information were available.

This chart illustrates several trends which are important to an understanding of the process by which a proliferator might gain a nuclear capability. At the same time, it indicates the few choke points where the control of technologies might be helpful. The top line shows advances over time in electronic components. The second and third lines show advances over time in the production of SNM. All five acknowledged nuclear weapons states (NWSs) are shown to have tested their first devices before computer numerically controlled machine tools and four- or five-axis machine tools were generally available.

Modern computers incorporating large amounts of solid-state fast memory did not make their appearance until the early 1970's, and even fast *transistorized* (not integrated circuit chips) computers were not generally available until the early 1960's. By the time such computers became available to the American design laboratories, most of the fundamental families of modern nuclear weapons had already been conceived, designed, and tested. Computation brought a new ability to design for nuclear weapon safety and a new capability to execute complex designs which might reduce the amount of fissile materials and other scarce fuels used in the weapons.

Finally, an inspection of the chart indicates very rapid qualitative progress in the early years of the U.S. nuclear effort, with new design types and wholly new weapon families emerging in rapid succession. In part, this occurred because the creative scientists were given permission to try almost any idea which sounded good, and in part it is because of the rapid interplay between conceptual advances and all-up nuclear tests. During the 1958–61 moratorium on testing the rate at which new ideas were introduced slowed, although a great deal of progress towards ensuring weapon safety was made. By the early 1970's the era of new concepts in nuclear weapon design had virtually come to an end, although qualitative improvements in yield, weight, and the efficient use of special materials were made.

Similar statements, differing in detail but not in outline, could probably be made for each of the five NWSs and any threshold states with active weapons projects. However, it is unlikely that the evolution of nuclear designs, means of assembly, and initiation followed the same course in any two countries.

More detailed descriptions of the various components of a nuclear weapons program will be found in the numbered sections below.

Production of Fuel for Nuclear Weapons

Ordinary uranium contains only 0.72 percent ^{235}U, the highly fissionable isotope, the rest of the material being largely the much less fissionable isotope ^{238}U (which cannot sustain a chain reaction). The fissile material must be separated from the rest of the uranium by a process known as enrichment. Several enrichment techniques have been used. The earliest successful methods were electromagnetic isotope separation (EMIS), in which large magnets are used to separate ions of the two isotopes,[3] and gaseous diffusion, in which the gas uranium hexafluoride (UF_6) is passed through a porous barrier material; the lighter molecules containing ^{235}U penetrate the barrier slightly more rapidly, and with enough stages significant separation can be accomplished. Both gaseous diffusion and EMIS require enormous amounts of electricity. More efficient methods have been developed.

The third method in widespread use is the gas centrifuge [Urenco (Netherlands, Germany, UK), Russia, Japan] in which UF_6 gas is whirled inside complex rotor assemblies and centrifugal force pushes molecules containing the heavier isotope to the outside. Again, many stages are needed to produce the highly enriched uranium needed for a weapon, but centrifuge enrichment requires much less electricity than either of the older technologies.

Atomic and molecular laser isotope separation (LIS) techniques use lasers to selectively excite atoms or molecules containing one isotope of uranium so that they can be preferentially extracted. Although LIS appears promising, the technology has proven to be extremely difficult to master and may be beyond the reach of even technically advanced states.

The South African nuclear program used an aerodynamic separation technique in an indigenously designed and built device called a vortex tube. In the vortex a mixture of UF_6 gas and hydrogen is injected tangentially into a tube, which tapers to a small exit aperture at one or both ends; centrifugal force provides the separation. The Becker Nozzle Process, also an aerodynamic separation technique, was developed in Germany. The Becker process is not in common use; the vortex tube was used in South Africa for producing reactor fuel with a ^{235}U content of around 3–5 percent in addition to making 80–93 percent ^{235}U for the weapons program. Aerodynamic enrichment processes require large amounts of electricity and are not generally considered economically competitive; even the South African enrichment plant has apparently been closed.

Uranium enriched to 20 percent or more ^{235}U is called highly enriched (HEU). Uranium enriched above the natural ^{235}U abundance but to less than 20 percent is called low-enriched (LEU).

Plutonium is produced in nuclear reactors by bombarding "fertile" ^{238}U with neutrons from the chain reaction. Since each fission produces only slightly more than two neutrons, on average, the neutron "economy" must be managed carefully, which requires good instrumentation and an understanding of reactor physics, to have enough neutrons to irradiate useful quantities of ^{238}U.[4] A typical production reactor produces about 0.8 atoms of plutonium for each nucleus of ^{235}U which fissions. A good rule of thumb is that 1 gram of plutonium is produced for each megawatt (thermal)-day of reactor operation. Light-water power reactors make fewer plutonium nuclei per uranium fission than graphite-moderated production reactors.

The plutonium must be extracted chemically in a *reprocessing plant.* Reprocessing is a complicated process involving the handling of highly radioactive materials and must be done by robots or by humans using remote manipulating equipment. At some stages of the process simple glove boxes with lead glass windows suffice. Reprocessing is intrinsically dangerous because of the use of hot acids in which plutonium and intensely radioactive short-lived fission products are dissolved. Some observers have, however, suggested that the safety measures could be relaxed to the extent that the proliferator deems his technicians to be "expendable." Disposal of the high-level waste from reprocessing is difficult. Any reprocessing facility requires large quantities of concrete for shielding and will vent radioactive gases (^{131}I, for example) to the atmosphere.

Tritium for thermonuclear weapons is usually produced in a nuclear reactor similar or identical to that used to make plutonium. Neutrons from the reactor are used to irradiate lithium metal, and the nuclear reaction produces a triton.

Lithium-6, an isotope of lithium, is used in some thermonuclear weapons. When struck by a neutron, ^{6}Li (actually the compound ^{7}Li nucleus formed in the collision) frequently disintegrates into tritium and ^{4}He. Thus, the tritium needed for the secondary of a fusion weapon can be formed in place within the nuclear device and need not be transported from the factory to the target as heavy hydrogen.

The lighter isotope, ^{6}Li, is separated from the principal isotope, ^{7}Li, in a process which exploits the fact that the lighter isotope more readily forms an amalgam with mercury than does the heavier one. This process is called "COLEX" (Column Exchange). Lithium hydroxide is dissolved in water, and the aqueous solution is brought into contact with the mercury. Lithium-6 ions in the solution tend to migrate into the mercury, while ^{7}Li in the amalgam tends to migrate back into the aqueous hydroxide solution. The reaction is generally carried out in large columnar processors. While other processes for separating the lithium isotopes have been tried, the United States found COLEX to be the most successful. It is believed that the Soviet Union chose the same process.

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[3] The first large-scale uranium enrichment facility, the Y-12 plant at Oak Ridge, Tennessee, used EMIS in devices called "calutrons." The process was abandoned in the United States because of its high consumption of electricity, but was adopted by the Iraqis because of its relative simplicity and their ability to procure the magnet material without encountering technology transfer obstacles.

[4] Note, however, that during the Manhattan Project the United States was able to scale an operating 250 **watt** reactor to a 250 **megawatt** production reactor. Although the instrumentation of the day was far less sophisticated than that in use today, the scientists working the problem were exceptional.

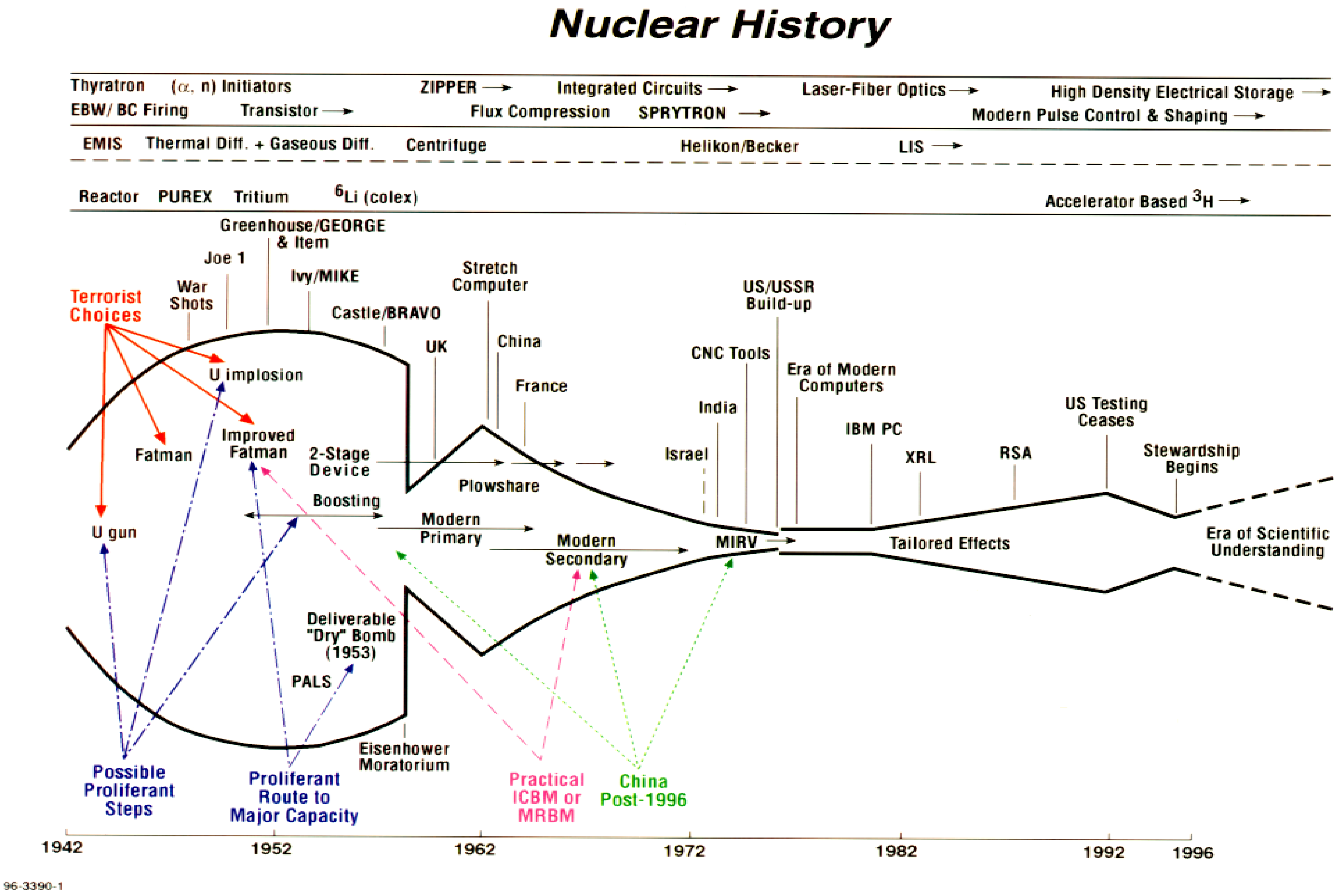

Figure 5.0-1. Nuclear History

RATIONALE

An ordinary "atomic" bomb of the kinds used in World War II uses the process of nuclear *fission* to release the binding energy in certain nuclei. The energy release is rapid and, because of the large amounts of energy locked in nuclei, violent. The principal materials used for fission weapons are ^{235}U and ^{239}Pu, which are termed *fissile* because they can be split into two roughly equal-mass fragments when struck by a neutron of even low energies. When a large enough mass of either material is assembled, a *self-sustaining chain reaction* results after the first fission is produced. Such a mass is termed *critical*. If any more material is added to a critical mass a condition of *supercriticality* results. The chain reaction in a supercritical mass increases rapidly in intensity until the heat generated by the nuclear reactions causes the mass to expand so greatly that the assembly is no longer critical.

Fission weapons require a system to assemble a supercritical mass from a subcritical mass in a very short time. Two classic assembly systems have been used, gun and implosion. In the simpler gun-type device, two subcritical masses are brought together by using a mechanism similar to an artillery gun to shoot one mass (the projectile) at the other mass (the target). The Hiroshima weapon was gun-assembled and used ^{235}U as a fuel. Gun-assembled weapons using highly enriched uranium are considered the easiest of all nuclear devices to construct and the most foolproof. Manhattan Project scientists were so confident in the performance of the "Little Boy" uranium bomb that the device was not even tested before it was dropped on Hiroshima.

Because of the short time interval between spontaneous neutron emissions (and, therefore, the large number of background neutrons) found in plutonium because of the decay by spontaneous fission of the isotope ^{240}Pu, Manhattan Project scientists devised the *implosion* method of assembly in which high explosives are arranged to form an imploding shock wave which compresses the fissile material to supercriticality.[5] Implosion systems can be built using either ^{239}Pu or ^{235}U, but the gun assembly only works for uranium. Implosion weapons are more difficult to build than gun weapons, but they are also more efficient, requiring less SNM and producing larger yields.

The six bombs built by the Republic of South Africa were gun-assembled and used uranium enriched to between 80 percent and 93 percent in the isotope ^{235}U; Iraq attempted to build an implosion bomb, also using ^{235}U. In contrast, North Korea chose to use ^{239}Pu produced in a nuclear reactor.

A more powerful but more complex weapon uses the *fusion* of heavy isotopes of hydrogen, deuterium, and tritium to release large numbers of neutrons when the *fusile* (sometimes termed "fusionable") material is compressed by the energy released by a fission device called a *primary*. The fusion part of the weapon is called a *secondary*.

In the words of Sidney D. Drell, the physics packages of "nuclear weapons are sophisticated, but not complicated." The remainder of the weapon may be quite complicated indeed.

Storage and Use Control Issues Regarding Nuclear Weapons

The United States has developed a complex and sophisticated system to ensure that nuclear weapons are used only on the orders of the President or his delegated representative. Some elements of the custodial system are the "two-man rule," which requires that no person be left alone with a weapon; permissive action links (PALs), coded locks which prevent detonation of the weapon unless the correct combination is entered; and careful psychological testing of personnel charged with the custody or eventual use of nuclear weapons. In addition, U.S. nuclear weapons must be certified as "one point safe," which means that there is less than a one-in-a-million chance of a nuclear yield greater than the equivalent of four pounds of TNT resulting from an accident in which the high explosive in the device is detonated at the point *most* likely to cause a nuclear yield.

It is believed to be unlikely that a new proliferator would insist upon one point safety as an inherent part of pit design; the United States did not until the late 1950's, relying instead upon other means to prevent detonation (e.g., a component of Little Boy was not inserted until after the Enola Gay had departed Tinian for Hiroshima). It is also unlikely that a new actor in the nuclear world would insist upon fitting PALs to every (or to any) nuclear weapon; the United States did not equip its submarine-launched strategic ballistic missiles with PALs until, at the earliest, 1996, and the very first U.S. PALs were not introduced until the mid-1950's, when American weapons were stationed at foreign bases where the possibility of theft or misuse was thought to be real.

Nonetheless, any possessor of nuclear weapons will take care that they are not used by unauthorized personnel and can be employed on the orders of duly constituted authority. Even—or, perhaps, especially—a dictator such as Saddam Hussein will insist upon a fairly sophisticated nuclear chain of command, if only to ensure that his weapons cannot be used by a revolutionary movement. It is also quite likely that even the newest proliferator would handle his weapons with care and seek to build some kind of safety devices and a reliable SAFF system into the units.

Developing Technologies

On the basis of experience, *one might expect to observe significant nuclear planning activity and the evolution of situation-specific nuclear doctrine* on the part of a new proliferator who would have to allocate carefully the "family jewels." The development of a nuclear strategy might be visible in the professional military literature of the proliferator.

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[5] The critical mass of compressed fissile material decreases as the inverse square of the density achieved.

Use Control and Weapons Delivery

Because of the high cost and high value of a new entrant's first few nuclear weapons, it is likely that the proliferant state would take great care to ensure that the crews selected to deliver the special ordnance would be highly proficient in the use of their weapon systems. This requires extensive training in the specialized procedures required to place nuclear weapons reliably on target.

Nuclear weapons training may be both distinctive and visible, particularly when it involves those parts of the stockpile-to-target sequence which are explicitly nuclear. Some observers believe, however, that such training will be difficult to observe and identify.

Expected Rates of Progress for New Proliferants

New proliferants with First-World technological bases can probably construct their first nuclear weapons 3 to 5 years after making a political decision to do so, even including constructing an infrastructure to make special nuclear materials, assuming that finances and resources are available.[6] The first intellectual steps towards reducing the size and mass of fission weapons should not take more than another 1 to 2 years to master. Boosting and multistage weapons may require anywhere from 3 to 10 more years to develop in the absence of yield testing, and some nations may still fail to succeed. China, however, progressed from a very simple fission design to a two-stage weapon by its fifth full-scale test—but one of the intervening tests was an end-to-end firing of a ballistic missile with a live nuclear warhead in its nosecone.

Radiological Weapons

Radioactive isotopes suitable for use as weapons include ^{137}Cs, ^{60}Co, ^{131}I, and other short-lived, relatively easy-to-produce fission products. The most readily available source for the materials of radiological weapons is spent fuel from nuclear reactors; indeed, the spent fuel rods themselves are sufficiently "hot" that they can be used essentially directly, although chopping or pulverization would be useful. Medical isotopes are another readily available source of radioactive material in quantities suitable for spreading terror.

Proliferation Implication Assessment

Many of the items on which the greatest control efforts have focused, at least in the public's perception—computers, switch tubes, capacitors—are either not controllable or, at a controllable level, are far more capable than what is required to design and build a weapon.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Five nations, the **United States, Russia, the United Kingdom, France,** and **China** are nuclear weapon states according to the definition in the Non-Proliferation Treaty (countries that tested a nuclear explosive device before 1 January 1967). All five possess all technologies needed to build modern compact nuclear weapons and all have produced both high-enriched uranium and weapons-grade plutonium.

India detonated a nuclear device using plutonium implosion in 1974. India has held no announced tests since then, although they have on occasion taken steps which would imply that a test is imminent. India does not enrich uranium. It has heavy-water moderated reactors, not all under international safeguards.

Pakistan has an operating uranium enrichment plant. Senior Pakistani officials have alluded to possession of a small nuclear stockpile.

South Africa constructed six simple gun-assembled uranium bombs but dismantled them and signed the Non-Proliferation Treaty as a non-weapons state. The HEU for these bombs was obtained from an aerodynamic isotope separation technique developed indigenously. South Africa has shut down its aerodynamic enrichment facilities, but is developing a molecular LIS (MLIS) process for producing LEU for commercial nuclear power reactors.

Israel is believed by some to possess nuclear weapons. It operates one unsafeguarded nuclear reactor at Dimona and presumably is capable of reprocessing spent fuel to extract plutonium. It is a technically advanced state and probably has all of the electronics needed to build and test nuclear weapons. Its elite air force may be nuclear trained.

Iraq had a flourishing nuclear weapons and civilian nuclear program until the 1991 Gulf War. It was able to enrich uranium using EMIS and was pursuing centrifuge enrichment as well. It anticipated constructing implosion weapons using HEU as the fuel.

Iran has many components of a nuclear weapons program in place and has been attempting to purchase turnkey nuclear reactors on the world market.

North Korea built and operated CO_2-cooled, graphite-moderated reactors and had built and operated a reprocessing facility before agreeing to allow the United States and South Korea to replace its gas-graphite "power" reactor with a light-water moderated unit less suited to the production of weapons-grade plutonium. The amount of plutonium it currently has in hand outside of that contained in its spent fuel storage facility is not well known by outsiders.

Sweden came very close to building nuclear weapons in the late 1960's and early 1970's. Many experts judge its weapon designs as sophisticated and efficient; the

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[6] Nations such as Germany and Japan, which have advanced civilian nuclear power programs and stocks of plutonium (either separated or still contained in spent fuel) may be able to produce their first weapons in even less time. Countries which have a nuclear infrastructure and which have expended considerable effort in learning how to build nuclear weapons while still not crossing the nuclear threshold (e.g., Sweden) also are in a favorable position to go nuclear in short order.

country has the industrial base to “go nuclear” in a short period and has adequate amounts of plutonium contained in stored spent reactor fuel.

Switzerland had a nuclear weapons program until the early 1970’s. Both Sweden and Switzerland are highly industrialized Western nations with broad access to a full spectrum of modern technology, whether developed indigenously or imported. Both operate nuclear reactors.

Germany has developed an indigenous uranium enrichment process (not believed to be currently in use) and has adequate stocks of spent fuel from which to prepare nuclear weapons.

Japan is as far advanced as Germany and also operates a reprocessing plant. Either nation could construct nuclear weapons in a short time.

Many other states have capabilities in some or all of the relevant technologies and could assemble a nuclear weapons program in a short time.

Country	Sec 5.1 Enrichment Feedstocks Production	Sec 5.2 Uranium Enrichment Processes	Sec 5.3 Nuclear Fission Reactors	Sec 5.4 Plutonium Extraction (Reprocessing)	Sec 5.5 Lithium Production	Sec 5.6 Nuclear Weapons Design and Development	Sec 5.7 Safing, Arming, Fuzing, and Firing	Sec 5.8 Radiological Weapons	Sec 5.9 Manufacturing of Nuclear Components	Sec 5.10 Nuclear Weapons Development Testing	Sec 5.11 Nuclear Weapons Custody, Transport, and Control	Sec 5.12 Heavy Water Production	Sec 5.13 Tritium Production
Argentina	♦		♦♦			♦♦				♦	♦♦	♦♦♦♦	♦♦
Austria			♦				♦			♦	♦		♦♦
Belgium			♦♦♦♦				♦			♦			♦♦
Brazil	♦♦		♦♦			♦♦				♦	♦♦	♦	♦♦
Canada	♦♦♦		♦♦♦♦			♦♦♦	♦			♦	♦	♦♦♦♦	♦♦♦♦
China	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦♦	♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Czech Republic			♦♦										
France	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦		♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
Germany		♦♦♦	♦♦♦♦			♦♦♦	♦♦♦		♦♦♦♦		♦♦	♦♦♦	♦♦♦
India	♦♦		♦♦♦♦			♦♦♦♦	♦♦		♦♦	♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
Iran		♦	♦♦			♦♦				♦	♦♦		
Iraq	♦♦	♦	♦♦♦	♦		♦♦♦	♦		♦♦	♦	♦♦		
Italy				♦♦♦			♦♦		♦♦			♦♦	♦♦
Japan		♦♦	♦♦♦♦	♦♦♦		♦♦♦♦	♦♦♦		♦♦♦♦		♦♦	♦♦	♦♦
Netherlands		♦♦♦	♦♦			♦♦	♦♦					♦♦	♦
North Korea	♦♦		♦♦	♦		♦♦♦				♦♦	♦♦		
Pakistan	♦♦	♦♦♦	♦♦			♦♦♦♦	♦		♦♦	♦♦	♦♦	♦	
Russia	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦		♦♦♦♦	♦♦♦♦	♦♦♦	♦♦♦♦	♦♦♦♦
South Africa	♦♦♦♦	♦♦	♦♦♦			♦♦♦	♦♦		♦	♦♦♦♦	♦♦	♦♦	♦♦
South Korea			♦♦♦♦			♦♦♦	♦					♦	♦
Sweden			♦♦♦♦			♦♦♦			♦♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦
Switzerland			♦♦♦♦			♦♦♦			♦♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦
Taiwan			♦♦♦			♦♦♦				♦♦♦		♦	♦
Ukraine			♦♦♦			♦				♦	♦♦	♦	
United Kingdom	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦		♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦		♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 5.0-2. Nuclear Weapons Foreign Technology Assessment Summary

SECTION 5.1—ENRICHMENT FEEDSTOCKS PRODUCTION

OVERVIEW

This subsection covers technologies utilized in the conversion of uranium ore concentrates to highly purified uranium hexafluoride (UF_6) and uranium tetrachloride (UCl_4) for subsequent use as feedstock in a uranium-enrichment process. Gaseous UF_6 is used as the feed in the gas centrifuge and gaseous diffusion processes, and UCl_4 is used as feed in the electromagnetic isotope separation (EMIS) process.

Uranium ore concentrates, also known as yellowcake, typically contain 60–80 percent uranium and up to 20 percent extraneous impurities. There are two commercial processes used to produce purified UF_6 from yellowcake. The primary difference between the two processes—solvent extraction/fluorination ("wet process") and fluorination/fractionation ("dry process")—is whether the uranium is purified by solvent extraction before conversion to UF_6 or by fractional distillation of the UF_6 after conversion.

In the *wet process*, yellowcake is dissolved in nitric acid (HNO_3), and the insoluble residue is removed by filtration or centrifugation. Uranium is separated from the acid solution with liquid-liquid extraction, the uranyl nitrate product is decomposed to uranium trioxide (UO_3) via thermal denitration, and the trioxide is reduced to uranium dioxide (UO_2) with hydrogen or cracked ammonia (NH_3). In most cases, the standard Purex process, using tri-n-butyl phosphate (TBP) in a hydrocarbon diluent, separates uranium from its impurities in the extraction step.

In the *dry process*, the conversion and purification steps occur throughout the process. If the yellowcake was produced by the alkali-leach process (yields $Na_2U_2O_7$), the sodium must be removed from the material by partial digestion in sulfuric acid followed by ammonia precipitation of ammonium diuranate [$(NH_4)_2U_2O_7$]. The ammonium-containing uranium salt is decomposed to UO_3 by heating, and this oxide is reduced to UO_2 with hydrogen or cracked NH_3.

The remaining steps used to produce UF_6 for both processes are similar in that the UO_2 is converted to UF_4 by hydrofluorination (using hydrogen fluoride gas—HF). The UF_4 (impure in the dry process) is converted to UF_6 using electrolytically generated fluorine gas (F_2). In the dry process, the UF_6 is purified in a two-stage distillation step. Direct fluorination of UO_3 to UF_6 has been used, but this procedure is more amenable to relatively small capacity plants.

Highlights

- UF_6 and UCl_4 are the principal compounds used as inputs to uranium enrichment processes.
- Manufacture of these feedstocks is straightforward industrial chemistry.
- These processes are unclassified and widely known.

The EMIS uranium-enrichment process uses UCl_4 for its feed material. Uranium tetrachloride is produced by the reaction of carbon tetrachloride (CCl_4) with pure UO_2 at 700 °F.

RATIONALE

A country choosing to join the nuclear weapons community must acquire the necessary weapons (fissile) material (^{235}U or ^{239}Pu). A state selecting uranium for its weapons must obtain a supply of uranium ore and construct an enrichment plant because the ^{235}U content in natural uranium is over two orders of magnitude lower than that found in weapons grade uranium (>90 percent ^{235}U). Nearly all uranium enrichment plants utilize UF_6 as their feed. A country may select the EMIS process, which uses UCl_4 as its feed material, for enriching uranium.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

The processes outlined above are unclassified and have been described extensively in the literature on the nuclear fuel cycle. Many countries around the world have extracted uranium from its ores or from yellowcake. The processes for preparing the feedstocks are basic industrial chemistry.

The enabling technologies are those which use HF, NH_3, F_2, CCL_4, and precursor uranium compounds to prepare UF_6 and UCL_4.

Table 5.1-1. Enrichment Feedstocks Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Purification of yellowcake (wet process)	Knowledge of liquid-liquid extraction systems Experience in using HNO_3	NTL 8F; NRC J	Yellowcake Nitric acid (HNO_3) tri-n-butyl phosphate (TBP) Refined kerosene	Filters; centrifuges; pulse columns; concentration/thermal denitration systems; tanks resistant to HNO_3	Distribution coefficients for many elements Aqueous solubility for many compounds
Purification of yellowcake (dry process: produces impure UO_2)	Ability to handle H_2 at elevated temperature	NTL 8F; NRC J	Yellowcake (should not contain high concentrations of sodium or magnesium) H_2SO_4 See citations below	Furnace; air filtration equipment; fluidized bed; temperature control; heat exchangers	None identified
UO_2 preparation	Ability to handle H_2 at elevated temperature	NTL 8F; NRC J	H_2 NH_3	Moving bed reactor; rotary kiln; air filtration equipment; fluidized bed; temperature control system	None identified
UF_4 preparation	Ability to manage HF at elevated temperature Ability to provide a dry environment	NTL 8F; NRC J	HF	Stirred fluidized bed reactors; rotary kiln; moving bed/screw reactor; air cleaning equipment (filters, scrubbers); fluoride-resistant equipment	None identified
UF_6 preparation (used in gaseous diffusion and gas centrifuge enrichment processes)	Capability to control quantities of fluorine gas. Ability to operate a flame tower with F_2. Experience in removing H_2 from electrolytic cells (F_2 production) . Experience in operating in an anhydrous environment	NTL 8F; NRC J	F_2 HF KF • 2HF	Flame tower reactor; fluidized bed reactor; condensers (cold traps); electrolytic cells (for F_2 production); high-amperage, low-voltage supply (for F_2 production); air-cleaning equipment; F_2-resistant equipment (Monel); fluoride-resistant equipment; UF_6 storage	Careful temperature control is required for fluorination
UCl_4 preparation (used in EMIS enrichment process)	Water-free environment must be provided	NTL 8F; NRC H	CCl_4	Stirred fluidized bed reactors; rotary kiln; moving bed/screw reactor; air-cleaning equipment (filters, scrubbers)	Reasonable control of temperature

Table 5.1-2. Enrichment Feedstocks Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Purification of yellowcake (wet process)	HNO_3 solutions are relatively hazardous and require moderate care in handling	None identified	Direct fluorination of UO_3
Purification of yellowcake (dry process produces impure UO_2)	H_2 presents an explosive hazard	None identified	Direct fluorination of UO_3
UO_2 preparation	H_2 presents an explosive hazard	None identified	Step may be bypassed using direct fluorination
UF_4 preparation	Inappropriate use of HF can present health problems. Improper operation of tower reactors may cause plugging (caking).	None identified	Step may be bypassed using direct fluorination
UF_6 preparation (used in gaseous diffusion and gas centrifuge enrichment processes)	Producing F_2 is not an easy task. Flame towers can be difficult to operate. Moisture-sensitive material difficult to handle.	UF_6 product is feed to most U enrichment processes	None identified
UCl_4 preparation (used in EMIS enrichment process)	Moisture-sensitive material difficult to handle	UCl_4 product is feed to the EMIS enrichment process	None identified

SECTION 5.2—URANIUM ENRICHMENT PROCESSES

OVERVIEW

It is generally recognized that the acquisition of fissile material in sufficient quantity is the most formidable obstacle to the production of nuclear weapons. Fissile material production consumes the vast majority of the technical, industrial, and financial resources required to produce nuclear weapons. For example, production of fissile materials—highly enriched uranium (HEU) and plutonium—accounted for more than 80 percent of the $1.9 billion (1945 dollars) spent on the Manhattan Project.[7]

Fissile materials can produce energy by nuclear fission, either in nuclear reactors or in nuclear weapons. The principal fissile materials of interest are ^{235}U, ^{233}U, and ^{239}Pu. Uranium-235 is of particular interest because it is the only fissile material that occurs in nature in significant quantity, and it can be used to construct a nuclear explosive device if a sufficient quantity can be acquired. In a typical sample of natural uranium, only 0.72 percent of the atoms are ^{235}U atoms, and it can be assumed that all of the remaining atoms are ^{238}U atoms.[8] Higher concentrations of ^{235}U are required for many applications, and the use of uranium isotope separation processes to increase the assay of ^{235}U above its natural value of 0.72 percent is called uranium enrichment.

While low-enriched uranium (LEU) could technically mean uranium with an assay anywhere between slightly greater than natural (0.72 percent) and 20 percent ^{235}U, it most commonly is used to denote uranium with an assay suitable for use in a light-water nuclear reactor (i.e., an assay of <5 percent). Similarly, the term "highly enriched" uranium (HEU) could be used to describe uranium with an assay >20 percent, but it is commonly used to refer to uranium enriched to 90 percent ^{235}U or higher (i.e., weapons-grade uranium). The term "oralloy" was used during World War II as a contraction of "Oak Ridge alloy," and it denoted uranium enriched to 93.5 percent ^{235}U.

When plutonium is produced in a nuclear reactor, inevitably some ^{240}Pu (as well as heavier plutonium isotopes, including ^{241}Pu and ^{242}Pu) is produced along with the more desirable ^{239}Pu. The heavier isotope is not as readily fissionable, and it also decays by spontaneous fission, producing unwanted background neutrons. Thus, nuclear weapon designers prefer to work with plutonium containing less than 7 percent ^{240}Pu. A method for separating plutonium isotopes could be used to remove the heavier isotopes of plutonium (e.g., ^{240}Pu) from reactor-grade plutonium, thus producing nearly pure ^{239}Pu. Uranium isotope separation techniques [e.g., atomic vapor laser isotope separation (AVLIS)] might be applied to this task. However, this would require mastery of production reactor and reprocessing technologies (to produce and extract the plutonium) in addition to isotope enrichment technology (to remove the heavier plutonium isotopes). In practice, it is simpler to alter the reactor refueling cycle to reduce the fraction of plutonium which is ^{240}Pu.

Highlights

- The acquisition of fissile material in sufficient quantity is the most formidable obstacle to the production of nuclear weapons.
- Gas centrifuges are today the technology of first choice for enriching uranium, based on process economics and minimum consumption of electricity.
- Technologies considered obsolete for commercial uranium enrichment, such as electromagnetic isotope separation (EMIS), can be employed by a proliferant state at some added cost in electric power and labor requirements.
- Aerodynamic separation processes developed in South Africa and Germany have proven satisfactory for a limited number of nuclear weapons, despite their high cost to operate.
- Laser isotope separation (LIS) techniques are based on advanced technologies and represent potential uranium enrichment processes of the future.

Manhattan Project scientists and engineers explored several uranium-enrichment technologies, and production plants employing three uranium-enrichment processes—electromagnetic isotope separation (EMIS), liquid thermal diffusion, and gaseous diffusion—were constructed at Oak Ridge, Tennessee, during the period from 1943 to 1945. Centrifugation was tried, but the technology needed to spin a rotor at an appropriate speed was not then practical on an industrial scale. The aerodynamic separation processes developed in Germany and South Africa did not exist during World War II;

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[7] Richard G. Hewlett and Oscar E. Anderson, *The New World: A History of the United States Atomic Energy Commission, Volume 1, 1939/1946*, University of California Press, a 1990 edition of a book originally published by Pennsylvania State University Press in 1962.

[8] Natural uranium typically has a composition of 0.0055 atom % ^{234}U, 0.7205 atom % ^{235}U, and 99.274 atom % ^{238}U. For most purposes, the tiny fraction of ^{234}U can be neglected.

neither, of course did laser isotope separation or plasma separation. The World War II Japanese nuclear program made some attempts to find a purely chemical process.

RATIONALE

Methods of Separation

Electromagnetic Isotope Separation

The EMIS process is based on the same physical principle as that of a simple mass spectrometer—that a charged particle will follow a circular trajectory when passing through a uniform magnetic field. Two ions with the same kinetic energy and electrical charge, but different masses (i.e., $^{235}U^+$ and $^{238}U^+$), will have different trajectories, with the heavier $^{238}U^+$ ion having the larger diameter. The different diameters of the trajectories of the two uranium ions allow for the separation and collection of the material in receivers or "collector pockets." EMIS is a batch process that can produce weapons-grade material from natural uranium in only two stages. However, hundreds to thousands of units would be required to produce large quantities of HEU because of the process's relatively low product collection rate and the long cycle time required to recover material between runs.

In the uranium EMIS process, uranium ions are generated within an evacuated enclosure (called a "tank") that is located in a strong magnetic field. For the EMIS ion source, solid uranium tetrachloride (UCl_4) is electrically heated to produce UCl_4 vapor. The UCl_4 molecules are bombarded with electrons, producing U^+ ions. The ions are accelerated by an electrical potential to high speed and follow a circular trajectory in the plane perpendicular to the magnetic field. In the U.S. EMIS separators, the ion beam traverses a 180-deg arc before the ions pass through slit apertures at the collector. A major problem with the EMIS process is that less than half of the UCl_4 feed is typically converted to the desired U^+ ions, and less than half of the desired U^+ ions are actually collected. Recovery of unused material deposited on the interior surfaces of the tanks is a laborious, time-consuming process that reduces the effective output of an EMIS facility and requires a large material recycle operation.

In the U.S. EMIS program, production of weapons-grade uranium took place in two enrichment stages, referred to as the α and β stages. The first (α) stage used natural or slightly enriched uranium as feed and enriched it to 12–20% ^{235}U. The second (β) stage used the product of the (α) stage as feed and further enriched it to weapons-grade uranium. To allow more efficient use of magnets and floor space, the individual stages were arranged in continuous oval or rectangular arrays (called "racetracks" or, simply, "tracks") with separator tanks alternated with electromagnetic units. The U.S. EMIS separators are referred to as "calutrons" because the development work was carried out at the University of California (Berkeley) during the early 1940's using cyclotrons.

Although most applications of the EMIS process have been applied to the commercial production of both stable and radioactive isotopes, all five recognized weapons states have tested or used the EMIS process for uranium enrichment. Even with the problems associated with using the process, an EMIS facility could be attractive for a country desiring a limited weapons-grade uranium enrichment program. The process might be especially appealing as a method for further enriching partially enriched material. It has been well documented that EMIS was the principal process pursued by the Iraqi uranium enrichment program. This occurred at a time when EMIS had been discarded and largely forgotten as a method for uranium enrichment because it is both energy intensive and labor intensive, and it is not economically competitive with other enrichment technologies.

Thermal Diffusion

Thermal diffusion utilizes the transfer of heat across a thin liquid or gas to accomplish isotope separation. By cooling a vertical film on one side and heating it on the other side, the resultant convection currents will produce an upward flow along the hot surface and a downward flow along the cold surface. Under these conditions, the lighter ^{235}U gas molecules will diffuse toward the hot surface, and the heavier ^{238}U molecules will diffuse toward the cold surface. These two diffusive motions combined with the convection currents will cause the lighter ^{235}U molecules to concentrate at the top of the film and the heavier ^{238}U molecules to concentrate at the bottom of the film.

The thermal-diffusion process is characterized by its simplicity, low capital cost, and high heat consumption. Thermal diffusion in liquid UF_6 was used during World War II to prepare feed material for the EMIS process. A production plant containing 2,100 columns (each approximately 15 meters long) was operated in Oak Ridge for less than 1 year and provided a product assay of less than 1% ^{235}U. Each of these columns consisted of three tubes. Cooling water was circulated between the outer and middle tubes, and the inner tube carried steam. The annular space between the inner and middle tubes was filled with liquid UF_6.

The thermal-diffusion plant in Oak Ridge was dismantled when the much more energy-efficient (by a factor of 140) gaseous-diffusion plant began operation in the 1940's. Today, thermal diffusion remains a practical process to separate isotopes of noble gases (e.g., xenon) and other light isotopes (e.g., carbon) for research purposes.

Gaseous Diffusion

The gaseous-diffusion process has been highly developed and employed to produce both HEU and commercial reactor-grade LEU. The United States first employed gaseous diffusion during WWII and expanded its capacity after the war to produce HEU. Since the late 1960's, the U.S. facilities have been used primarily to produce commercial LEU, with the last remaining HEU capacity being shut down in 1992. China and France currently have operating diffusion plants. Russia's enrichment facilities have been converted from diffusion to centrifuge technology. Britain's diffusion facility was shut down and dismantled.

The gaseous-diffusion process depends on the separation effect arising from molecular effusion (i.e., the flow of gas through small holes). On average, lighter gas molecules travel faster than heavier gas molecules and consequently tend to collide more often with the porous barrier material. Thus, lighter molecules are more likely to enter the barrier pores than are heavier molecules. For UF_6, the difference in velocities between molecules containing ^{235}U and ^{238}U is small (0.4 percent), and, consequently, the amount of separation achieved by a single stage of gaseous diffusion is small. Therefore, many cascade stages are required to achieve even LEU assays.

The production of a sustainable, efficient separating membrane (barrier) is the key to the successful operation of a diffusion plant. To obtain an efficient porous barrier, the holes must be very small (on the order of one-millionth of an inch in diameter) and of uniform size. The porosity of the barrier must be high to obtain high flow rates through the barrier. The barrier must also be able to withstand years of operation while exposed to corrosive UF_6 gas. Typical materials for the barrier are nickel and aluminum oxide.

Diffusion equipment tends to be rather large and consumes significant amounts of energy. The main components of a single gaseous-diffusion stage are (1) a large cylindrical vessel, called a diffuser or converter, that contains the barrier; (2) a compressor used to compress the gas to the pressures needed for flow through the barrier; (3) an electric motor to drive the compressor; (4) a heat exchanger to remove the heat of compression; and (5) piping and valves for stage and interstage connections and process control. The entire system must be essentially leak free, and the compressors require special seals to prevent both out-leakage of UF_6 and in-leakage of air. The chemical corrosiveness of UF_6 requires use of metals such as nickel or aluminum for surfaces exposed to the gas (e.g., piping and compressors). In addition to the stage equipment, auxiliary facilities for a gaseous-diffusion plant could include a large electrical power distribution system, cooling towers to dissipate the waste process heat, a fluorination facility, a steam plant, a barrier production plant, and a plant to produce dry air and nitrogen.

Gaseous diffusion is unlikely to be the preferred technology of a proliferator due to difficulties associated with making and maintaining a suitable barrier, large energy consumption, the requirement for procuring large quantities of specialized stage equipment, large in-process inventory requirements, and long equilibrium times.

Gas Centrifuge

The use of centrifugal fields for isotope separation was first suggested in 1919; but efforts in this direction were unsuccessful until 1934, when J.W. Beams and coworkers at the University of Virginia applied a vacuum ultracentrifuge to the separation of chlorine isotopes. Although abandoned midway through the Manhattan Project, the gas centrifuge uranium-enrichment process has been highly developed and used to produce both HEU and LEU. It is likely to be the preferred technology of the future due to its relatively low-energy consumption, short equilibrium time, and modular design features.

In the gas centrifuge uranium-enrichment process, gaseous UF_6 is fed into a cylindrical rotor that spins at high speed inside an evacuated casing. Because the rotor spins so rapidly, centrifugal force results in the gas occupying only a thin layer next to the rotor wall, with the gas moving at approximately the speed of the wall. Centrifugal force also causes the heavier $^{238}UF_6$ molecules to tend to move closer to the wall than the lighter $^{235}UF_6$ molecules, thus partially separating the uranium isotopes. This separation is increased by a relatively slow axial countercurrent flow of gas within the centrifuge that concentrates enriched gas at one end and depleted gas at the other. This flow can be driven mechanically by scoops and baffles or thermally by heating one of the end caps.

The main subsystems of the centrifuge are (1) rotor and end caps; (2) top and bottom bearing/suspension system; (3) electric motor and power supply (frequency changer); (4) center post, scoops and baffles; (5) vacuum system; and (6) casing. Because of the corrosive nature of UF_6, all components that come in direct contact with UF_6 must be must be fabricated from, or lined with, corrosion-resistant materials.

The separative capacity of a single centrifuge increases with the length of the rotor and the rotor wall speed. Consequently, centrifuges containing long, high-speed rotors are the goal of centrifuge development programs (subject to mechanical constraints).

The primary limitation on rotor wall speed is the strength-to-weight ratio of the rotor material. Suitable rotor materials include alloys of aluminum or titanium, maraging steel, or composites reinforced by certain glass, aramid, or carbon fibers. At present, maraging steel is the most popular rotor material for proliferants. With maraging steel, the maximum rotor wall speed is approximately 500 m/s. Fiber-reinforced composite rotors may achieve even higher speeds; however, the needed composite technology is not within the grasp of many potential proliferants. Another limitation on rotor speed is the lifetime of the bearings at either end of the rotor.

Rotor length is limited by the vibrations a rotor experiences as it spins. The rotors can undergo vibrations similar to those of a guitar string, with characteristic frequencies of vibration. Balancing of rotors to minimize their vibrations is especially critical to avoid early failure of the bearing and suspension systems. Because perfect balancing is not possible, the suspension system must be capable of damping some amount of vibration.

One of the key components of a gas centrifuge enrichment plant is the power supply (frequency converter) for the gas centrifuge machines. The power supply must accept alternating current (ac) input at the 50- or 60-Hz line frequency available from the electric power grid and provide an ac output at a much higher frequency (typically 600 Hz or more). The high-frequency output from the frequency changer is fed to the high-speed gas centrifuge drive motors (the speed of an ac motor is proportional to the frequency of the supplied current). The centrifuge power supplies must operate at high efficiency, provide low harmonic distortion, and provide precise control of the output frequency.

The casing is needed both to maintain a vacuum and to contain the rapidly spinning components in the event of a failure. If the shrapnel from a single centrifuge failure is not contained, a "domino effect" may result and destroy adjacent centrifuges. A single casing may enclose one or several rotors.

Although the separation factors obtainable from a centrifuge are large compared to gaseous diffusion, several cascade stages are still required to produce even LEU material. Furthermore, the throughput of a single centrifuge is usually small, which leads to rather small separative capacities for typical proliferator centrifuges. To be able to produce only one weapon per year, several thousand centrifuges would be required.

The electrical consumption of a gas centrifuge facility is much less than that of a gaseous diffusion plant. Consequently, a centrifuge plant will not have the easily identified electrical and cooling systems typically required by a gaseous diffusion plant.

Aerodynamic Processes

Aerodynamic uranium enrichment processes include the separation nozzle process and the vortex tube separation process. These aerodynamic separation processes depend upon diffusion driven by pressure gradients, as does the gas centrifuge. In effect, aerodynamic processes can be considered as nonrotating centrifuges. Enhancement of the centrifugal forces is achieved by dilution of UF_6 with a carrier gas (i.e., hydrogen or helium). This achieves a much higher flow velocity for the gas than could be obtained using pure UF_6.

The separation nozzle process was developed by E.W. Becker and associates at the Karlsruhe Nuclear Research Center in Germany. In this process, a mixture of gaseous UF_6 and H_2 (or helium) is compressed and then directed along a curved wall at high velocity. The heavier ^{238}U-bearing molecules move preferentially out to the wall relative to those containing ^{235}U. At the end of the deflection, the gas jet is split by a knife edge into a light fraction and a heavy fraction, which are withdrawn separately.

Economic considerations drive process designers to select separation nozzles with physical dimensions as small as manufacturing technology will allow. The curved wall of the nozzle may have a radius of curvature as small as 10 µm (0.0004 in.). Production of these tiny nozzles by such processes as stacking photo-etched metal foils is technically demanding.

A typical stage consists of a vertical cylindrical vessel containing the separation elements, a cross piece for gas distribution, a gas cooler to remove the heat of compression, and a centrifugal compressor driven by a electric motor.

The Uranium Enrichment Corporation of South Africa, Ltd. (UCOR) developed and deployed its own aerodynamic process characterized as an "advanced vortex tube" or "stationary-walled centrifuge" at the so called "Y" plant at Valindaba to produce hundreds of kilograms of HEU. In this process, a mixture of UF_6 and H_2 is compressed and enters a vortex tube tangentially at one end through nozzles or holes at velocities close to the speed of sound. This tangential injection of gas results in a spiral or vortex motion within the tube, and two gas streams are withdrawn at opposite ends of the vortex tube. The spiral swirling flow decays downstream of the feed inlet due to friction at the tube wall. Consequently, the inside diameter of the tube is typically tapered to reduce the decay in the swirling flow velocity. This process is characterized by a separating element with very small stage cut (ratio of product flow to feed flow) of about 1/20 and high process-operating pressures.

Due to the very small cut of the vortex tube stages and the extremely difficult piping requirements that would be necessary based on traditional methods of piping stages together, the South Africans developed a cascade design technique, called *Helikon*. In essence, the Helikon technique permits 20 separation stages to be combined into one large module, and all 20 stages share a common pair of axial-flow compressors. A basic requirement for the success of this method is that the axial-flow compressors successfully transmit parallel streams of different isotopic compositions without significant mixing. A typical Helikon module consists of a large cylindrical steel vessel that houses a separating element assembly, two axial-flow compressors (one mounted on each end), and two water-cooled heat exchangers.

For both of these aerodynamic processes, the high proportion of carrier gas required in relation to UF_6 process gas results in high specific-energy consumption and substantial requirements for removal of waste heat.

Laser Isotope Separation

In the early 1970's, significant work began on the development of laser isotope separation technologies for uranium enrichment. Present systems for enrichment processes using lasers fall into two categories: those in which the process medium is atomic uranium vapor and those in which the process medium is the vapor of a uranium compound. Common nomenclature for such processes include "first category—atomic vapor laser isotope separation (AVLIS or SILVA)" and "second category—molecular laser isotope separation (MLIS or MOLIS)."

The systems, equipment, and components for laser-enrichment plants embrace (a) devices to feed uranium-metal vapor (for selective photoionization) or devices to feed the vapor of a uranium compound (for photo-dissociation or chemical activation); (b) devices to collect enriched and depleted uranium metal as product and tails in the first category and devices to collect dissociated or reacted compounds as product and unaffected material as tails in the second category; (c) process laser systems to selectively excite the ^{235}U species; and (d) feed preparation and product conversion equipment. The complexity of the spectroscopy of uranium atoms and compounds may require incorporation of any number of available laser technologies.

AVLIS

The atomic vapor laser isotope separation (AVLIS) process is based on the fact that ^{235}U atoms and ^{238}U atoms absorb light of different frequencies (or colors). Although the absorption frequencies of these two isotopes differ only by a very small amount (about one part in a million), the dye lasers used in AVLIS can be tuned so that only the ^{235}U atoms absorb the laser light. As the ^{235}U atom absorbs the laser light, its electrons are excited to a higher energy state. With the absorption of sufficient energy, a ^{235}U atom will eject an electron and become a positively charged ion. The ^{235}U ions may then be deflected by an electrostatic field to a product collector. The ^{238}U atoms remain neutral and pass through the product collector section and are deposited on a tails collector.

The AVLIS process consists of a laser system and a separation system. The separator system contains a vaporizer and a collector. In the vaporizer, metallic uranium is melted and vaporized to form an atomic vapor stream. The vapor stream flows through the collector, where it is illuminated by the precisely tuned laser light. The AVLIS laser system is a pumped laser system comprised of one laser used to optically pump a separate dye laser, which produces the light used in the separation process. Dye master oscillator lasers provide precise laser beam frequency, timing, and quality control. The laser light emerging from the dye master oscillator laser is increased in power by passage through a dye laser amplifier. A total of three colors are used to ionize the ^{235}U atoms.

Many countries are pursuing some level of AVLIS research and/or development, and major programs exist in the United States, France, Japan, and probably Russia. Principal advantages of the AVLIS process include a high separation factor, low energy consumption (approximately the same as the centrifuge process), and a small volume of generated waste. However, no country has yet deployed an AVLIS process, although several have demonstrated the capability to enrich uranium with the process. While conceptually simple, the actual implementation of the process is likely to be difficult and expensive, especially for countries with limited technical resources. The AVLIS process requires much sophisticated hardware constructed of specialized materials that must be capable of reliable operation for extended periods of time in a harsh environment.

MLIS

The idea for the molecular laser isotope separation (MLIS) process was conceived by a group of scientists at the Los Alamos National Laboratory in 1971. There are two basic steps involved in the MLIS process. In the first step, UF_6 is irradiated by an infrared laser system operating near the 16 µm wavelength, which selectively excites the $^{235}UF_6$, leaving the $^{238}UF_6$ relatively unexcited. In the second step, photons from a second laser system (infrared or ultraviolet) preferentially dissociate the excited $^{235}UF_6$ to form $^{235}UF_5$ and free fluorine atoms. The $^{235}UF_5$ formed from the dissociation precipitates from the gas as a powder that can be filtered from the gas stream.

MLIS is a stagewise process, and each stage requires conversion of the enriched UF_5 product back to UF_6 for further enrichment. CO_2 lasers are suitable for exciting the $^{235}UF_6$ during the first step. A XeCl excimer laser producing ultraviolet light may be suitable for the dissociation of $^{235}UF_6$ during the second step. However, there is currently no known MLIS optical system which has been successfully designed to handle both infrared and ultraviolet. Consequently, most MLIS concepts use an all infrared optical system.

In terms of the gas flow for the MLIS process, gaseous UF_6 mixed with a carrier gas and a scavenger gas is expanded through a supersonic nozzle that cools the gas to low temperatures. Hydrogen or a noble gas are suitable as carriers. A scavenger gas (such as methane) is used to capture the fluorine atoms that are released as a result of the dissociation of $^{235}UF_6$ molecules.

There are many complexities associated with the process, and the United States, UK, France, and Germany have stated that their MLIS programs have been terminated. Japan also has had a small MLIS program. South Africa has recently stated that their MLIS program is ready to be deployed for low-enriched uranium (LEU) production. Principal advantages of the MLIS process are its low power consumption and its use of UF_6 as its process gas.

Chemical and Ion Exchange

Chemical-exchange isotope separation requires segregation of two forms of an element into separate but contacting streams. Since many contacts are required to achieve the desired separation, the contacting process must be fast and achieve as much separation as possible. For heavy elements such as uranium, achieving a suitable separation factor involves contact between two valence (oxidation state) forms such as hexavalent [U^{6+} as in uranyl chloride (UO_2Cl_2)] and the quadrivalent [U^{4+} as in uranium tetrachloride (UCl_4)]. The ^{235}U isotope exhibits a slight preference for the higher valence, for example, the hexavalent over the quadrivalent in the Asahi process or the quadrivalent over the trivalent (U^{3+}) in the French solvent-extraction process.

The chemical-exchange process, developed by the French, is commonly referred to as CHEMEX. It uses the exchange reaction that takes place between two valence states (U^{3+} and U^{4+}) of uranium ions in aqueous solution. Isotopic enrichment results from the tendency of ^{238}U to concentrate in the U^{3+} compound while ^{235}U concentrates in the U^{4+} compound. It is therefore possible to obtain enriched uranium by removing the U^{4+} ions with an organic solvent that is immiscible with the aqueous phase (concentrated hydrochloric acid). Several possible extractants are available; however, tributyl phosphate (TBP), the choice of the French, is typically used. TBP is diluted with an aromatic solvent, and this organic phase moves countercurrent to the aqueous phase through a series of pulsed columns.

In the pulse column, the heavier aqueous phase is fed into the top of the column, and the lighter organic phase is fed into the bottom of the column. A rapid reciprocating motion is applied to the contents of the column, providing efficient and intimate contact of the two phases. In an HEU plant, centrifugal contactors might be employed particularly for the higher assay sections, since the stage times and corresponding specific uranium inventory could be reduced significantly.

After passing through the column, the enriched and depleted uranium streams must be chemically treated so that they can be recirculated through the column again (refluxed) or sent to another column for additional enrichment. This requires complicated refluxing equipment at both ends of the column.

The ion-exchange process was developed by the Asahi Chemical Company in Japan and uses the chemical isotope effect between two valences (U^{4+} and U^{6+}) of uranium. In this process, the organic phase is replaced by a proprietary ion-exchange resin. The aqueous phase flows through the stationary resin held in a column, and the net effect of all the chemical reactions is a “band” of uranium that moves through the ion-exchange column. The exchange between the unadsorbed uranium flowing through the band and that adsorbed on the resin enhances the isotopic separation. In this continuous separation system, ^{235}U and ^{238}U tend to accumulate respectively at the entrance and exit ends of the adsorption band. In this process, it is economical to regenerate many of the chemicals by reaction with oxygen and hydrogen in separate equipment.

The development and manufacture of the appropriate adsorbent beads are based on technology and know-how gained by Asahi in over 25 years of ion-exchange membrane development and manufacture. The adsorbent is a spherical bead of porous anion-exchange resin with a very high separation efficiency and an exchange rate over 1,000 times faster than the rates obtained in most commercially available resins.

The two exchange processes discussed here are representative of exchange processes now under study in several countries. At present, no country has built or operated a full-scale uranium enrichment plant based on an exchange process. The primary proliferation concern is that they are based on standard chemical engineering technology (except for the proprietary ion-exchange resins).

Plasma Separation

The plasma separation process (PSP) has been studied as a potentially more efficient uranium-enrichment technique that makes use of the advancing technologies in superconducting magnets and plasma physics. In this process, the principle of ion cyclotron resonance is used to selectively energize the ^{235}U isotope in a plasma containing ^{235}U and ^{238}U ions. A feed plate of solid uranium serves as the source of neutral uranium atoms. These atoms are vaporized by bombarding the plate with energetic ions in a process called sputtering. A microwave antenna located in front of the plate energizes free electrons which collide with neutral uranium atoms in the vapor sputtering off the plate. This in turn displaces electrons from the uranium atoms and produces a plasma of ^{235}U and ^{238}U ions.

The plasma is subjected to a uniform magnetic field along the axis of a cylindrical vacuum chamber as the plasma flows from source to collector. The magnetic field is produced by a superconducting magnet located around the outside of the chamber. The high-strength magnetic field produces helical motions of the ions, with the lighter ^{235}U ions spiraling faster and having a higher ion cyclotron frequency than the heavier ^{238}U ions. As the ions move toward the collector, they pass through an electric field produced by an excitation coil oscillating at the same frequency as the ion cyclotron frequency of the ^{235}U ions. This causes the helical orbit of the ^{235}U ions to increase in radius while having minimal effect on the orbit of the heavier ^{238}U ions. The plasma flows through a collector of closely spaced, parallel slats, the physical appearance of which roughly resembles a venetian blind. The large-orbit ^{235}U ions are more likely to deposit on the slats, while the remaining plasma, depleted in ^{235}U, accumulates on an end plate of the collector. PSP is a batch process that would require several stages to produce HEU from natural feed.

The only countries known to have had serious PSP experimental programs are the United States and France. PSP became a part of DOE’s Advanced Isotope Separation research and development program in 1976, but development was dropped in 1982 when AVLIS was chosen as the advanced technology of choice. The French developed their own version of PSP, which they called RCI. Funding for RCI was drastically reduced in 1986, and the program was suspended around 1990, although RCI is still used for stable isotope separation.

Proliferation Implication Assessment

Uranium gun-assembled weapons are the easiest of all nuclear devices to design and build. It is generally conceded to be impossible to prevent any nation having the requisite amount of HEU from building one or more gun-assembled weapons. Therefore, the acquisition of significant quantities of ^{235}U or a facility in which to separate the fissile material is an indicator that the acquiring state *could* be in the process of gaining a rudimentary nuclear capability. Because HEU is used in certain research reactors, another interpretation is possible. Because of the weapons potential, the United States and France have sought to replace HEU-fueled reactors with ones using a lower grade ($<20\%$ ^{235}U, for example) of uranium which cannot be so readily converted to weapons use. The uranium gun-bomb route was successfully taken by South Africa. Any nation having uranium ore in sufficient quantity, a sufficiently well-developed technological and industrial infrastructure, sufficient electric power, and the desire to acquire nuclear weapons might well choose the uranium gun technology.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

All five nuclear weapon states have demonstrated the ability to enrich uranium to weapons grade. In addition, enrichment is a commercial process in The Netherlands and Japan. Germany has also demonstrated the ability to enrich uranium; the South African nuclear weapons were made from 80–90% ^{235}U produced indigenously. Brazil and Argentina sought to build enrichment plants but have abandoned the effort. Iraq used EMIS to enrich uranium prior to the Gulf War and was in the process of building a centrifuge enrichment cascade. Iraq produced some enriched uranium (not weapons grade) before the Gulf War terminated its program. Iran has invested large sums in various enrichment schemes, some of which appear to have been clever scams by outsiders, without achieving any significant enrichment capability. Pakistan has built a gas centrifuge enrichment facility, believed to produce material for nuclear weapons.

The nozzle enrichment process was to be used in Germany and in a plant to be built in Brazil by NUCLEBRAS (a Brazilian firm) in cooperation with a German company, Interatom. Neither plant appears to have been completed and placed in commercial service.

Germany operates a commercial centrifuge enrichment plant for its nuclear power industry. The Becker nozzle process is not believed to be in use anywhere in the world today.

Table 5.2-1. Uranium Enrichment Processes Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
ELECTROMAGNETIC ISOTOPE SEPARATION					
Ion Source	Single or multiple uranium ion sources consisting of a vapor source, ionizer, and beam accelerator. Capable of providing a total ion beam current of ≥50 mA	NTL B5; NDUL 3; NRC H	Uranium chloride, graphite, stainless steel, copper, tantalum, tungsten	None identified	Validated ion source models including 3-dimensional solution of Poisson's equation for multiple species and taking into account the effect of the accelerating structure.
Ion Collectors	Collector plates of two or more slits and pockets for collection of enriched and depleted uranium ion beams, minimize sputtering	NTL B5; NDUL 3; NRC H	Graphite, stainless steel, copper	None identified	Validated ion beam dynamics software and algorithms that optimize isotope separation design from ion source through vacuum and into collector.
Vacuum Housings	Large enough for 1–2 meter orbit radius, multiple orbits, operation at pressures of 0.1 Pa or lower	NTL B5; NDUL 3; NRC H	Nonmagnetic materials (e.g., stainless steel)	None identified	None identified
Magnet pole pieces	Diameter >2 meters, able to maintain a time-invariant magnetic field within a separator, ability to transfer magnetic field between adjoining separators.	NTL B5; NDUL 3; NRC H	Low resistance wire, magnet iron	Precision field measurement and adjustment. Precision shaping of pole tips, precisely controlled windings.	Validated 3-dimensional singly (predominant) and multiply charged high current ion beam dynamics codes and algorithms
High-voltage DC power supplies	Capable of continuous operation, output voltage ≥20,000 V , output current ≥1 Å, voltage regulation <0.01% over 8-hour interval	NTL B5; NDUL 3; NRC H	None identified	None identified	None identified
DC magnet power supplies	Capable of continuously producing a voltage ≥100 V, current ≥500 Å, and current or voltage regulation <0.01% over 8-hour interval.	NTL B5; NDUL 3; NRC H	None identified	None Identified	None identified

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Vacuum pumps	Input throat size ≥38 cm, pumping speed ≥15,000 liters/sec, vacuum <10^{-4} Torr (1.33 x 10^{-4} mbar), oil-diffusion pump systems of sufficient capacity to provide minimum downtime when removing collectors.	NDUL 3; CCL Cat 2B	Pumping fluid, such as a hydrocarbon oil	Fast-acting shutoff valves to protect vacuum system and minimize downtime	None identified
Uranium recovery	Extract enriched uranium in small batches without going critical, efficient chemical processes to extract enriched uranium from graphite collector	NTL B3; NRC I	Cadmium (neutron poison) used to prevent criticality. Must be removed at end of process	Mass spectrometers	None identified
THERMAL DIFFUSION					
Thermal Diffusion Columns	Tall columns (10–15 meters in height) consisting of three concentric tubes: inner tube copper, middle nickel, outer iron. Small annular gap maintained between inner and middle tube.	NTL B5	UF_6 corrosion-resistant materials	Thermal diffusion test columns for optimizing performance	Thermal diffusion coefficients and performance models
Product and Tails Header Piping Systems	Arrays of pipes made of or lined with UF_6-resistant materials, fabricated for containment of UF_6 liquid at pressures of 7 MPa, and for interconnection of individual thermal diffusion columns at the top and bottom ends.	NTL B5	UF_6 corrosion-resistant materials	None identified	None identified
Liquid UF_6 Transfer Pumps	Pumps capable of pressurizing liquid UF_6 to 7 MPa , leak tight and corrosion resistant to UF_6.	NTL B5	Materials resistant to UF_6 corrosion.	None identified	None identified
Product and Tails Withdrawal Systems	Expansion valves and heat exchangers for cooling liquid UF_6 to 65 °C and for removal into product and tails cylinders.	NTL B5	UF_6 corrosion-resistant materials	UF_6 mass spectrometers/ion sources. UF_6-compatible flow, mass, pressure and temperature instrumentation.	None identified

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Cooling Water Systems	Cooling water systems for removal of 200 MW at temperatures of 67–70 °C	CCL EAR 99	None identified	None identified	None identified
Steam Plant	Large steam plant needed even for small uranium enrichment capacity (200 MW for 5,000 SWU/yr in U.S. thermal diffusion plant)	CCL EAR 99	None identified	None identified	None identified
GASEOUS DIFFUSION					
Barrier material	Thin, porous filters with small pore size (100 to 1,000 Å), thickness of ≤5 mm, diameter ≤25 mm, sufficient mechanical strength, stable, chemically inert to UF_6	NTL B5; NRC C	UF_6-corrosion resistant metallic, polymer or ceramic materials. Compounds and powders including nickel or alloys containing ≥ 60% nickel, aluminum oxide, fully fluorinated hydrocarbon polymers, etching acid such as HNO_3.	Scanning or transmission microscope, x-ray diffraction system, and other test equipment for measuring the following barrier properties: mechanical strength, corrosion resistance, porosity, and permeability	Barrier performance models
Diffuser Housings	Hermetically sealed cylindrical vessels >20-cm diam. and >70-cm length (or comparable rectangular vessel) having inlet and outlet connections all >5-cm diameter, designed for operation at high vacuum, designed for horizontal or vertical installation	NTL B5; NRC C	Nickel-plated steel, aluminum, or nickel alloys containing ≥ 60% nickel; special UF_6-compatible gaskets for bolted flanges	None identified	None identified
Gas blowers and compressors	Axial, centrifugal, or positive displacement compressors/ blowers with suction capacity ≥ 1 m^3/min of UF_6 and with discharge pressure up to 100 psi designed to operate in UF_6 environment. Pressure ratio between 2:1 and 6:1	NTL B5; NRC C	Nickel or high nickel alloy casing or plating on casing; rotor blades and impellers of same material or Al alloys.	UF_6 test loop and instrumentation to determine compressor performance characteristics	Compressor design and performance models and blade design codes for heavy gases.

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Rotary shaft seals	Vacuum seals with seal feed and seal exhaust connections. Seals designed for a buffer gas inleakage of <1,000 cm^3/min. Adaptable to wide range of gas pressures and pressure disturbances, ease of maintenance, and UF_6 corrosion resistance.	NTL B5; NRC C	Materials resistant to UF_6 corrosion.	Instrumentation to measure seal feed and exhaust pressures and flows to check seal performance.	Seal design and performance models for heavy gases.
Heat Exchangers	Heat exchangers made of, or lined with UF_6-corrosion resistant materials, and intended for a leakage pressure change rate <10 N/m^2 (0.0015 psi) per hour under a pressure difference of 100 kN/m^2 (15 psi).	NTL B5; NRC C	UF_6 corrosion-resistant materials	Test loop to determine heat transfer coefficients and pressure drop.	Heat transfer codes for compact heat transfer surfaces and heavy gases.
Feed systems	Process systems including feed autoclaves for passing UF_6 to the gaseous diffusion cascades and capable of operating at pressures $\le$ 300 kN/m^2 (45 psi). Cylinders and autoclaves ~ 3-m long and 1.8-m in diameter, and UF_6 corrosion resistant.	NTL B5; NRC C	UF_6 corrosion-resistant materials.	UF_6 mass spectrometers/ion sources. Autoclaves. UF_6-compatible flow, mass, pressure, and temperature instrumentation.	None identified
Product and Tails Withdrawal Systems	Compression liquefaction or desublimation (cold traps) systems for withdrawal. Cylindrical equipment is ~1 m in diam. when insulated, and 2–3 m long. For HEU: diam. <12.5 cm, may include Boron alloys to preclude criticality.	NTL B5; NRC C	Nickel, high-nickel alloys, aluminum, or copper	UF_6 mass spectrometers/ion sources. UF_6-compatible flow, mass, pressure, and temperature instrumentation.	Compressor design codes and heat transfer design codes applicable to UF_6

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Header piping systems	Arrays of pipes ≥5 cm in diam. made of or lined with UF_6-resistant materials, normally of the double header system type, fabricated to very high vacuum and cleanliness standards, for handling UF_6 within the gaseous diffusion cascades,	NTL B5; NRC C	Materials resistant to UF_6 including stainless steel, aluminum, aluminum alloys, nickel, or alloys containing ≥60% nickel.	None identified	None identified
Vacuum systems	Large vacuum manifolds, vacuum headers, and vacuum suction pumps having a suction capacity of $5m^3$/min or more. UF_6 corrosion-resistant positive displacement vacuum pumps that may have special working fluids.	NTL B5; NRC C	Aluminum, nickel, or alloys bearing ≥60% nickel. Hydrocarbon or fluorocarbon vacuum pump oils.	None identified	None identified
Shut-off and control valves	Manually or automatically operated, 5 mm or greater in nominal size, made of UF_6-resistant materials.	NTL B5; NDUL 3; NRC C; CCL Cat 0B	UF_6-resistant materials. Bellows seals rather than packing glands to isolate the process vacuum system from the atmosphere.	None identified	None identified
Product storage and sampling cylinders	Cylinders designed for operation up to 30 atmospheres, with appropriate diameter and length to avoid criticality with HEU	CCL EAR 99	Valves and connectors resistant to corrosion from UF_6.	None identified	None identified

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
GAS CENTRIFUGE					
Rotating Component: Complete Rotor Assemblies	Thin-walled cylinders (>30 cm in length) or interconnected thin-walled cylinders up to 15 m in length made from high strength-to-density ratio material.	NTL B5; NRC B	High strength-to-density ratio (HSD) materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.	Equipment to manufacture, assemble, and balance complete rotor assembly.	Rotor dynamics/stress analysis software
Rotating Component: Rotor Tubes	Thin-walled cylinders w/ thickness ≤12 mm, diameter 75 to 400 mm, made from high strength-to-density material, length-to-diameter ratio typically >2	NTL B5; NRC B	HSD materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.	Equipment to manufacture and balance rotor tubes; spin-forming and flow-forming machines, filament winding machines. Spin-testing equipment.	Rotor dynamics/stress analysis software
Rotating Component: Rings or Bellows	Cylinder of wall thickness ≤3 mm, diameter 75 to 400 mm, made of high strength-to-density ratio material, and having a convolute. Used to provide local support to rotor tube or to join rotor tubes.	NTL B5; NRC B	HSD materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.	Equipment to manufacture and balance rings and bellows. Spin-testing equipment.	Rotor dynamics/stress analysis software
Rotating Component: Baffles	Disc-shaped high strength-to-density ratio components, 60 to 500 mm in diameter, designed to be mounted in rotor tubes to isolate take-off chamber of rotor tube and/or to assist UF_6 gas circulation in main separation chamber.	NTL B5; NRC B	HSD materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.	Equipment to manufacture and balance baffles. Spin-testing equipment.	Rotor dynamics/stress analysis software
Rotating Component: top caps/bottom caps	Disc-shaped or cup-shaped HSD components, 75 to 400 mm in diameter, designed to fit the ends of rotor tubes, contain the UF_6 within the rotor, and support the upper bearing elements or to carry rotating elements of motor	NTL B5; NRC B	HSD materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.	Equipment to manufature and balance end caps. Spin-testing equipment.	Rotor dynamics/stress analysis software

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Static Component: Magnetic Suspension Bearings (includes ring magnets)	Homogeneous ring-shaped annular magnet suspended within UF_6-resistant housing, deviation of the magnetic axes from the geometrical axes limited to very small tolerances	NTL B5; NRC B	Ring magnet: samarium-cobalt, Alnico	Precision balancing and magnetic properties measuring equipment.	None identified
Static Component: Bearings, Dampers (for lower end of rotor tube)	Bearing comprised of pivot/cup assembly mounted on a damper. Pivot is normally hardened steel shaft polished into a hemisphere. Cup has a hemispherical indentation in one surface. Shaft may have hydrodynamic bearing.	NTL B5; NRC B	Hardened steel, stainless steel, aluminum having high-quality machined surface.	None identified	None identified
Static Component: Molecular Pumps	Cylinders having internally helical grooves and internally machined bores. Grooves are typically rectangular in cross section.	NTL B5; NRC B	Steel, stainless steel, aluminum	Precision manufacturing and mensuration equipment.	None identified
Static Component: Motor Stators	Ring-shaped stators having multiphase windings on low-loss laminated iron core for synchronous operation of AC hysteresis motors in vacuum. Power range is 50 to 1,000 VA for frequencies 600 to 2,000 Hz.	NTL B5; NRC B	Low-loss iron core	Precision manufacturing of laminated structure, coil winding and mounting.	Motor design software for unusual motor geometries and high frequency operation.
Static Component: Scoops	Tubes up to 12 mm (0.5 in) internal diameter for extraction of UF_6 from within the rotor tube by Pitot tube action and capable of being fixed to the central gas extraction system.	NTL B5; NRC B	UF_6-resistant materials	None identified	CFD codes for heavy gases in strong rotation with shocks.
Feed Systems/Product and Tails Withdrawal Systems	Feed autoclaves that pass UF_6 to centrifuge cascades, desublimers that remove UF_6 from the cascades, product and tails stations for trapping UF_6 into containers.	NTL B5; NRC B	UF_6-resistant materials used in piping	Mass spectrometers/ion sources. Autoclaves. UF_6-compatible flow, mass, pressure, and temperature instrumentation.	Heat transfer codes applicable to UF_6 desublimers.

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Machine Header Piping System	Piping network normally of the "triple" header system with each centrifuge connected to each of the headers. Line connections at the centrifuge may be individually flanged or combined in a single flange.	NTL B5; NRC B	UF_6-resistant materials used in piping	Fabrication techniques applicable to very high vacuum and cleanliness standards.	None identified
Frequency changers (also called converters or inverters)	Multiphase output capable of providing an output of ≥40 W, operating in the range of 600 to 2,000 Hz, high stability with frequency control ≤0.1%, harmonic distortion ≤10%, high efficiency, large MTBF, ability to drive one or more centrifuges.	NTL B5; NRC B; NDUL 3; CCL Cat 3A	None identified	None identified	None identified
AERODYNAMIC SEPARATION					
Separator elements: nozzles, jets and vortex tubes	Nozzle: slit-shaped, curved channels with a radius of curvature less than 1 mm, knife-edge to separate the gas flow. Vortex tubes: cylindrical or tapered, 0.5-cm to 4-cm diameter, length to diameter ratio of ≤20:1, one or more tangential inlets	NTL B5; NRC D	UF_6-resistant materials	Test facility to measure isotopic separation performance, pressure drops, etc.	CFD software for nozzle design and performance
UF_6/carrier gas separation systems	Designed to reduce UF_6 content in carrier gas to ≤1 ppm. Use of cryogenic heat exchangers and cryoseparators, cryogenic refrigeration units, separation nozzle or vortex tube units, or UF_6 cold traps.	NTL B5; NRC D	UF_6-resistant materials	None identified	None identified
Separation element housings	Cylindrical vessels >30 cm in diameter and 90 cm in length, or rectangular vessels of comparable dimensions. Made of or protected by UF_6-resistant materials.	NTL B5; NRC D	UF_6-resistant materials	None identified	None identified

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
UF_6-hydrogen (or helium) gas compressors, gas blowers, and rotary shaft seals	Axial, centrifugal, or positive displacement compressors or gas blowers, suction volume capacity of ≥ 2 m^3/min, typical pressure ratio between 1.2:1 and 6:1. Seals with feed and exhaust connections, provide a reliable seal against outleakage or inleakage.	NTL B5; NRC D	UF_6-resistant materials	UF_6 -hydrogen test loop and instrumentation to determine compressor performance characteristics. Instrumentation to measure seal feed and exhaust pressures and flows to check seal performance.	Compressor and seal design and performance models. Blade design codes.
Heat Exchangers	Provide adequate gas cooling, made or protected by materials resistant to UF_6	NTL B5; NRC D	UF_6-resistant materials	Test loop to determine heat transfer coefficients and pressure drop.	Heat transfer codes for compact heat transfer surfaces.
Shut-off, control, and bellows-sealed valves	Manually or automatically operated, 40 to 1,500 mm in diameter, made of or protected by UF_6 resistant materials	NTL B5; NRC D	UF_6-resistant materials; bellows seals rather than packing glands	None identified	None identified
Feed systems/product and tail withdrawal systems	Feed autoclaves to pass UF_6 to the enrichment process; desublimers (cold traps) or solidification or liquefaction stations for removal of UF_6 from the process, product and tails stations for transferring UF_6 into containers	NTL B5; NRC D	UF_6-resistant materials	Mass spectrometers/ion sources. Autoclaves. Flow, mass, pressure. and temperature instrumentation.	None identified
Process piping systems and header systems	Piping network normally of the “double” header design with each stage or group of stages connected to each header.	NTL B5; NRC D	UF_6-resistant materials	None identified	None identified
Vacuum systems and pumps	Vacuum systems having a suction capacity of ≥ 5 m^3/min with vacuum manifolds, headers, and pumps designed for service in corrosive atmosphere. Pumps may have fluorocarbon seals and special working fluids.	NTl B5; NRC D	UF_6-resistant materials. Hydrocarbon or fluorocarbon vacuum pump oils.	None identified	None identified

(cont’d)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
CHEMICAL EXCHANGE AND ION EXCHANGE					
Liquid-liquid exchange columns	Ability to produce pipes of various diameters and lengths which are internally coated with material resistant to HCl and have mechanical power input systems to provide mixing of two immiscible liquids with residence times of ≤ 30 seconds.	NTL B5; NRC E	Corrosion resistant pipes and their internals made of or protected by suitable plastic materials (such as fluorocarbon polymers) or glass	Mechanical power systems. Sieve plates, reciprocating plates. or internal turbine mixers	None identified
Liquid-liquid centrifugal contactors	Capability to build and operate centrifuge systems which disperse and then separate two immiscible liquids with stage residence times of ≤ 30 seconds and are corrosion resistant to concentrated HCl.	NTL B5; NRC E	None identified	Contactors made of or are lined with suitable plastic materials (such as fluorocarbon polymers) or with glass	None identified
Electrochemical reduction systems and reduction cells	Skills in the design, produc– tion, and operation of reduction cells that are corrosion resistant to concentrated HCl and prevent the reoxidation of U^{3+} to U^{4+}.	NTL B5; NRC E	Parts in contact with process stream: suitable materials (glass, fluorocarbon polymers, polyphenyl sulfate, polyether sulfone, and resin-impregnated graphite) to avoid contamination of aqueous stream with certain metal ions. Electrodes (graphite).	Potentiometers	Precise control of uranium valence

(cont’d)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Feed preparation systems	Ability to prepare high-purity aqueous solutions of uranium chloride. Concentration of certain metal ions such as chromium, iron, vanadium, molybdenum, and other bivalent or higher multivalent cations must be more than a few parts per million.	NTL B5; NRC E	Parts in contact with final feed solutions: suitable materials (glass, fluorocarbon polymers, polyphenyl sulfate, polyether sulfone, and resin-impregnated graphite) to avoid contamination of the aqueous stream with certain metal ions.	Analytical equipment to monitor purity of solutions	None identified
Uranium oxidation systems	Knowledgeable in the operation of systems for the oxidation of U^{3+} to U^{4+}. Familiarity with the handling of chlorine and oxygen gases and distillation of HCl solutions.	NTL B5; NRC E	For portions of system processing high-purity U^{3+} streams: suitable materials (glass, fluorocarbon polymers, polyphenyl sulfate, polyether sulfone, and resin-impregnated graphite) to avoid contamination	Potentiometers	Accurate control of uranium valence
Ion exchange columns	Ability to design, construct, and operate cylindrical columns >1 m in diameter made of or protected by materials resistant to concentrated HCl and are capa–ble of operating at a temper–ature of 100 °C to 200 °C and pressures >0.7 MPa (102 psi)	NTL B5; NRC E	Fast-reacting ion exchange resins or adsorbents	Provide characteristics of glass substrate and resin	Physical and chemical characteristics of resin
Ion exchange reflux systems	Knowledgeable in the chemical and electrochemical reduction systems for regeneration of chemical reducing agent(s) in ion exchange	NTL B5; NRC E	Elements (e.g., Ti, Fe, V) which possess the proper electrochemical behavior to be used in the regeneration steps	Potentiometers, Spectrometers	Careful control of solution chemistry

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Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
ATOMIC VAPOR LASER ISOTOPE SEPARATION (AVLIS)					
Laser systems	Systems designed for separating uranium isotopes, usually consisting of copper vapor lasers and dye lasers. A spectrum frequency stabilizer is required for operation over extended periods of time.	NTL B5; NDUL 3; NRC F; CCL Cat 6	Laser gases, laser dyes	Lasers, laser amplifiers, and oscillators: copper vapor, argon ion, neodymium-doped (other than glass), dye laser amplifier and oscillators.	Software for laser safety systems, timing systems
Uranium vaporization systems	Melting and casting technologies. Vaporization systems containing high-power strip or scanning electron beam guns with delivered power on the target of >2.5 kW/cm.	NTL B5; NRC F	Filaments: tungsten	Electron beam guns	Interlocks between electron beam gun power and magnetic field
Liquid uranium metal handling systems	Ability to handle molten uranium or uranium alloys, consisting of crucibles and cooling equipment for crucibles. Made of or protected by materials of suitable corrosion and heat resistance.	NTL B5; NRC F	Copper, tantalum, yttria-coated graphite, graphite coated with other rare earth oxides.	Water-cooled copper crucibles	None identified
Product and tails collector assemblies	Handle uranium metal in liquid or solid form. May include pipes, valves, fittings, “gutters,” feed-throughs, heat exchangers and collector plates.	NTL B5; NRC F	Tantalum, yttria-coated graphite, graphite coated with other rare earth oxides	None identified	None identified
Separator module housings	Cylindrical or rectangular vessels with multiplicity of ports for electrical and water feed-throughs, laser beam windows, vacuum pump connections, and instrumentation diagnostics and monitoring.	NTL B5; NRC F	Austenitic steel	Protection from x-rays generated by electron beam guns	None identified

(cont’d)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
MOLECULAR LASER ISOTOPE SEPARATION (MLIS)					
Laser Systems	Systems designed for separating uranium isotopes, usually consisting of CO_2 or excimer lasers and para-hydrogen Raman shifters. A spectrum frequency stabilizer is required for operation over extended periods of time.	NTL B5; NDUL 3; NRC F; CCL Cat 6	Lasing medium: CO_2, N_2, He, Ar, Kr, Xe, HCl, Cl_2, F_2	Pulsed CO_2 lasers, pulsed excimer lasers, para-hydrogen Raman shifters	Software for laser system frequency control, timing, and safety
Supersonic expansion nozzles	Nozzles capable of cooling mixtures of UF_6 and carrier gas to ≤150 K and which are corrosion resistant to UF_6	NTL B5; NRC F	UF_6 corrosion-resistant materials Ar, N_2	Test facility to measure diffuser pressure recovery	CFD software for compressible gas flow with shocks and significant viscous effects
UF_5 product collectors	Uranium pentafluoride (UF_5) solid product collectors consisting of filter, impact, or cyclone-type collectors, or combinations thereof.	NTL B5; NRC F	UF_5/ UF_6 corrosion-resistant materials	Test facility to measure pressure drop as a function of collector loading	None identified
UF_6/carrier gas compressors and rotary shaft seals	Compressors designed for long term operation in UF_6 environment. Seals with feed and exhaust connections; provide a reliable seal against outleakage or inleakage.	NTL B5; NRC F	UF_6 corrosion-resistant materials	UF_6/carrier gas test facility and instrumentation to determine compressor performance characteristics. Instrumentation to measure seal feed and exhaust pressures and flows to check seal performance.	Compressor design and performance models and blade design codes. Seal performance and design models.
Fluorination systems	Systems designed for fluorinating UF_5 (solid) to UF_6 (gas) for subsequent collection in product containers or for transfer for additional enrichment.	NTL B5; NRC F	Fluorinating agent (e.g., ClF_3), corrosion-resistant materials	Equipment for storage and transfer of fluorinating agent and for collection and transfer of UF_6. Reaction vessel (e.g., fluidized-bed reactor, screw reactor, flame tower), temperature and pressure probes, cold traps. Equipment for in-situ fluorination.	Safety systems, thermal control

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Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Feed systems/product and tail withdrawal systems	Feed autoclaves to pass UF_6 to the enrichment process; desublimers (cold traps) or solidification or liquefaction stations for removal of UF_6 from the process, product and tails stations for transferring UF_6 into containers	NTL B5; NRC F	UF_6 corrosion-resistant materials	Mass spectrometers/ion sources. Autoclaves. UF_6-compatible flow, mass, pressure, and temperature instrumentation.	None identified
UF_6/carrier gas separation systems	Systems designed to separate UF_6 from carrier gas (N_2, Ar).	NTL B5; NRC F	UF_6 corrosion-resistant materials	Cryogenic heat exchangers or cryo-separators, cryogenic refrigeration units, or UF_6 cold traps.	None identified
PLASMA SEPARATION PROCESS					
Microwave power sources and antennae	Producing or accelerating ions and having the following characteristics: >30 GHz frequency and >50 kW mean power output for ion production.	NTL B5; NRC G	None	None identified	Validated algorithms and related computer programs to compute the flow and trajectories of U-235 and U-238 ion isotopes in rf-heated plasma
Product and tails collector assemblies	Assemblies for collecting uranium metal in solid form. Made of or protected by materials of suitable corrosion and heat resistance to uranium metal vapor. Graphite shop, uranium recovery and recycle support facilities.	NTL B5; NRC G	Tantalum, yttria-coated graphite	None identified	Validated algorithms and related computer programs to compute the flow and trajectories of U-235 and U-238 ion isotopes in rf-heated plasma
RF ion excitation coils	Frequencies of more than 100 kHz and capable of handling >40 kW mean power.	NTL B5; NRC G	None	None identified	Particle dynamics, particle interactions
Liquid uranium handling systems	Ability to handle molten uranium or uranium alloys, consisting of crucibles and cooling equipment for crucibles. Made of or protected by materials of suitable corrosion and heat resistance.	NTL B5; NRC G	Tantalum, yttria-coated graphite, graphite coated with other rare earth oxides	None identified	None identified

(cont'd)

Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Plasma generation systems	Systems for the generation of uranium plasma. May contain high-power strip or scanning electron beam guns with a delivered power on the target of >2.5 kW/cm.	NTL B5; NRC G	Uranium metal	Electron beam guns	None identified
Superconducting magnets	Superconducting solenoidal electromagnet with an inner diameter of >30 cm, providing a very uniform magnetic field of high strength (>2 teslas).	NDUL B3; CCL Cat 3A	Liquid He, liquid N_2	Liquid He and N_2 controllers and monitors, cryo-thermometers, cryogenic tubing	None identified

Table 5.2-2. Uranium Enrichment Processes Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
ELECTROMAGNETIC ISOTOPE SEPARATION (EMIS)		Production of HEU for use in nuclear weapons, naval propulsion, research reactors	Other uranium enrichment technologies
Ion source	Obtaining high U^+ beam currents from source, controlling expansion of beam, properly focus ion beam on collector slits, heater life, insulator breakdown, damage to source components due to high energy ions	None identified	Several types of ion source exist.
Ion collectors	Retain and measure collected uranium, retain shape over wide temperature range, resist sputtering, conduct heat, permit recovery of deposited uranium.	None identified	None
Vacuum housings	Leakage rate; opening and closing with minimum downtime	None identified	None
Magnet pole pieces	Maintain low magnetic field ripple	None identified	Superconducting magnets
High-voltage power supplies	Maintain stable voltage	None identified	None
DC magnet power supplies	Maintain stable current	None identified	None
Vacuum pumps	Maintain high vacuum in large evacuated region	Other isotope separation processes (e.g., AVLIS, PSP)	None
Uranium recovery	Substantial chemical processing facility required, labor intensive	None identified	None
THERMAL DIFFUSION		Production of uranium enriched up to 1.2% ^{235}U as feed to electromagnetic separators enriching to weapons grade uranium.	Other uranium enrichment technologies
Thermal Diffusion Columns	Precisely machined tubing. Operation at high pressures and temperatures without leaks. Maintaining a small gap between hot and cold walls. UF_6 freezing and plugging.	None identified	None identified
Product and Tails Header Piping Systems	Minimize leakage and corrosion, sealing and welding technologies	None identified	None identified
Liquid UF_6 Transfer pumps	Minimize leakage and corrosion, sealing technology	None identified	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Product and Tails Withdrawal Systems	Minimize leakage and corrosion, sealing and welding technologies	None identified	None identified
Cooling Water Systems	Temperature control	None identified	None identified
Steam Plant	Large steam plant needed even for small uranium enrichment capacity	None identified	None identified
GASEOUS DIFFUSION		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Barrier Materials	Fabrication of barrier. Maintain fine pore size, high permeability, and structural integrity over long periods of operation. Control nonseparative flow mechanisms.	None identified	None identified
Diffuser Housings	Procurement of large quantities required, sealing and welding technologies, aerodynamic efficiency, minimum leakage and corrosion.	None identified	None identified
Gas Blowers and Compressors	Procurement of large quantities required, blade design, nozzle design, lubrication system for bearings, minimum leakage and corrosion.	None identified	None identified
Rotary Shaft Seals	Procurement of large quantities required, minimize inleakage and outleakage, long-term running reliability	None identified	Hermetically sealed compressors with UF_6 gas bearings
Heat Exchangers	Minimize leakage and corrosion, cooling tower design	None identified	None identified
Feed Systems	Maintain material balance: reveal cascade leakage, consumption on surfaces or material freeze-outs	None identified	None identified
Product and Tails Withdrawal Systems	Maintain material balance: reveal cascade leakage, consumption on surfaces or material freeze-outs. Criticality concerns with HEU.	None identified	None identified
Vacuum Systems	Minimize leakage. Containment and cleanliness.	None identified	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Vacuum Systems	Minimize leakage. Containment and cleanliness.	None identified	None identified
Shutoff and Control Systems	Procurement of large quantities required, minimize leakage and corrosion, provide proper pressure drop to move UF_6 inventory and minimize stage efficiency losses, isolation of stages for maintenance	None identified	None identified
Product Storage and Sampling Cylinders	Maintain operational integrity with minimum leakage and corrosion. Criticality concerns with HEU.	None identified	None identified
GAS CENTRIFUGE		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Rotating Component: Complete Rotor Assemblies	Rotor dynamics, critical frequencies, proper balancing and damping, continuous operation	None identified	None identified
Rotating Component: Rotor Tubes	Material properties, balancing, resistance to corrosion attack, continuous operation, uniformity of manufacture	None identified	None identified
Rotating Component: Rings or Bellows	Material properties, balancing, resistance to corrosion attack, continuous operation, uniformity of manufacture	None identified	None identified
Rotating Component: Baffles	Material properties, balancing, resistance to corrosion attack, continuous operation, uniformity of manufacture	None identified	None identified
Rotating Component: top caps/bottom caps	Material properties, balancing, resistance to corrosion attack, continuous operation, uniformity of manufacture	None identified	None identified
Static Component: Magnetic Suspension Bearings (includes ring magnets)	Homogeneity of magnet material, deviation of magnetic axes	None identified	None identified
Static Component: Bearings, Dampers (for lower end of rotor tube)	Prope damping to control rotor vibration and restrain lateral movement	None identified	None identified
Static Component: Molecular Pumps	Maintain low pressure in casing	None identified	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Static Component: Motor Stators	Provide low-loss, high speed, high frequency, synchronous and uninterrupted service.	None identified	None identified
Static Component: Scoops	Aerodynamics and materials	None identified	None identified
Feed Systems/Product and Tails Withdrawal Systems	Maintain material balance. Criticality concerns with HEU.	None identified	None identified
Machine Header Piping System	Minimize leakage and corrosion, sealing, and welding technologies	None identified	None identified
Frequency Changers (also called converters or inverters)	Trouble-free operation for extended periods of operation, no maintenance requirements	Drive high-speed spindle motors for grinders and machine tools.	None identified
AERODYNAMIC SEPARATION		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Separator elements: nozzles, jets and vortex tubes	Precision in fabricating very small nozzles, sophisticated machine shop	None identified	None identified
UF_6 carrier-gas separation equipment	Large building ventilation system, H_2 generating site, explosive mixture concerns	None identified	None identified
Separation element housings	Sealing and welding technologies, aerodynamic efficiency, minimum leakage and corrosion.	None identified	None identified
UF_6-hydrogen (or helium) gas compressors, gas blowers, and rotary shaft seals	Aerodynamics, rotor dynamics, lubrication, blade/vane stress and vibration, minimize leakage, corrosion, failure rates	None identified	None identified
Heat Exchangers	Substantial waste heat, cooling tower design	None identified	None identified
Shut-off, control, and bellows-sealed valves	Minimize leakage and corrosion	Valves could be used in other flow systems.	None identified
Feed Systems/Product and Tail Withdrawal Systems	Maintain material balance. Criticality concerns with HEU.	None identified	None identified
Process piping systems and header systems	Minimize leakage and corrosion, sealing and welding technologies	None identified	None identified
Vacuum Systems and Pumps	Minimize leakage. Containment and cleanliness.	Other vacuum systems	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
CHEMICAL AND ION EXCHANGE		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Liquid-liquid exchange columns	Judicious handling of columns to prevent breaching of interior coating or lining. The instability of U^{3+} in aqueous solution demands expertise in uranium solution chemistry.	None identified	Use mixer/settlers or centrifugal contactors.
Liquid-liquid centrifugal contactors	Protection of corrosion resistant lining is paramount. The instability of U^{3+} in aqueous solution demands expertise in uranium solution chemistry.	None identified	Use mixer/settlers or liquid-liquid exchange columns.
Electrochemical reduction systems and reduction cells	Must prevent reoxidation of uranium	None identified	May use other chemicals (zinc) for reduction
Feed preparation systems	Product must be of very high-purity with little metallic contamination.	None identified	None identified
Uranium oxidation systems	Chlorine gas is highly toxic and must be handled with extreme care. Pure oxygen gas may bring about rapid combustion and fire.	None identified	May oxidize systems electrolytically but process will be more expensive.
Ion exchange columns	The preparation of the resin / adsorbent is the key and has proven very difficult.	None identified	None identified
Ion exchange reflux systems	The appropriate metals to use in the regeneration system have not been well identified.	None identified	None identified
ATOMIC VAPOR LASER ISOTOPE SEPARATION (AVLIS)		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors), Pu separation, Li enrichment	Other uranium enrichment technologies
Laser systems	Precise tuning, control and modulate wavelengths, sufficient pulse repetition frequency and pulse length, laser power per pulse, beam quality, beam propagation, optics	Lidar Guidestar	None identified
Uranium vaporization systems	High power density	None identified	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Liquid uranium metal handling systems	Withstanding heat from electron beam gun and corrosive effects of liquid uranium	None identified	None identified
Product and tails collector assemblies	Uranium corrosion at high temperatures	None identified	None identified
Separator module housings	Maintaining a very high vacuum, reliability of large pump system	None identified	None identified
MOLECULAR LASER ISOTOPE SEPARATION (MLIS)		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Laser Systems	High energy pulses, high repetition rates, beam quality, beam propagation, optics, para-hydrogen Raman cells, high capacity gas flow systems for lasing gas, gas cleanup systems	None identified	None identified
Supersonic expansion nozzles	Specially contoured to produce uniform gas flow in irradiation chamber, provide efficient utilization of laser light, corrosion resistance	None identified	None identified
UF_5 product collectors	High UF_5 collection efficiency, criticality concerns with HEU collection, corrosion resistance	None identified	None identified
UF_6 /carrier gas compressors and rotary shaft seals	Aerodynamics, rotor dynamics, lubrication, blade/vane stress and vibration, minimize leakage, corrosion, failure rates	None identified	None identified
Fluorination systems	Efficient removal of UF_5 enriched product in a timely manner, corrosion resistance	None identified	None identified
Feed systems/product and tail withdrawal systems	Criticality concerns for HEU, corrosion resistance	None identified	None identified
UF_5 /carrier gas separation systems	Protection of carrier gases from chemical contamination by processing equipment, removal of reaction products, rebalancing process gas composition, corrosion resistance	None identified	None identified

(cont'd)

Table 5.2-2. Uranium Enrichment Processes Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
PLASMA SEPARATION PROCESS SYSTEMS		Production of LEU (fuel for nuclear power reactors) or HEU (nuclear weapons, naval propulsion, research reactors)	Other uranium enrichment technologies
Microwave power sources and antennae	Power input and voltage, plasma density, electron temperature	None identified	None identified
Product and tails collector assemblies	Criticality concerns for HEU, corrosion resistance	None identified	None identified
RF ion excitation coils	Collisional effects, orientation of electric fields, ^{235}U selectivity	None identified	None identified
Liquid uranium handling systems	Throughput, corrosive effects of liquid uranium	None identified	None identified
Plasma generation systems	High plasma density	None identified	None identified
Superconducting magnets	Strength and uniformity of magnetic field, cryogenic refrigeration	None identified	None identified

SECTION 5.3—NUCLEAR FISSION REACTORS

OVERVIEW

This subsection discusses nuclear fission reactors in general, but emphasizes that the types which have been found most suitable for producing plutonium are graphite-moderated nuclear reactors using gas or water cooling at atmospheric pressure and with the capability of having fuel elements exchanged while on line.

The first nuclear reactor, CP-1, went critical for the first time on 2 December 1942 in a squash court under Stagg Field at the University of Chicago. Construction on CP-1 began less than a month before criticality was achieved; the reactor used lumped uranium metal fuel elements moderated by high-purity graphite. Within 2 years the United States first scaled up reactor technology from this essentially zero-power test bed to the 3.5 MW (thermal) X-10 reactor built at Oak Ridge, Tennessee, and then again to the 250-megawatt production reactors at Hanford. The Hanford reactors supplied the plutonium for the Trinity test and the Nagasaki war drop. Clearly, reactor technology does not stress the capabilities of a reasonably well-industrialized state at the end of the twentieth century.

Some problems did arise with the scale-up to hundreds of megawatts: the graphite lattice changed crystal state, which caused some deformation, and the buildup of a neutron-absorbing xenon isotope poisoned the fission reaction. This latter problem was curable because of the foresight of the duPont engineers, who built the reactor with many additional fuel channels which, when loaded, increased the reactivity enough to offset the neutron absorption by the xenon fission product.

Finally, the problem of spontaneous emission of neutrons by ^{240}Pu produced in reactor plutonium became apparent as soon as the first samples of Hanford output were supplied to Los Alamos. The high risk of nuclear pre-initiation associated with ^{240}Pu caused the abandonment of the notion of a gun-assembled plutonium weapon and led directly to the adoption of an implosion design.

Several distinct classes of reactor exist, each optimized for one purpose, generally using fuel carefully chosen for the job at hand. These classes include the following:

(1) Research reactors. Usually operates at very low power, often only 1–2 MW or less. Frequently uses high-enriched uranium fuel, although most newer models use no more than 20-percent enrichments to make the theft of fuel less attractive. Fertile material (^{238}U for Pu, ^{6}Li for tritium) can be encapsulated in elements known as “targets” for insertion into the reactor core. The reactor can also employ a fertile blanket of ^{238}U in which plutonium can be bred. Cooling requirements and shielding requirements are relatively modest. Some research reactors can be refueled while operating, and such reactors are of special concern for plutonium production because they can limit fuel burnup, which enhances the quality of the plutonium compared to that obtained from reactors that require high burnup before shutdown and refueling.

Highlights

- Plutonium, used in many nuclear weapons, can only be made in sufficient quantities in a nuclear reactor.
- The graphite-moderated, air- or gas-cooled reactor using natural uranium as its fuel was first built in 1942. Scale-up of these types of reactors from low power to quite high power is straightforward.
- Reactors have been built in many countries of the world, including some of real proliferation concern.
- Reactors using natural uranium can make relatively high quality plutonium.
- Reactors are generally purpose-built, and reactors built and operated for plutonium production are less efficient for electricity production than standard nuclear electric power plants because of the low burnup restriction for production of weapons grade plutonium.

(2) Power reactors. These are used to generate electric power. Few use fuel enriched to greater than 5–7% ^{235}U. Practical power levels range from a few hundred MW(e) (three times that in terms of thermal power output) to 1,000 or 1,500 MW(e)—meaning 3,000–4,000 MW(t). Power reactors designs have included water cooled-graphite moderated (the Soviet RBMK used at Chernobyl), boiling (light) water, pressurized (light) water, heavy water-moderated and cooled, graphite-moderated/helium cooled, and liquid metal-moderated. Most power reactors operate under pressure and cannot be refueled in operation. The RBMK and CANDU reactors are notable exceptions to this rule. The CANDU reactor was developed for the Canadian nuclear power program and is a deuterium oxide (heavy water) moderated reactor which can operate on natural uranium fuel.

(3) Production reactors. These are used to make plutonium (and often tritium) efficiently. Production reactors are frequently graphite-moderated and either air-, CO_2-, or helium-cooled. The longer a given sample of fuel is irradiated, the greater the build-up of ^{240}Pu, an isotope which decays by spontaneous fission and which should be minimized in weapon fuel. Consequently, plutonium production reactors usually are designed to be refueled while operating (on-line refueling) so that relatively little ^{240}Pu is found in the "spent" fuel.

(4) Breeder reactors. These reactors generate plutonium at a rate greater (numbers of nuclei per unit time) than they burn their fissile fuel (numbers of nuclei per unit time). Normally, breeders use fast neutrons and irradiate a fissile ^{238}U blanket. Plutonium produced in the fuel generally has a higher fraction of ^{240}Pu than that produced in other reactors, but the Pu made in the *blanket* of uranium surrounding the core is usually of a high quality, containing very little ^{240}Pu .

(5) Propulsion reactors. Primarily found on submarines and large-surface combatant ships, nuclear reactors have given new operational freedom to the underwater navy and deliver increased time on station combined with high speed for both the submarine service and the surface navy. The United States and Russia have built most of the world's shipboard reactors. The world's first nuclear powered cargo ship was the *U.S.N.S. Savannah*; however, nuclear propulsion power has not been particularly successful in the commercial world. Today, the only operating commercial vessels using nuclear propulsion are Russian icebreakers. To keep the core size small, propulsion reactors generally use highly enriched uranium as fuel. In principle, a propulsion reactor core could be surrounded with a fertile blanket and used to produce plutonium. In practice, this has never been done.

(6) Space reactors and mobile power systems. Nuclear reactors have been used from time to time, usually by the former Soviet Union, to provide on-orbit electrical power to spacecraft. In principle, they will use HEU as fuel to keep the core mass and volume small. Other spacecraft have been powered by the heat released by the radioactive decay of ^{238}Pu.

RATIONALE

Plutonium, one of the two fissile elements used to fuel nuclear explosives, is not found in significant quantities in nature. Instead, it must be "bred," or produced, one atomic nucleus at a time by bombarding ^{238}U with neutrons to produce the isotope ^{239}U, which beta decays (half-life 23 minutes), emitting an electron to become the (almost equally) radioactive ^{239}Np (neptunium). The neptunium isotope again beta decays (half-life 56 hours) to ^{239}Pu, the desired fissile material. The only proven and practical source for the large quantities of neutrons needed to make plutonium at a reasonable speed is a nuclear reactor in which a controlled but self-sustaining ^{235}U fission chain reaction takes place. Accelerator-based transmutation to produce plutonium is theoretically possible, and experiments to develop its potential have been started, but the feasibility of large-scale production by the process has not been demonstrated.

In addition to production of plutonium, nuclear reactors can also be used to make tritium, ^{3}H, the heaviest isotope of hydrogen. Tritium is an essential component of boosted fission weapons and multi-stage thermonuclear weapons. The same reactor design features which promote plutonium production are also consistent with efficient tritium production, which adds to the proliferation risk associated with nuclear reactors.

The "size" of a nuclear reactor is generally indicated by its power output. Reactors to generate electricity are rated in terms of the electrical generating capacity, MW(e), meaning megawatts of electricity. A more important rating with regard to production of nuclear explosive material is MW(t), the *thermal* power produced by the reactor. As a general rule, the thermal output of a power reactor is *three times* the electrical capacity. That is, a 1,000 MW(e) reactor produces about 3,000 MW(t), reflecting the inefficiencies in converting heat energy to electricity.

A useful rule of thumb for gauging the proliferation potential of any given reactor is that *1 megawatt-day (thermal energy release, not electricity output) of operation produces 1 gram of plutonium* in any reactor using 20-percent or lower enriched uranium; consequently, a 100 MW(t) reactor produces 100 grams of plutonium per day and could produce roughly enough plutonium for one weapon every 2 months. Research reactors using nearly 100-percent enriched material produce almost no plutonium in their fuel because the fertile species, ^{238}U, has been removed. These reactors can, however, be built with a surrounding "blanket" of natural or depleted uranium in which plutonium can be bred efficiently. The *Osirak* reactor built in Iraq and destroyed by Israeli aircraft was of this type.

A typical form of production reactor fuel is natural uranium metal encased in a simple steel or aluminum cladding. Because uranium metal is not as dimensionally stable when irradiated as is uranium oxide used in high burnup fuel, reactors fueled with the uranium metal must be confined to very low burnup operation, which is not economical for electricity production. This operational restriction for uranium metal fuel results in the production of plutonium with only a small admixture of the undesirable isotope, ^{240}Pu. Thus, it is almost certain that a reactor using metallic fuel is intended to produce weapons grade plutonium, and operation of such a reactor is a strong indicator that proliferation is occurring.

Many technologies are useful in the construction and operation of nuclear reactors. The following are nuclear reactor related technologies:

- Conversion of uranium to the appropriate chemical form (e.g., UO_2,) from fluorides or from yellowcake.
- Fuel fabrication including conversion, melting or casting, alloying, and the production of rods or billets. Operations would include machining, heat treatment, extrusion, and rolling.

- Fuel rod cladding.
- Control systems and appropriate instrumentation. Cooling systems including those for use in emergencies and, for power reactors, coupling to electrical generation equipment.
- Containment/confinement structures to minimize fission product release from the reactor site.
- Refueling equipment.
- Reprocessing facilities including facilities to chop highly radioactive fuel rods into small pieces, dissolve the fuel in acid, and extract plutonium from the radioactive liquid process streams.
- Spent fuel storage (temporary or permanent) including facilities to cool the discharged fuel.

Proliferation Implications Assessment

It is unlikely that any nuclear state or threshold state has produced nuclear weapons by diverting material from a safeguarded nuclear reactor or from other safeguarded parts of the nuclear fuel cycle. This result is due in part because the typical power reactor uranium fuel is enriched to only 3 percent to 5 percent, and it is not usable directly in a nuclear weapon; most such reactors cannot be refueled without extended, easily detected shutdowns. While the large quantity of low-quality plutonium produced in civilian nuclear power reactors is of concern because even high-burnup plutonium containing more than 10 percent ^{240}Pu can be used in a nuclear explosive, individual power reactors provide little opportunity for the proliferator to obtain fuel for a weapon. It is difficult to irradiate fertile material in power reactors and uneconomical to shut down frequently to extract the fuel at the low burnup levels that yield high-quality plutonium.

The existence of a nuclear power industry in a country is, however, proof that the state has the necessary skilled manpower to design and build large parts of the infrastructure for a nuclear weapons program. The experience gained operating a civilian power reactor would be valuable should a country elect to pursue nuclear weapons. The risk associated with a power reactor program is that some of the technology legitimately acquired for the electricity-producing power reactor could be transferred without detection to the construction and operation of a plutonium production reactor.

To reduce such risk of nuclear proliferation, nations that supply nuclear-related equipment and materials have joined in an organization known as the Nuclear Suppliers Group (NSG). The NSG, through the International Atomic Energy Agency (IAEA), has published guidelines which trigger the requirement for full scope safeguards to be in place in the receiving nation before the nuclear reactor components of interest can be exported by member nations. These guidelines are referred to as the “Trigger List” and are designated “NTL” in the “Export Control Reference” column of Table 5.3-1. (IAEA INFCIRC/254/Rev. 2/Part 1, 17 June 1996.)

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Six countries are known to have detonated nuclear explosive devices. Of these six, five elected to test a plutonium device before experimenting with uranium-based weapons. Only China chose to go the uranium route. Of the suspected threshold states and former threshold states (Iraq, North Korea, Israel, South Africa, Pakistan) which have not exploded a device, three are believed to have pursued the plutonium route as their first choice. South Africa and Pakistan appear to have preferred enriching uranium; after the *Osirak* reactor was destroyed, Iraq switched to a uranium-based design. Although uranium enrichment (see Section 5.2, Uranium Enrichment Processes) is one way of obtaining the special materials to join the nuclear club, nuclear reactors provide an equally satisfactory route in the event the path to enrichment is blocked or rejected.[9] Indeed, in a well-designed production reactor, one uranium fission is likely to produce on average about 0.8 plutonium nuclei, and many fewer atoms of plutonium than ^{235}U atoms are required to make a fission device.[10]

Many nations (see Figure 5.0-2) have the ability to design, build or operate nuclear reactors. In addition to U.S. firms, Swiss and Swedish (ASEA-Brown Boveri, ABB), French, British, and Chinese enterprises have sold power or research reactors on the international market.

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[9] Lack of an adequate supply of electricity is one obstacle to a sucessful enrichment program; inability to acquire uranium or specialized technologies can be another.

[10] Plutonium and uranium densities are nearly the same, but the critical mass of plutonium is only about 20 percent that of HEU because of plutonium's greater reactivity.

Table 5.3-1. Nuclear Fission Reactors Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Power Reactors (Fast): Liquid Metal Fast Breeder Reactor (LMFBR)	Ability to extract plutonium from irradiated fuel or targets. Liquid metal handling systems, oxide fuel fabrication, uranium enrichment capability.	NTL B1; NRC A	*Fuel:* stainless steel clad UO_2/PuO_2 fuel pellets. *Coolant*: usually liquid metal (e.g., sodium).	Equipment specially designed to extract enriched uranium and/or plutonium fuel sources from reactor core; fuel fabrication techniques specially designed for fast reactors. Equipment for handling solid and liquid sodium.	None Identified
Power Reactors (Thermal): Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), Heavy Water Reactor (HWR)	Control criticality, establish uniform temperature rise in reactor core, ability to remove fuel elements and extract enriched uranium and/or plutonium. Heavy water production. Oxide fuel fabrication. BWR and PWR require uranium enrichment.	NTL B1; NRC A	*Fuel:* basic fission fuels-U-235, U-233, Pu-239; U-238 (for use in creating Pu-239), natural uranium, enriched uranium, uranium oxide, alloys of uranium-plutonium, mixtures of uranium-plutonium oxides and carbides, thorium-232 (for use in creating U-233); *Moderator:* ordinary (light) water, heavy water (deuterium oxide); *Coolant:* ordinary (light) water, heavy water (deuterium oxide).	Methods for producing cylindrical fuel elements by compacting and sintering cylindrical pellets(e.g., uranium oxide); zirconium alloy (Zircaloy) tube about 13 mm in diameter and 3.7 m long (typical); equipment specially designed to extract fuel from reactor core.	None Identified
Power Reactors (Thermal): High Temperature Gas Cooled Reactor (HTGR), Advanced Gas Reactor (AGR)	Fabrication of refractory fuel elements from high-purity graphite. High pressure, high volume coolant gas circulating pumps (turbines).	NTL B1; NRC A	*Fuel:* usually Low Enriched Uranium (LEU); *Moderator:* graphite. *Coolant:* Helium (HTGR), carbon dioxide (AGR)	Specially designed production equipment to fabricate special fuel assemblies. High pressure CO_2 or He gas handling equipment.	None Identified

(cont'd)

Table 5.3-1. Nuclear Fission Reactors Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Production Reactors	Target and fuel reprocessing facilities to extract plutonium or tritium. High purity graphite. Heavy water production. Uranium metal production.	NTL	*Fuel:*natural or slightly enriched uranium for plutonium production, HEU and ^{6}Li - enriched target for tritium production. *Moderator:* heavy water, can be graphite. *Coolant:* air, light water, heavy water	Fuel and target reprocessing facilities usually located at the same site or nearby. Hot cell facilities. Specially designed equipment for fabrication of fuel elements and targets for breeding plutonium and/or tritium.	None Identified
Research Reactors	Fuel technology spans light water, heavy water, graphite, organic, and hydride moderated types.	NTL	*Fuel:* HEU or LEU; *Moderator:* graphite, hydrides, organic materials (hydrocarbons), light water, heavy water. *Coolant:* light water, heavy water	Equipment configured for frequent shutdowns associated with insertion withdrawal of target elements. Hot cell facilities to support research and development.	None Identified

Table 5.3-2. Nuclear Fission Reactors Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Power Reactors (Fast) Liquid Metal Fast Breeder Reactor (LMFBR)	Pu-239 extraction (reprocessing). Ability to design and fabricate containment vessels and operate safely for extended periods. Availability of HEU or plutonium. Liquid metal (e.g., sodium) handling.	Nuclear weapons	Enrichment technologies, thermal power reactors, production reactors, research reactors.
Power Reactors (Thermal): Pressurized Water Reactor (PWR), Boiling Water Reactor (BWR), Heavy Water Reactor (HWR)	Ability to design and construct pressure vessels and cooling systems. Ability to process highly radioactive spent fuel assemblies	Nuclear weapons	Enrichment technologies, fast power reactors, intermediate power reactors, production reactors, research reactors
Power Reactors (Thermal): High Temperature Gas Cooled Reactor (HTGR), Advanced Gas Reactor (AGR)	Removal of refractory cladding from fuel. Reprocessing facilities.	Nuclear weapons	Enrichment technologies, fast power reactors, intermediate power reactors, production reactors, research reactors
Production Reactors	Methods for extracting Pu-239 and/or tritium from fuel or targets.	Nuclear weapons	Enrichment technologies, fast power reactors, thermal power reactors, research reactors.
Research Reactors	Methods for extracting enriched uranium and/or Pu-239 and/or tritium from fuel or targets. Facility for irradiating quantities of fertile material.	Nuclear weapons	Enrichment technologies, fast power reactors, thermal power reactors, production reactors

SECTION 5.4—PLUTONIUM EXTRACTION (REPROCESSING)

OVERVIEW

This subsection covers technologies involved in the recovery and purification of uranium and plutonium in spent (irradiated) reactor fuel and irradiated targets. Unlike fuel from fossil plants that discharge ash with negligible heat content, fuel discharged from nuclear reactors contains appreciable quantities of fissile uranium and plutonium ("unburned" fuel). These fuel elements must be removed from a reactor before the fissile material has been completely consumed, primarily because of fission product buildup. Fission products capture large numbers of neutrons, which are necessary to sustain a chain fission reaction. In the interest of economic utilization of nuclear fuels and the conservation of valuable resources, several countries have constructed reprocessing plants to recover the residual uranium and plutonium values, utilizing a variety of physical and chemical methods.

Plutonium is one of the two elements which have been used in fission explosives. It does not exist naturally in any significant quantities but must be made nucleus by nucleus in a nuclear reactor by the process of neutron absorption on ^{238}U followed by two beta decays producing first neptunium and then plutonium. The plutonium is removed from the spent fuel by chemical separation; no nuclear or physical separation (as for example in uranium enrichment) is needed. To be used in a nuclear weapon, plutonium must be separated from the much larger mass of non-fissile material in the irradiated fuel.

After being separated chemically from the irradiated fuel and reduced to metal, the plutonium is immediately ready for use in a nuclear explosive device.

If the reactor involved uses thorium fuel, ^{233}U, also a fissile isotope, is produced and can be recovered in a process similar to plutonium extraction.

The first plutonium extraction (reprocessing) plants to operate on an industrial scale were built at Hanford, Washington, during the Manhattan Project. The initial plant was built before the final parameters of the extraction process were well defined. Reprocessing plants are generally characterized by heavy reinforced concrete construction to provide shielding against the intense gamma radiation produced by the decay of short-lived isotopes produced as fission products. Plutonium extraction and uranium reprocessing are generally combined in the same facility in the civilian nuclear fuel cycle. Although the United States no longer reprocesses civil reactor fuel and does not produce plutonium for weapons, other countries have made different choices. Britain, France, Japan, and Russia (among others) operate reprocessing plants.

A brief description of the main features/processes (and related technology) of a reprocessing plant follows.

Highlights

- Plutonium is extracted from spent reactor fuel and irradiated targets.
- Fuel choppers can be as simple as a power-driven saw. The most challenging technical component of a reprocessing plant is the separation system (mixer/settlers, extracted columns, or centrifugal contractors). Flow rates must be monitored precisely, the chemistry must be exact, and a critical excursion must be prevented.
- Although the steps used in reprocessing are standard chemical operations and the literature on the chemistry and equipment required has been widely disseminated, the successful separation of uranium and plutonium is a formidable task.

- **Heavy industrial construction.** All operations are performed in a facility that is usually divided into two structural sections (hardened and nonhardened) and two utility categories (radiation and ventilation/contamination). The hardened portion of the building (reprocessing cells) is designed to withstand the most severe probable natural phenomena without compromising the capability to bring the processes and plant to a safe shutdown condition. Other parts of the building (i.e., offices and shops), while important for normal functions, are not considered essential and are built to less rigorous structural requirements. Radiation is primarily addressed by using 4- to 6-ft thick, high-density concrete walls to enclose the primary containment area (hot cells). A proliferator who wishes to reprocess fuel covertly for a relatively short time—less than a year would be typical—may use concrete slabs for the cell walls. Holes for periscopes could be cast in the slabs. This is particularly feasible if the proliferator cares little about personnel health and safety issues.
- **Fuel storage and movement.** Fuel is transported to the reprocessing plant in specially designed casks. After being checked for contamination, the clean fuel is lowered into a storage pool via a heavy-duty crane. Pools are normally 30-ft deep for radiation protection and contain a transfer pool, approximately

15-ft deep, that provides an underwater system to move the fuel into an adjacent hot cell.

- **Fuel disassembly.** Fuel elements are breached (often chopped) to expose the fuel material for subsequent leaching in nitric acid (HNO_3). Fuel cladding is frequently not soluble in nitric acid, so the fuel itself must be opened to chemical attack.
- **Fuel dissolution.** Residual uranium and plutonium values are leached from the fuel with HNO_3. The cladding material remains intact and is separated as a waste. The dissolver must be designed so that no critical mass of plutonium (and uranium) can accumulate anywhere in its volume, and, of course, it must function in contact with hot nitric acid, a particularly corrosive agent. Dissolvers are typically limited-life components and must be replaced. The first French civilian reprocessing plant at La Hague, near Cherbourg, had serious problems with leakage of the plutonium-containing solutions.

Dissolvers may operate in batch mode using a fuel basket or in continuous mode using a rotary dissolver (wheel configuration).

- **Fissile element separation.** The PUREX (Plutonium Uranium Recovery by EXtraction) solvent extraction process separates the uranium and plutonium from the fission products. After adjustment of the acidity, the resultant aqueous solution is equilibrated with an immiscible solution of tri-n-butyl phosphate (TBP) in refined kerosene. The TBP solution preferentially extracts uranium and plutonium nitrates, leaving fission products and other nitrates in the aqueous phase. Then, chemical conditions are adjusted so that the plutonium and uranium are reextracted into a fresh aqueous phase. Normally, two solvent extraction cycles are used for the separation; the first removes the fission products from the uranium and plutonium, while the second provides further decontamination. Uranium and plutonium are separated from one another in a similar second extraction operation. TBP is a common industrial chemical used in plasticizers and paints. Solvent extraction usually takes place in a pulse column, a several-inch diameter metal tube resistant to nitric acid and used to mix together the two immiscible phases (organic phase containing TBP and an aqueous phase containing U, Pu, and the fission products). The mixing is accomplished by forcing one of the phases through the other via a series of pulses with a repetition rate of 30 to 120 cycles/minute and amplitudes of 0.5 to 2.0 inches. The metal tube contains a series of perforated plates which disperses the two immiscible liquids.
- **U & Pu product purification.** Although plutonium and uranium from solvent extraction are nearly chemically pure, additional decontamination from each other, fission products, and other impurities may be required. Large plants use additional solvent extraction cycles to provide this service, but small plants may use ion exchange for the final purification step (polishing).
- **Metal preparation.** Plutonium may be precipitated as PuF_3 from aqueous nitrate solution by reducing its charge from +4 to +3 with ascorbic acid and adding hydrofluoric acid (HF). The resulting solid is separated by filtration and dried. Reprocessed uranium is rarely reduced to the metal, but it is converted to the oxide and stored or to the hexafluoride and re-enriched. Plutonium (and uranium) metal may be produced by the reaction of an active metal (calcium or magnesium) with a fluoride salt at elevated temperature in a sealed metal vessel (called a “bomb”). The metal product is freed from the slag, washed in concentrated HNO_3 to remove residue, washed with water, dried, and then remelted in a high temperature furnace (arc).
- **Waste treatment/recycle.** Reprocessing operations generate a myriad of waste streams containing radioactivity. Several of the chemicals (HNO_3) and streams (TBP/kerosene mixture) are recycled. All streams must be monitored to protect against accidental discharge of radioactivity into the environment. Gaseous effluents are passed through a series of cleaning and filtering operations before being discharged ,while liquid waste streams are concentrated by evaporation and stored or solidified with concrete. In the ultimate analysis, the only way to safely handle radioactivity is to retain the material until the activity of each nuclide disappears by natural decay.

Early plants used “mixer-settler” facilities in which the two immiscible fluids were mixed by a propeller, and gravity was used to separate the liquids in a separate chamber. Successful separation requires that the operation be conducted many times in sequence. More modern plants use pulse columns with perforated plates along their length. The (heavier) nitric acid solution is fed in at the top and the lighter TBP-kerosene from the bottom. The liquids mix when they are pulsed through the perforations in the plates, effectively making a single reactor vessel serve to carry out a series of operations in the column. Centrifugal contractors using centrifugal force have also been used in place of mixer-settlers. The process must still be repeated many times, but the equipment is compact. New plants are built this way, although the gravity-based mixer-settler technology has been proven to be satisfactory, if expensive and space-consuming.

A single bank of mixer-settler stages about the size of a kitchen refrigerator can separate enough plutonium for a nuclear weapon in 1–2 months. A bank of eight centrifugal contactors can produce enough plutonium for an explosive device within a few days and takes up about the same space as the mixer-settler.

Hot cells with thick radiation shielding and leaded glass for direct viewing, along with a glove box with minimal radiation shielding, are adequate for research-scale plutonium extraction, are very low technology items, and would probably suffice for a program designed to produce a small number of weapons each year. The concrete canyons housing many smaller cells with remotely operated machinery are characteristic of large-scale production of plutonium.

Different organic extraction reagents and different acids may be used. Ion exchange can be substituted for solvent extraction, but the exchange materials are susceptible to radiation damage.

Nonaqueous technologies have also been studied, including pyrochemical processes in advanced development in the US for EBR-II. Russia and Japan are apparently also interested.

Proliferation Implication Assessment

Roughly five times as many nuclei of ^{235}U as of ^{239}Pu are required to make a critical mass. A proliferator can choose between laboriously extracting the fissile uranium isotope from the 99.3 percent of natural uranium which is not useful in a fission bomb, or laboriously breeding the necessary plutonium, nucleus-by-nucleus, in a reactor and then extracting the plutonium from the spent fuel. Intense radiation emitted by certain components in spent reactor fuel makes this separation especially difficult and hazardous. The processing equipment must be surrounded by massive shielding; provision must be made to remove substantial amounts of heat that are associated with this radioactivity; and in some instances, damage to chemicals and construction materials become an impediment to a successful separation campaign. However, several hundred metric tons (MT) of both weapons-grade and reactor-grade plutonium have been separated, and present worldwide reprocessing capacity is >3,000 MT of fuel per year (>27 MT of plutonium).

Plutonium-fueled weapons must be assembled by implosion.

RATIONALE

The production of weapons-grade uranium is a formidable task because the concentration of the fissile isotope ^{235}U in natural uranium (0.7 percent) is much lower than the concentration normally used in fission weapons (>90 percent), and the enrichment of ^{235}U is difficult because of the very slight differences in the physical and chemical properties of the uranium isotopes.

Alternatively, ^{239}PU may be selected as weapons material. The problems associated with enrichment are replaced with those of acquiring plutonium—a man-made element. The element can be produced from ^{238}U during the fissioning process and can be separated chemically from undesirable waste products.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Reprocessing plants have been operated by all five declared nuclear powers. India reprocessed spent fuel for its one nuclear explosion. It is believed that North Korea reprocessed spent fuel from one of its reactors. Iraq reprocessed at least gram-quantities of plutonium according to IAEA inspection reports. Sweden and Switzerland at least considered the design of reprocessing plants for their (now defunct) weapons programs.

Germany and France operate reprocessing facilities for civilian nuclear fuel; Japan is constructing such a facility.

Table 5.4-1. Plutonium Extraction (Reprocessing) Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Heavy industrial construction	Ability to fabricate a facility which will protect workers and the environment from radioactivity and hazardous materials (note: some countries may have different criteria than the United States in this regard).	NTL B3; NDUL 1; NDUL 8; CCL Cat 2B	High-density concrete	Radiation monitoring (applies to all processes) Fuel storage pool Cranes Hot cells Remote manipulators High-density radiation shielding windows Radiation-hardened TV cameras Air filtration Evaporators	Shielding software Criticality software Radiation generation/ depletion software
Fuel storage and movement	Sufficient storage pool capacity and depth. Ability to move radioactive material.	NTL B3; NRC A	None identified	Remotely operated cranes Specially designed shipping casks Criticality control	None identified
Fuel disassembly (breaching)	Capability to separate cladding from fissile material mechanically or chemically.	NTL B3; NRC A	None identified	Cut-off wheel Shear dissolver (for Al cladding) Laser	None identified
Fuel dissolution	Ability to handle highly corrosive liquids containing radioactivity. Adequate knowledge of uranium, plutonium, and fission product chemistry.	NTL B3; NRC A	Nitric acid (HNO_3) Hydrogen fluoride (HF) HNO_3 resistant tanks of a specific configuration to prevent a nuclear excursion	Analytical chemistry facility for fission products, U and Pu	None identified
Fissile element separation (solvent extraction)	Familiar with liquid-liquid extraction systems. Understand distribution of uranium, plutonium, and fission products between two immiscible liquids.	NTL B3; NRC A	None identified	Mixer/settlers Pulse columns Centrifugal contactors	Distribution coefficients for many elements. Aqueous solubility for many substances.

(cont'd)

Table 5.4-1. Plutonium Extraction (Reprocessing) Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
U and Pu product purification	Cognizant of liquid-liquid extraction systems Familiar with ion exchange resin systems	NTL B3; NTL 3; NRC A	Tri-n-butyl phosphate (TBP) Refined kerosene Ion exchange resins	Mixer/settlers Pulse columns Centrifugal contactors Chemical holding or storage vessels	Distribution coefficients for many elements Aqueous solubility for many substances
Metal preparation (Pu exclusively)	Ability to handle plutonium in glove boxes	NTL B3; NDUL 2; CCL Cat 1C; NRC A	HF Reducing agents (high-purity Ca or Mg) CaF_2 or MgF_2 (used as liner for reduction bomb) Iodine (serves as catalyst in reduction)	Drying Furnace; Fluoride resistant (Monel) Furnace capable of reaching 600 °F Sealed reaction tube Temperature control/measurement High temperature furnace (arc)	None identified
Waste treatment/recycle	Ability to recycle valuable components (TBP, HNO_3) Ability to process streams containing high levels of radioactivity and hazardous materials	NTL B3; NRC A	Resistant to HNO_3 (stainless steel, titanium alloys)	Chemical storage tanks	None identified

Table 5.4-2. Plutonium Extraction (Reprocessing) Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Heavy industrial construction	Ability to construct a thick-walled, relatively sealed structure with adequate shielding.	Provides shielded facility for all reprocessing operations	May not be needed if nation unconcerned about its workers or the environment and reprocessing is to be a short-term endeavor.
Fuel storage and movement	Adequate depth of storage pool to shield spent fuel. Sufficient storage capacity for fuel. Cranes of sufficient capacity to handle shipping casks.	None identified	Use reactor storage pool if close proximity to reprocessing facility. Possible storage (dry) in specially designed casks.
Fuel disassembly (breaching)	Capability to remove as much extraneous material from fuel element as possible. Knowledgeable in the construction and use of one of the breaching tools.	None identified	None identified
Fuel dissolution	Ability to prevent a nuclear excursion	None identified	Several nonaqueous processes have been developed but most are complicated (pyro-metallurgical, pyrochemical, and fluoride volatility)
Fissile element separation (solvent extraction)	Ability to prevent a nuclear excursion. Aqueous solution from separation process contains extremely hazardous radioactive materials.	None identified	Use one of the nonaqueous processes. Replace solvent extraction with ion exchange process. Use a precipitation process (bismuth phosphate).
U and Pu product purification	Ability to obtain a pure product. Availability of ion exchange resins and sufficient knowledge of their use.	None identified	Use one of the precipitation processes (peroxide, oxalate)
Metal preparation (Pu exclusively)	Capability to handle molten Pu metal.	Produces metallic Pu	Electrolytic process (requires molten salts—1,300 °F). Reduction of other halides
Waste treatment/recycle	High level radioactive waste must be handled with extreme care.	None identified	Discharge all aqueous waste solutions to the environment. Minimal recycling (expensive but may be used for limited production).

SECTION 5.5—LITHIUM PRODUCTION

OVERVIEW

This subsection discusses chemical methods for separation of ^{6}Li from natural lithium, which is predominantly composed of the isotope ^{7}Li. ^{6}Li is a critical material for the manufacture of the secondaries of so-called dry thermonuclear devices, which do not require the use of liquid deuterium and tritium. It is inconvenient to carry deuterium and tritium as gases in a thermonuclear weapon, and certainly impractical to carry them as *liquefied* gases, which requires high pressures and cryogenic temperatures. Instead, one can make a "dry" device in which ^{6}Li is combined with deuterium to form the compound ^{6}Li D (lithium-6 deuteride). Neutrons from a fission "primary" device bombard the ^{6}Li in the compound, liberating tritium, which quickly fuses with the nearby deuterium. The α particles, being electrically charged and at high temperatures, contribute directly to forming the nuclear fireball. The neutrons can bombard additional ^{6}Li nuclei or cause the remaining uranium and plutonium in the weapon to undergo fission. This two-stage thermonuclear weapon has explosive yields far greater than can be achieved with one point safe designs of pure fission weapons, and thermonuclear fusion stages can be ignited in sequence to deliver any desired yield. The largest nuclear device ever detonated was a multi-stage Soviet product with a yield of nearly 60 *megatons*. It was exploded at only half of its design maximum yield of about 100 megatons.

Lithium enriched in the isotope ^{6}Li remains a controlled material because of its utility in the production of compact and highly efficient thermonuclear secondaries. Two-stage nuclear weapons incorporating a lithium-deuteride-fueled component can deliver greater nuclear yield from a smaller and lighter package than if a pure fission device were used. The tradeoff is that the design and construction of reliable two-stage "dry" weapons may require significant knowledge of nuclear weapons physics and technology, knowledge which is hard to acquire without a program involving full-yield testing of the fission primary to be used and measurement of its production of x-rays and their transport through a case surrounding both primary and secondary stages. Therefore, ^{6}Li is more likely to be of interest to a state with nuclear weapons experience than it is to a beginning nuclear state.

Lithium is a very low-density silvery metal, prone to spontaneous combustion. On the periodic table of the elements it lies directly beneath hydrogen and has but three protons. It is the lightest solid element. The most common stable isotope is ^{7}Li, consisting of three protons and four neutrons; less common, comprising 7.4 percent of normal lithium, is ^{6}Li, which has three protons and three neutrons in its nucleus. In a relatively crude sense, ^{6}Li can be thought of as consisting of an alpha particle (^{4}He) and a deuteron (^{2}H) bound together. When bombarded by neutrons, ^{6}Li disintegrates into a triton (^{3}H) and an alpha:

$$^6\text{Li} + \text{Neutron} \rightarrow {}^3\text{H} + {}^3\text{He} + \text{Energy}.$$

This is the key to its importance in nuclear weapons physics.

The nuclear fusion reaction which ignites most readily is

$$^2\text{H} + {}^3\text{H} \rightarrow {}^4\text{He} + \text{n} + 17.6 \text{ MeV},$$

or, phrased in other terms, deuterium plus tritium produces ^{4}He plus a neutron plus 17.6 MeV of free energy:

$$\text{D} + \text{T} \rightarrow {}^4\text{He} + \text{n} + 17.6 \text{ MeV}.$$

Lithium-7 also contributes to the production of tritium in a thermonuclear secondary, albeit at a lower rate than ^{6}Li. The fusion reactions derived from tritium produced from ^{7}Li contributed many unexpected neutrons (and hence far more energy release than planned) to the final stage of the infamous 1953 Castle/BRAVO atmospheric test, nearly doubling its expected yield.

Highlights

- Lithium-6, combined with deuterium, is a key ingredient of modern thermonuclear weapons.
- Lithium-6 can be separated from the more common ^{7} Li isotope by purely chemical means using the fact that ^{6}Li will migrate to a mercury amalgam and ^{7}Li to a lithium hydroxide solution when the amalgam and hydroxide solutions are intimately mixed.
- The presence of a ^{6} Li enrichment facility is a good indicator that a proliferant state has confidence in its fission primaries and seeks more powerful weapons.
- The United States ceased the production of ^{6}Li in 1963 because it had acquired an adequate stockpile of the material for the foreseeable future.

RATIONALE

Lithium-6 is most often separated from natural lithium by the *COLEX* (Column exchange) electrochemical process, which exploits the fact that ^{6}Li has a greater affinity for mercury than does ^{7}Li. A lithium-mercury amalgam is first prepared using the natural material. The amalgam is then agitated with a lithium hydroxide solution, also prepared from natural lithium. The desired ^{6}Li concentrates in the amalgam, and the more common ^{7}Li migrates to the hydroxide. A counter flow of amalgam and hydroxide passes through a cascade of stages until the desired enrichment in ^{6}Li is reached. The ^{6}Li product can be separated from the amalgam, and the "tails" fraction of ^{7}Li electrolyzed from the aqueous lithium hydroxide solution. The mercury is recovered and can be reused with fresh feedstock.

Proliferation Initiation Assessment:

Thermonuclear weapons require the acquisition of reliable, compact, and predictable fission primaries. It is unlikely that a proliferator will reach the point of designing a thermonuclear device until long after it has developed its first family of compact primaries. Accordingly, it is likely that no new proliferator would embark on a hydrogen weapon as its first priority or seek separated lithium isotopes before having an assured supply of HEU or plutonium. Therefore, an attempt by a potential proliferant state to acquire ^{6}Li or the technologies to produce it might well be taken as an indicator that the state has already progressed at least a long way toward obtaining a nuclear capability.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Russia, the UK, France, and China are all believed to be capable of making ^{6}Li in the quantities needed for the manufacture of large nuclear stockpiles. Russia exploded a device making use of ^{6}Li before the United States did; however, the Soviet device was not a "true" thermonuclear weapon capable of being scaled to any desired yield.

United States production of ^{6}Li ceased in 1963.

Table 5.5-1. Lithium Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Electrolysis	Supply large d.c. currents at low and variable voltages. Provide adequate temperature control. Produce pure lithium salts for feed material. Experience in fabricating columns, trays, etc. Sufficient knowledge of the chemistry of lithium hydroxide aqueous solutions and mercury and its amalgams.	NDUL 8; NRC 110.8	Mercury Lithium salts Nickel Carbon steel	Electrolysis cells Liquid flow and pressure control	Voltages needed for electrolysis. Variation of solubility of lithium in mercury with temperature.
Enrichment	Experience in liquid-liquid extraction systems. Expertise in the chemistry of mercury-lithium distribution coefficients. Capability in cascade theory and operations.	NDUL 8; NRC 110.8	Mercury Lithium hydroxide	Packed liquid-liquid exchange columns. Pumps resistant to mercury. Analytical chemistry laboratory. Mass spectrometer. Valves resistant to mercury.	Lithium distribution data (amalgam/aqueous)
Decomposition of amalgam	Knowledgeable in disposing of hydrogen gas. Experience in using packed-bed columns.	NDUL 8; NRC 110.8	Graphite	Packed columns. Pumps for mercury. Metallic filters. Evaporators for mercury amalgam.	Voltages needed for decomposition
Mercury recycle	Experience in purifying mercury	NDUL 8; NRC 110.8	Mercury Nitric acid	Mercury cleaning system	None identified

Table 5.5-2. Lithium Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Electrolysis	Ability to control large d.c. currents at low voltages	Fusion weapons	None
Enrichment	Adequate supply of high purity lithium salts and mercury. Knowledge of lithium hydroxide/ mercury/aqueous chemistry	^{6}LiD (lithium-6 deuteride) used as fusion weapon fuel. ^{6}Li used as target material in tritium production	Electroexchange (ELEX) process using a series of stirred tray contactors. Liquid-liquid extraction systems using marcrocyclic compounds (i.e., benzo-15-crown-5 and cryptands) in a diluent
Decomposition of amalgam	Availability of high-purity graphite. Expertise in preventing hydrogen explosion.	Fusion weapons	Utilization of newer liquid-liquid extraction systems
Mercury recycle	Ability to handle corrosive liquids	Fusion weapons	Discard mercury when it is no longer effective

SECTION 5.6—NUCLEAR WEAPONS DESIGN AND DEVELOPMENT

OVERVIEW

Weapons

Nuclear weapons are small, light, and inexpensive compared to the conventional ordnance needed to destroy large area targets. Although the infrastructure for a nuclear enterprise is complex, the weapons themselves use relatively straightforward designs. Nuclear explosives enable a single missile or aircraft to destroy an entire city, giving great leverage to a state or subnational group with even a small stockpile of such devices. Nuclear weapons were first developed more than a half century ago with technology and knowledge of physics far less than available today.

Identifying some of the key technologies needed to acquire a nuclear weapons capability may allow effective intervention and/or identification of trends of concern. Although a great deal of information, much of which is not correct, on the principles of nuclear explosives is available in the public domain, development of nuclear weapons, even in the early stages, requires an understanding and mastery of the relevant physical principles. Such an understanding, which is necessary even to plan a program to achieve a nuclear weapon capability, contains elements from fields not generally familiar to today's scientists. A number of steps are necessary to develop nuclear weapons, and if these steps are not well understood, false starts will be made, and valuable resources will be allocated to inappropriate tasks. In the worst case, skilled personnel may be lost to radiation or to other accidents. Misallocation of resources can delay, and in some cases prevent, achievement of the goals of a weapons program.

The nuclear weapons publicly known to have been fielded use only two fundamental principles for releasing nuclear energy: fission and fusion.

Under these major categories, "boosting," "staging," and the use of either high-explosive-driven implosion or a propellant-powered gun mechanism to assemble a supercritical mass constitute the major elements of the taxonomy of known nuclear weapon types. The various systems may be combined in many different ways, with the single requirement that a fission chain reaction is needed to ignite nuclear fusion in a weapon.

Nuclear Weapon Neutron Initiator Design

One of the key elements in the proper operation of a nuclear weapon is initiation of the fission chain reaction at the proper time. To obtain a significant nuclear yield of the nuclear explosive, sufficient neutrons must be present within the supercritical core at the right time. If the chain reaction starts too soon, the result will be only a "fizzle yield," much below the design specification; if it occurs too late, there may be no yield whatever. Several ways to produce neutrons at the appropriate moment have been developed.

Highlights

- Nuclear weapons operate on the well-known principles of nuclear fission and nuclear fusion.
- If fissile material is available, subnational or terrorist groups can likely produce an "improvised nuclear explosive device" which will detonate with a significant nuclear yield.
- High explosives or propellants can be used to assemble the "pit" of a nuclear weapon, and there are several ways to accomplish the task.
- Neutron generators to initiate the fission chain reaction can be purchased or made indigenously.

Technologies Particularly Appropriate to a Subnational Group

Terrorism has become nearly as much of a public and governmental concern in the last few years as proliferation by nations hostile to the United States. Subnational groups of concern may be independent actors (e.g., the bombing of the Federal Building in Oklahoma City), those acting to promote a cause with foreign roots (e.g., the World Trade Center bombing), or surrogates for hostile states themselves (e.g., the bombing of Pan Am 103). This section will examine nuclear techniques useful to subnational adversaries.

In recent years terrorist acts have escalated from pipe bombs to many tons of high explosives (e.g., the bombing of major U.S. targets including the embassy and Marine barracks in Lebanon as well as U.S. forces' residences at the Khobar Towers in Riyadh, Saudi Arabia, as well as domestic incidents in Oklahoma City and at the World Trade Center) and to the explicit use of chemical warfare agents, as in Aum Shinrikyo's Sarin attack on the Tokyo subway system. For many years it was generally believed that terrorist groups did not seek to kill large numbers of people at a time but rather wished to demonstrate that they could execute attacks at will against civilian (and military) targets. In the wake of the use of Sarin gas in Tokyo as well as the Oklahoma City, Pan Am, and Riyadh bombings, it is no longer possible to assume that genuine mass murder is not an intended component of subnational forces—particularly if they are acting as state surrogates.

Since chemical weapons have already been used by terrorists, it may be simply a matter of time before some form of nuclear attack is employed by similar groups. In this context,“nuclear weaponry” includes radiological weapons as a subset.

RATIONALE

Weapons

This subsection describes the general process and the capabilities required for understanding and designing nuclear weapons. Some of the information and computational tools may be controlled, and some may be generally available on the open market. The paths a proliferator might take can be quite different than the paths that the nuclear powers have taken in the past.

The first part of this subsection will focus on the design milestones for nuclear weapons, and on key elements to be achieved. The next part describes neutron initiators, a particular technology necessary for many nuclear weapons and for some technologies unique to nuclear weapons. Finally, the question of nuclear terrorism is briefly discussed and some relevant technologies identified.

The tables accompanying this subsection are designed around the following topics, which have been identified by some as being among the more important areas of technology a proliferator must master to be able to convert a supply of special nuclear material into actual nuclear explosives:

- Fast-fission chain reaction theory and practice,
- Fast assembly of critical and supercritical masses of fissile material,
- High explosive (HE) and propellant characteristics and design,
- HE initiation,
- Firing sets for HE initiation,
- Thermonuclear boosting of fission primary, and
- Thermonuclear/second stage of nuclear weapons.

The fission reactions commonly studied in nuclear reactor physics use thermal neutrons, and the cross sections usually tabulated are those for low-energy particles. In a nuclear weapon, the time scales dealt with do not allow full thermalization of the neutrons, hence “fast” neutrons, that is, the neutrons emitted and interacting at higher energies must be considered. Thus, the important neutron interactions for the weapons designer are those which occur at roughly MeV energies. In addition, reactor neutron transport codes need to be modified to fully account for the different physical regimes. A comprehensive understanding of the similarities and differences between nuclear reactor physics and nuclear weapon physics is essential to make progress in nuclear weapon design.

For a nuclear weapon to release its energy in a time which is short compared to the hydrodynamic disassembly time, rapid assembly to form a supercritical mass is essential. This assembly can be accomplished in a linear fashion, as in a gun-assembled weapon, or it can be accomplished in a spherical fashion, as in an implosion weapon. In the first case, two subcritical masses of the fissile material are rapidly assembled into a supercritical mass, one mass being fired by the gun at the other mass. In the second case, the fissile material is initially in a subcritical configuration, and then energy contributed by conventional explosives is concentrated on the fissile material to achieve a supercritical mass. The fissile materials will be driven to high pressure/high energy conditions by the high-explosive energy. This will require calculations of initial, intermediate, and final configurations, using hydrodynamic programs and appropriate equations of state for these regimes of temperature and pressure.

HE or propellants are the means of choice for assembly of most nuclear weapons. Given this, the potential proliferator must understand and master the data and design of systems to accomplish such assembly. Propellants are used to assemble gun-type weapons, and are usually relatively slow burning. Much useful data from conventional artillery tube-fired weapons development is generally available. Much data concerning implosion is also available from the development of modern conventional HE weapons including shaped charges.

Special considerations applicable to nuclear weapons development involve shock wave propagation and focusing. Such considerations go beyond much of conventional explosive design work, and would require specialized programs, equations of state in HE pressure and temperature regimes, and data on detonation velocities and strengths.

Initiation of the main charge of a nuclear explosive in such a way as to provide the desired final configuration of the fissile material often proves to be a major design challenge. Traditionally, this challenge has been met by initiating the charge at a number of discrete points, and then tailoring the converging shock wave through the use of lenses consisting of slower and faster burning explosives. Such initiation can be accomplished either by electrical signals or by fuze trains, both ending at a detonator which initiates the shock wave at the lens charge.

Firing sets for nuclear devices, the means for activating the initiation of the main charge of HE for a nuclear weapon, can also have performance characteristics which lie outside the range of conventional engineering. If the proliferator is relying on initiation at a discrete number of points, then these points must be activated nearly simultaneously to have a smooth implosion. The simultaneity required depends on the internal design of the explosive, but it is common to require a higher degree of simultaneity than is usually the case for conventional explosives. Thus, high energy must be delivered to all the detonators at nearly the same time. This will require high-energy, low-impedance capacitors, and high-current, high-speed switches.

Once the potential proliferator has begun to understand the operation of a simple fission weapon, he may well want to increase the yield to make more efficient use of his special nuclear material. One way to do this is to boost the fission yield by incorporating thermonuclear reactions into the design of the weapon. Introduction of the neutrons from thermonuclear reactions at the time of supercriticality of the fissile material can have a dramatic effect on the yield. The usual fusion material used for this purpose is a mixture of deuterium and tritium gas.

When the proliferator begins to think in terms of greatly increasing the yield of his nuclear weapons, he may consider design and development of thermonuclear and/or second stages. To do this, he would have to obtain and master hydrodynamic computer programs which correctly describe regimes of extremely high temperatures and pressures. He would show interest in equations of state of special nuclear materials under these conditions. He would also be interested in neutron and reaction cross sections for both fissionable materials and thermonuclear materials at these high temperatures and pressures. Finally, he would attempt to obtain lithium (and/or lithium deuteride), tritium and deuterium.

Finally, the actual coupling of the nuclear weapon primary with a thermonuclear/boosted-fission secondary will require mastery of a complex set of physical principles. The proliferator will not only have to understand hydrodynamic calculations under extreme physical conditions, he will have to obtain and understand the flow of energy from the primary to and around the secondary. Energy flow and the behavior of materials under these extreme conditions of temperature and pressure comprise a complex set of problems, well beyond the experience of most of today's physicists.

Nuclear Weapon Neutron Initiator Design

In a gun-assembled weapon, the assembly speed is relatively slow. This requires a strong source of alpha particles such as ^{210}Po or some similarly active alpha emitter. The South African uranium gun-assembled devices did not use any neutron source other than background radiation.

An implosion weapon may require a source which can produce a precisely timed burst of neutrons.

The type of neutron initiator used in early implosion devices utilized the emission of neutrons caused by bombardment of ^{9}Be or some other light element by alpha particles. This requires a strong source of alpha particles, something of the order of 10 curies of ^{210}Po or a similarly active alpha emitter. This isotope of polonium has a half life of almost 140 days, and a neutron initiator using this material needs to have the polonium replaced frequently. Since the ^{210}Po is made in a nuclear reactor, this means that potential proliferators need either to have a nuclear reactor of their own, or to have access to one. To supply the initiation pulse of neutrons at the right time, the polonium and the beryllium need to be kept apart until the appropriate moment and then thoroughly and rapidly mixed.

One of the ways to make an external neutron generator is by using an electronically controlled particle accelerator called a pulse neutron tube. Such a system might use the deuterium-deuterium or deuterium-tritium fusion reactions to produce large amounts of neutrons. Typically, deuterium nuclei are accelerated to an energy sufficient to cause a fusion reaction when they strike a deuterium- or tritium-rich target. This impact can result in a short pulse of neutrons sufficient to initiate the fission chain reaction. The timing of the pulse can be precisely controlled. Similar devices are used in oil well logging.

Technologies Particularly Appropriate to a Subnational Group

Nuclear Explosives

For most of the nuclear era, it was accepted dogma that acquisition of a nuclear weapon required the construction of either an enrichment plant for uranium or a reactor and reprocessing unit for plutonium. Great care was taken in the design of U.S.-supplied nuclear facilities to ensure that neither ^{235}U nor plutonium could be surreptitiously diverted from the nuclear fuel cycle to be used in a weapon, whether built by a state or by a subnational group. One hoped that such measures could severely constrict the illicit or unsafeguarded supply of special nuclear material of a quality useful in a weapon. With the dissolution of the Soviet Union, the safeguarding of hundreds of metric tons of fissile material has broken down so seriously that in one famous court case a Russian judge remarked (in jest, one hopes), "In the Murmansk area potatoes are more carefully guarded than enriched uranium." Further, recent arrests in the Federal Republic of Germany (FRG) have yielded up gram and larger size quantities of partially enriched uranium and may also have resulted in the seizure of other fissionable materials, including plutonium.

Thus, it is wrong to discount the possibility of a terrorist nuclear weapon on the grounds that subnational groups cannot gain access to the fissile material needed to make a device. It is entirely possible that special nuclear material (or even an entire nuclear weapon) may, indeed, become available on the nuclear black market in the foreseeable future. Since 90 percent[11] of the overall difficulty in making a nuclear weapon lies in the production of special nuclear material (if no outside source is readily available), a terrorist nuclear device is no longer an impossibility, particularly if SNM can be obtained on the black market and the terrorist group itself need not steal SNM from a poorly guarded facility.

Types of Nuclear Design Useful for a Terrorist

Uranium Gun-Assembled Devices

A terrorist with access to >50 kg of HEU would almost certainly opt for a gun-assembled weapon despite the inherent inefficiencies of such a device, both because of its simplicity and the perceived lack of a need to test a gun assembly. Building an

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[11] More than 90 percent of the entire Manhattan Project budget went to the production of fissile materials; less than 4 percent went to the weapon laboratory at Los Alamos.

effective gun assembly is certainly easier than demonstrating that a simple "implosion system" will actually work.

The disadvantage of a gun design is that it needs significantly more fissile material than an efficient implosion device of similar yield. This may be important to a subnational group intending to explode a series of devices, but would be of much less importance if only one blast were contemplated.

Implosion assembly

If the subnational group had only ^{239}Pu or needed to be economical with a limited supply of HEU, then it would likely turn to an implosion assembly. The simplest design of an implosion weapon places a solid plutonium (or HEU) pit at the center of a sphere, surrounded by a certain amount of tamper material such as ^{238}U, to be compressed by the large amount of high explosive filling the sphere. In the design chosen for the first U.S. and Soviet devices tested, the necessary imploding moving shock wave was produced by the use of explosive lenses made of appropriately shaped fast- and slow-detonating HE. It is generally asserted in the open literature that 32 lens charges were used for the Fatman device, the charges arranged in much the same way as the segments on a soccer ball.

FOREIGN TECHNOLOGY ASSESSMENT

Weapons

Six nations are known to have exploded nuclear devices: the United States, Russia, the UK, France, China, and India. Some suspect that Pakistan and Israel have built nuclear weapons. It is known that South Africa built and then dismantled six gun-assembled nuclear devices. Many countries, including Iran, Iraq, and North Korea, are believed to have active or recently dormant nuclear programs based generally on older technologies. Taiwan, South Korea, Sweden, and Switzerland explored the possibilities of going nuclear during the 1960's and 1970's, and they, Japan, and Germany are generally credited with the ability to build a bomb in a relatively short time. Spain, Brazil, and Argentina, among other nations, have pursued the idea of constructing nuclear weapons but have apparently abandoned their programs. Many countries have the necessary expertise in nuclear technologies to build weapons using their domestic nuclear power experience.

Nuclear Weapon Neutron Initiator Design

Few nations other than the five nuclear weapons states have mastered the techniques of constructing initiators. Presumably the three nuclear threshold states have; Iraq made substantial progress, and South Africa elected not to use an initiator.

Technologies Particularly Appropriate to a Subnational Group

Efforts directed at preventing the acquisition of fissile material are the first line of defense against nuclear terrorism. The technical problems confronting the designer of an implosion-assembled improvised nuclear device (IND) are relatively simple in comparison to obtaining special nuclear materials, particularly if the IND does not have to be very safe or predictable in yield.

Despite fictional accounts to the contrary, it is most unlikely that a terrorist group could fabricate a boosted or thermonuclear device on its own.

Table 5.6-1. Nuclear Weapons Design and Development Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
WEAPONS					
Fast fission chain reaction; prompt criticality; high-energy neutrons	Operational understanding; neutron transport theory; high explosive means of device assembly	WA ML 4; USML IV	Special nuclear materials, reliable high explosives and detonators	General machining capability, dimensional mensuration capability; fast neutron and gamma counters capable of handling in excess of one million events total per microsecond. Fast streak and framing cameras (see NDUL) and oscilloscopes.	Validated fast nuclear reactor operations software, neutron cross-sections (fission, scattering and absorption) as a function of neutron energy, neutrons per fission as a function of energy.
Reflector design	Understanding of effects of reflectors on reactivity; ability to cast or machine beryllium or other suitable reflector material	WA ML 4; USML IV	Beryllium, uranium, tungsten, special machining capabilities for refractory materials	Fast neutron counters, gamma counters to measure effects of reflector parameters.	Validated nuclear reactor software, neutron cross-sections (scattering and absorption) as a function of energy.
Fast assembly of critical mass of fissile material	For simple designs the ability to construct simple implosion systems, understanding of interplay of nuclear energy release disassembling device, and continuing HE energy input	WA ML 4; USML IV	Beryllium, uranium (>20% U-235) U-233, or plutonium, tungsten, special machining capabilities for refractory materials; energetic high explosives; detonators and firing sets	Fast neutron counters, gamma counters; streak and framing cameras; flash x-ray cameras; pinhole gamma or neutron cameras.	High pressure/energy equations of state.
High explosives and propellants: characteristics and design	Ability to assemble propellant or implosion systems incorporating explosives such as baratol and composition B. Fabrication with few voids/ bubbles. Possible vacuum casting or isostatic pressing. Propellant for gun-assembled devices	NDUL 6; CCL Cat 3A	High-energy, high explosives and detonators. Common propellants including, e.g., propellant for gun-assembled devices.	HE test sites, high-speed photography, flash x-rays, high-speed mechanical and electronic diagnostics including pin-domes. Fractional microsecond timing.	Validated shock-wave propagation programs, detonation velocities, HE pressure regime equations of state
High explosive initiation	Understanding of HE systems	NDUL 6; CCL Cat 3A	Explosives of varying types and sensitivities; bridge wires; slappers	HE test sites, high-speed photography, flash x-rays, high-speed mechanical and electronic diagnostics	Validated shock-wave propagation programs, detonation velocities, HE pressure regime equations of state

(cont'd)

Table 5.6-1. Nuclear Weapons Design and Development Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Firing sets	Understanding of and procurement of firing sets. NDUL: 15 microsec pulse, 100 Å output; rise <10 microsec into load <40 ohms.	NDUL 6; CCL Cat 3A	High-energy, low-impedance capacitor banks; high current, high-speed switches (e.g., thyratrons, krytrons, sprytrons). Thyratrons date from the 1940's.	High-speed simultaneous measurement devices (e.g., high-speed oscilloscopes, streak cameras, etc.)	Electronic circuit performance software
Thermonuclear boosting of fission primary	Ability to construct or obtain fission devices capable of being boosted; tritium supplies.	WA ML 4; USML IV	Tritium, high-pressure gas bottles and fill systems, both design and utilization capabilities. Welds satisfactory for hydrogen gas transfer systems. Materials compatible simultaneously with fissile metals and hydrogen.	High pressure gauges, pin dome diagnostics, flash x-ray diagnostics, neutron diagnostics	Validated thermonuclear fusion programs, deuterium-tritium reaction cross-section tables. Equations of state for hydrogen and Helium-3 at very high densities.
Thermonuclear second stage of nuclear weapons	Understanding of transport physics. Construct compact and efficient fission primary.	WA ML 4; USML IV	Enriched uranium, plutonium, lithium deuteride/tritide, natural/depleted uranium, lithium-6.	General machining capability, dimensional mensuration capability, ability to handle and machine special nuclear materials. See NDUL, Wassenaar Arrangement, and MCTL, Part II, sections on machine tools and mensuration/metrology	Validated thermonuclear fusion programs, deuterium-tritium reaction cross-sections, neutron cross sections for various isotopes of uranium and transuranics
INITIATORS					
Alpha-induced neutron emission (crushable initiators such as the one used at Trinity).	Identification of performance characteristics of alpha-n initiators.	NDUL 8; CCL Cat 3A	Radioactive alpha emitting materials (e.g., Po-210 and Pu-238). Target materials (e.g., beryllium).	General machining capability, dimensional mensuration capability, ability to handle and machine radioactive nuclear materials, fast neutron counters for demonstrating successful operation.	Beryllium alpha-n cross-sections. Alpha range in various component materials.

(cont'd)

Table 5.6-1. Nuclear Weapons Design and Development Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Miniature linear accelerator to generate DD/DT reactions and resultant neutrons. (Deuteron beam usually bombards tritiated plastic target)	Identification of performance characteristics of linear accelerator neutron initiators.	NDUL 8; CCL Cat 3A	Tritium, deuterium, titanium, plating equipment, miniature power supplies/capacitors	Fast neutron detectors, precision machining capability, precision mensuration capability	Validated ionization and acceleration software, DT reaction rates as a function of center of mass energy
Dense plasma focus to generate DD/DT reactions and resultant neutrons.	Identification of performance characteristics of dense plasma focus neutron initiators.	NDUL 8; CCL Cat 3A	Tritium, deuterium, miniature power supplies/capacitors	Fast neutron detectors, precision machining capability, precision mensuration capability	Validated plasma ionization and acceleration software, DT reaction rates as a function of center of mass energy

Table 5.6-2. Nuclear Weapons Design and Development Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
WEAPONS			
Fast fission chain reaction; prompt criticality; high energy neutrons.	Obtaining fissile material of adequate purity and (for uranium) enrichment. Determination by computation and experiment that proposed geometry and fissile material mass are sufficient.	Fundamental technology of nuclear explosive devices. Provides simple fission weapons.	None identified
Reflector design	Understanding of neutron transport; absorption cross sections and scattering cross sections of reflector material; computation of contribution of reflected neutrons to the chain reaction.	Reduces requirements for special nuclear materials; increases efficiency with which fission fuel is "burned."	Use additional fissile material and accept significantly lower performance.
Fast assembly of critical mass of fissile material	Design of gun system for U-235; design and fabrication of predictable, reliable, and compact implosion system for plutonium weapons. Neutron background and spontaneous fission rate in fuel. Introduction of neutrons at correct moment.	The critical mass of a nuclear explosive device must be rapidly assembled from a subcritical configuration in order to produce an explosion and not a "fizzle."	None identified
High explosives and propellants: characteristics and design	Safety; energy content; shaping of charges in order to achieve efficient implosion without disruption of the fissile pit.	See section on high explosives in MCTL Part I.	None identified
High explosive initiation	Obtaining adequate simultaneity among many detonators; reliability of detonators.	See section on detonators in MCTL, Part I.	Various forms of detonators have been successfully used.
Firing sets	Storage of electrical energy; rapid delivery of sufficient current to fire all detonators simultaneously; pulse rise time.	Initiates the detonation of HE used for implosion or the deflagration of the propellant in a gun-assembled device.	Different types of firing sets have proven usable.
Thermonuclear boosting of fission primary	Mixing of pit material and boost gas.	Reduces the weight and the fissile materials requirements for a (primarily) fission weapon; improves yield to weight ratio.	No obvious alternative for achieving compact, efficient, high yield primaries.
Thermonuclear/second stage of nuclear weapons	Compressing and heating of secondary.	By using a fission stage plus one or more thermonuclear stages, the designer can scale the weapon to any desired yield, no matter how large. Useful for attacking hard targets with highly accurate delivery systems or for annihilating large area soft targets.	No lower technology substitutes for achieving device yields in the megaton and above range.

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Table 5.6-2. Nuclear Weapons Design and Development Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
INITIATORS			
Alpha-induced neutron emission (crushable initiators such as the one used at Trinity).	Need to understand physics of alpha-n reactions and neutron yields from such reactions. Procurement of suitable alpha-source isotope; ability to replace short half-life materials; mixing of source and target materials on crushing. Heat dissipation.	Neutron initiator capability. Starts neutron chain reaction at correct time.	Other suitable technologies are more difficult.
Miniature linear accelerator to generate DD/DT reactions and resultant neutrons.	Need to understand yield of neutrons from DD/DT reactions	Miniaturized, high output neutron initiator; permits more precise timing of neutron pulse than crushable initiator. Does not take up space within the pit itself, simplifying design, testing, and development of the device.	Alpha-induced neutron initiators; dense plasma focus device. Similar devices are used in oil well logging.
Dense plasma focus to generate DD/DT reactions and resultant neutrons.	Need to understand yield of neutrons from DD/DT reactions	Miniaturized, high-output neutron initiator	Need to obtain materials and/or fabricated devices

SECTION 5.7—SAFING, ARMING, FUZING, AND FIRING

OVERVIEW

This subsection describes technologies to (1) prevent an unwanted nuclear detonation and (2) initiate a nuclear explosion in response to proper orders. It also addresses one part of the set of command and control technologies, permissive action links (PALs), which are peculiar to nuclear weapons in U.S. practice.

Nuclear weapons are particularly destructive, with immediate effects including blast and thermal radiation and delayed effects produced by ionizing radiation, neutrons, and radioactive fallout. They are expensive to build, maintain, and employ, requiring a significant fraction of the total defense resources of a small nation. In a totalitarian state the leader must always worry that they will be used against the government; in a democracy the possibility of an unauthorized or accidental use must never be discounted. A nuclear detonation as the result of an accident would be a local catastrophe.

Because of their destructiveness, nuclear weapons require precautions to prevent accidental detonation during any part of their manufacture and lifetime. And because of their value, the weapons require reliable arming and fuzing mechanisms to ensure that they explode when delivered to target.

Therefore, any nuclear power is likely to pay some attention to the issues of safing and safety, arming, fuzing, and firing of its nuclear weapons. The solutions adopted depend upon the level of technology in the proliferant state, the number of weapons in its stockpile, and the political consequences of an accidental detonation.

From the very first nuclear weapons built, safety was a consideration. The two bombs used in the war drops on Hiroshima and Nagasaki posed significant risk of accidental detonation if the B-29 strike aircraft had crashed on takeoff. As a result, critical components were removed from each bomb and installed only after takeoff and initial climb to altitude were completed. Both weapons used similar arming and fuzing components. Arming could be accomplished by removing a safety connector plug and replacing it with a distinctively colored arming connector. Fuzing used redundant systems including a primitive radar and a barometric switch. No provision was incorporated in the weapons themselves to prevent unauthorized use or to protect against misappropriation or theft.

Highlights

- All nuclear weapon possessors will find it important to control access to their weapons.
- Safing, arming, fuzing, and firing (SAFF) problems generally have simple engineering solutions.

In later years, the United States developed mechanical safing devices. These were later replaced with weapons designed to a goal of less than a 1 in a 1 million chance of the weapon delivering more than 4 pounds of nuclear yield if the high explosives were detonated at the single most critical possible point. Other nations have adopted different safety criteria and have achieved their safety goals in other ways.

In the 1950's, to prevent unauthorized use of U.S. weapons stored abroad, permissive action links (PALs) were developed. These began as simple combination locks and evolved into the modern systems which allow only a few tries to arm the weapon and before disabling the physics package should an intruder persist in attempts to defeat the PAL.

RATIONALE

The ability of a country or extranational organization to make effective use of a nuclear weapon is limited unless the device can be handled safely, taken safely from storage when required, delivered to its intended target, and then detonated at the correct point in space and time to achieve the desired goal. Although the intended scenarios for use of its weapons and the threat a proliferator perceives (or the region it wishes to dominate) will strongly influence specific weaponization concepts and approaches, functional capabilities for safing, arming, fuzing, and firing (SAFF) will be fundamental. The generic requirements for these functions are described below.

SAFF Subsystem Generic Functions

Subsystem	**Generic Functions**
Safing	To ensure that the nuclear warhead can be stored, handled, deployed, and employed in a wide spectrum of intended and unintended environmental and threat conditions, with assurance that it will not experience a nuclear detonation. *In U.S. practice, safing generally involves multiple mechanical interruptions of both power sources and pyrotechnic/explosive firing trains. The nuclear components may be designed so that an accidental detonation of the high explosives is intrinsically unable to produce a significant (>4 pounds TNT equivalent) nuclear yield; it is simpler to insert mechanical devices into the pit to prevent the assembly of a critical mass into the pit or to remove a portion of the fissile material from inside the high explosives.*[12] *All U.S. weapons have been designed to be intrinsically one-point safe in the event of accidental detonation of the high explosives, but it is not anticipated that a new proliferator would take such care.*
Arming	Placing the nuclear warhead in a ready operational state, such that it can be initiated under specified firing conditions. *Arming generally involves mechanical restoration of the safing interrupts in response to conditions that are unique to the operational environment (launch or deployment) of the system. A further feature is that the environment typically provides the energy source to drive the arming action. If a weapon is safed by inserting mechanical devices into the pit (e.g., chains, coils of wire, bearing balls) to prevent complete implosion, arming involves removal of those devices. It may not always be possible to safe a mechanically armed device once the physical barrier to implosion has been removed.*
Fuzing	To ensure optimum weapon effectiveness by detecting that the desired conditions for warhead detonation have been met and to provide an appropriate command signal to the firing set to initiate nuclear detonation. *Fuzing generally involves devices to detect the location of the warhead with respect to the target, signal processing and logic, and an output circuit to initiate firing.*
Firing	To ensure nuclear detonation by delivering a precise level of precisely timed electrical or pyrotechnic energy to one or more warhead detonating devices. *A variety of techniques are used, depending on the warhead design and type of detonation devices.*

Depending on the specific military operations to be carried out and the specific delivery system chosen, nuclear weapons pose special technological problems in terms of primary power and power-conditioning, overall weapon integration, and operational control and security.

This subsection also includes technologies for PALs required to enable the use of these subsystems, as well as primary power sources and power conditioning, and technologies for packaging and integration. In particular, one must address component and subsystem technologies for safing, arming, fuzing, and firing a nuclear weapon. In describing the technologies which can be used for nuclear device weaponization, it is important to distinguish among requirements for different objective levels of capability. Not all weapons possessors will face the same problems or opt for the same levels of confidence, particularly in the inherent security of their weapons. One must take care to avoid mirror imaging U.S. or other decisions at any time from 1945 until the present.

The operational objectives will in turn dictate the technological requirements (see table below) for the SAFF subsystems.

Nominal Operational Requirements

Objectives	**Requirements could be met by:**
Minimal	Surface burst (including impact fuzing of relatively slow moving warhead) or crude preset height of burst based on simple timer or barometric switch or simple radar altimeter.
Modest	More precise HOB (height of burst) based on improved radar triggering or other methods of measuring distance above ground to maximize radius of selected weapons effects (see section on weapons effects), with point-contact salvage fuzing. Parachute delivery of bombs to allow deliberate laydown and surface burst.
Substantial	Variable HOB, including low-altitude for ensured destruction of protected strategic targets. Possible underwater or exoatmospheric capabilities.

Whether to protect their investment in nuclear arms or to deny potential access to and use of the weapons by unauthorized persons, proliferators or subnational groups will almost certainly seek special measures to ensure security and operational control of nuclear weapons. These are likely to include physical security and access control

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[12] Mechanical safing of a gun-assembled weapon is fairly straightforward; one can simply insert a hardened steel or tungsten rod across a diameter of the gun barrel, disrupting the projectile. Because few gun-assembled weapons are believed to be in use anywhere in the world, and are conceptually easy to safe, this section will only discuss implosion-assembled systems unless specifically stated. The safing of the electronics and arming systems is common to both types of weapons.

technologies at minimum and may include use control. The techniques used today by the existing western nuclear weapon states represent the culmination of a half-century of evolution in highly classified military programs, and proliferators may well choose simpler solutions, perhaps by adapting physical security, access, and operational controls used in the commercial sector for high-value/high-risk assets.

Preventing access to the development of a minimal SAFF capability will not be feasible. Experts have surmised that barometric pressure switching may have been employed to fuze the bomb used to destroy Pan Am Flight 103. Such a sensor would meet the basic requirements for one potential terrorist use of nuclear explosives.

The requirements to achieve a "modest" or "substantial" capability level are much more demanding. Both safety and protection of investment demand very low probability of failure of safing and arming mechanisms, with very high probability of proper initiation of the warhead. The specific technologies associated with each of the key elements of SAFF and weapons physical and operational security are addressed in the technology and reference data tables. This level of technology meets the criterion of "sufficiency" for achieving a usable military capability. The items required to meet this criterion are generally specially designed or not widely available. Licensing may be ineffective as a mechanism for monitoring proliferant activity. By contrast, alternative technologies which might require the proliferator to accept greater risk of failure or misappropriation of his weapons are generally available to any organization desiring to obtain a minimal nuclear capability.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Virtually any country or extranational group with the resources to construct a nuclear device has sufficient capability to attain the minimum SAFF capability that would be needed to meet terrorist or minimal national aims. All of the recognized nuclear weapons states and many other countries have (or have ready access to) both the design know-how and components required to implement a significant capability. In terms of sophistication, safety, and reliability of design, past U.S. weapons programs provide a legacy of world leadership in SAFF and related technology. France and the UK follow closely in overall SAFF design and may actually hold slight leads in specific component technologies. SAFF technologies of other nuclear powers—notably Russia and China—do not compare. Japan and Germany have technological capabilities roughly on a par with the United States, UK, and France, and doubtless have the capability to design and build nuclear SAFF subsystems.

Reliable fuzing and firing systems suitable for nuclear use have been built since 1945 and do not need to incorporate any modern technology, although the substitution of integrated circuit electronics for vacuum tubes will almost certainly occur. Many kinds of mechanical safing systems have been employed, and several of these require nothing more complex than removable wires or chains or the exchanging of arming/safing connector plugs. Safing a gun-assembled system is especially simple.

Arming systems range from hand insertion of critical components in flight to extremely sophisticated instruments which detect specific events in the stockpile to target sequence (STS). Fuzing and firing systems span an equally great range of technical complexity.

Very few, if any, countries approach the ability of the United States, UK, and France in terms of safety and reliability of SAFF functions. However, a proliferator would not necessarily seek to "mirror-image" U.S. practice and may adopt different techniques and criteria. Any country with the electronics capability to build aircraft radar altimeter equipment should have access to the capability for building a reasonably adequate, simple HOB fuze. China, India, Israel, Taiwan, South Korea, Brazil, Singapore, the Russian Federation and the Ukraine, and South Africa all have built conventional weapons with design features that could be adapted to more sophisticated designs, providing variable burst height and rudimentary Electronic Counter Counter Measure (ECCM) features.

With regard to physical security measures and use control, the rapid growth in the availability and performance of low-cost, highly reliable microprocessing equipment has led to a proliferation of electronic lock and security devices suitable for protecting and controlling high-value/at-risk assets. Such technology may likely meet the needs of most proliferant organizations.

Table 5.7-1. Safing, Arming, Fuzing, and Firing Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
SAFING DEVICES					
Mechanical devices designed to provide for positive interruption and connection of explosive or pyrotechnic devices	Any capability is a concern.	WA ML 3; USML III; MTCR 2; USML 121.16	None identified	None identified	None identified
Mechanical techniques and devices for preventing assembly or high order (nuclear) detonation of nuclear explosive devices	Any capability is a concern.	WA ML 3; USML III; USML 121.16	None identified	None identified	None identified
Devices designed to detect one or more of the following phenomena: - air flow - linear or angular acceleration - barometric pressure	Simple barometric sensor Low-cost accelerometer	WA ML 3; USML III	None identified	None identified	None identified
ARMING DEVICES					
Precision mechanical devices designed to use any of the following: - air flow - linear or angular acceleration - barometric pressure	Externally powered (spring or electrical) switches enabled by one or more of the stimuli listed in Technology Column	WA ML 4; USML IV	Long-life lubricating fluids	None identified	None identified

(cont'd)

Table 5.7-1. Safing, Arming, Fuzing, and Firing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
FUZING					
Radar altimeter sensors, having unambiguous range measurement capability at ranges >100 ft.	Radar altimeter with simple height-measuring capabilities	WA ML 3, 4; USML III, IV; CCL Cat 7A; MTCR 11	Specially fabricated high thermal diffusivity (e.g., beryllium oxide) components.	Specially designed programmable microwave delay lines	None Identified
Active IR/EO altimeter for low HOB	For low-velocity approach, low-power laser ranging device	WA ML 3, 4; USML III, IV; MTCR 11; CCL Cat 2A	Solid state laser and optical detector materials. IR window materials to withstand erosion from rain particles, stagnation temperatures, and aerodynamic erosion associated with ballistic reentry.	Semiconductor detector and laser manufacturing	None identified
Primary and reserve (including thermal reserve) batteries	Aerospace qualified primary batteries could be acquired and installed as part of the operational deployment sequence	WA Cat 3A; CCL Cat 3A	Proprietary electrolyte additives and catalysts for thermal batteries.	None identified	None identified
Barometric switch	Barometric altimeters	None identified	None identified	None identified	None identified
Power conditioning systems, for producing high voltage d.c. and pulsed power for fuzing applications	Aerospace qualified conventional power supply	NDUL 6; CCL Cat 3A	High permeability magnetic materials, designed or charaterized for use in low-loss transformers operating at frequencies above 120 Hz.	None identified	None identified
Microwave antennas	Standard microwave horn antenna	WA ML 5AP1; CCL Cat 5A P1	Low-loss dielectric materials designed to withstand temperatures in excess of 125 °C.	Antenna and ECM test facilities	Empirically validated engineering models and design databases for waveguide antennas

(cont'd)

Table 5.7-1. Safing, Arming, Fuzing, and Firing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Compact, high-performance stripline or microstrip microwave components, including-- - low-noise balanced mixers - high ratio circulators	Conventional stripline design techniques	None Identified	Low-loss dielectric substrate materials	Swept frequency analyzers Engineering models	None identified
FIRING SETS					
Capacitive discharge units	Conventional high-voltage (>300 V) capacitors, with capacitance greater than 25 nanofarads	NDUL 6; CCL Cat 3A	None identified	None identified	None identified
Cold cathode tubes and switches	Anode delay: <10 micro-seconds; Peak voltage: 2,500 V; Peak current: >100 Å	NDUL 6; CCL Cat 3A	None identified	None identified	None identified
Pyrotechnic logic and delay devices	Any capability is a concern.	NDUL 6; CCL Cat 3A	None identified	None identified	None identified
Detonators and initiator couplers and connectors, including: - exploding bridge wires - exploding foil - hot wire - semiconductor bridge	Conventional weapons squibs.	NDUL 6; CCL Cat 3A	None identified	Specially designed explosive component test facilities or load simulators which do not require the use of explosives	None identified
OPERATIONAL SECURITY					
Lock systems incorporating combined electronic and positive mechanical "keying," useful but not necessary	Electronic or physical keyed system.	None identified	None identified	None identified	Encryption
Physical security	Fences and guard dogs; commercial intrusion detectors.	None identified	None identified	None identified	None identified

Table 5.7-2. Safing, Arming, Fuzing, and Firing Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
SAFING DEVICES			
Mechanical devices designed to provide for positive interruption and connection of explosive or pyrotechnic devices	Ensured reliability of precision mechanical and electromechanical devices	For some delivery methods, components and technologies could be common to conventional bombs and cluster/canister munitions.	Electrical switching
Mechanical techniques and devices for preventing assembly or high order (nuclear) detonation of nuclear explosive devices	None identified	None. Techniques unique to nuclear explosives.	None Identified
Devices designed to detect one or more of the following phenomena: - air flow - linear or angular acceleration - barometric pressure	Selection and design of sensor systems for unique operational conditions	For some delivery methods, components and technologies could be common to conventional bombs and cluster/canister munitions.	Spring- or electrically powered mechanical timing devices
ARMING DEVICES			
Precision mechanical devices designed to use any of the following: - air flow - linear or angular acceleration - barometric pressure	Mechanical reliability	For some delivery methods, components and technologies could be common to conventional bombs and cluster/canister munitions.	Externally powered mechanisms, operator enabled (including those designed to be powered by chemical, electrochemical, or mechanical energy sources).
FUZING			
Radar altimeter sensors, having unambiguous range measurement capability at ranges >100 ft	Hermetic sealing of high-voltage (>300 V) subsystems	Possible use as high-altitude fuzing for canister weapons.	Barometric switch
Active IR/EO altimeter for low HOB	Thermal management techniques	Conventional free-fall and smart weapons.	Point contact
Primary and reserve batteries	Hermetic sealing, and thermal management, particularly in high-energy density lithium thermal batteries	Other high altitude fuzing and one-shot power applications (e.g., torpedo guidance sets).	Commercial primary batteries
Power conditioning systems	Efficient transformation of low voltage (<50 V to high-voltage >1 kV) d.c.-d.c. conversion.	Aircraft and other space/weight constrained power conditioning requirements.	Larger, heavier transformers

(cont'd)

Table 5.7-2. Safing, Arming, Fuzing, and Firing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
MIcrowave antennas	Antenna must conform to delivery system packaging constraints. Must retain r.f. characteristics after exposure to rain erosion and aerodynamic heating effects	Communications and ECM systems	Needed only for radar altimeter fuzing
Compact, high-performance stripline or microstrip microwave components, including: - low-noise balanced mixers - high ratio circulators	Techniques to extend operating bandwidth of low-noise balance mixers and high ratio isolation circulators	Communications and ECM systems	Coaxial or waveguide components (at severe space and weight penalty). Alternative system concepts.
Barometric switch	None identified	Detonation at specific altitude	All other fuzing systems
FIRING SETS			
Capacitive discharge units	Energy density and one-shot reliability	Conventional weapons fuzing	None identified
Cold cathode tubes and switches	Energy density and one-shot reliability	Directed energy weapons; High pulse power, x-ray machines	None identified
Pyrotechnic logic and delay devices	Characterization of detonation velocity in end configurations	Device design will most likely be specific to nuclear weapon design	None identified
Detonators and initiator couplers and connectors, including: - exploding bridge wires - exploding foil - hot wire - semiconductor bridge	Reliability and precision of initiation vs. safety	Technology common to some aimable ordnance warhead concepts	Detonating devices derived from commercial civil explosives
OPERATIONAL SECURITY			
Lock systems incorporating combined electronic and positive mechanical or physical "keying"	Balancing ease of use and reliability against security and probability of unauthorized penetration	Elements of technology may be common to conventional physical security of highly classified or high value/high risk assets	Single-keyed, mechanical system
Physical security	Probability of detection vs. false alarm rate	Elements of technology may be common to conventional physical security of highly classified or high value/high risk assets	Conventional passive infrared and ultrasonic detection, manual backup

SECTION 5.8—RADIOLOGICAL WEAPONS

OVERVIEW

Radiological weapons use the beta rays, neutrons, and gamma rays emitted by the decay of highly radioactive isotopes to kill or incapacitate. In general, the latency period between exposure to high doses of radiation and the onset of symptoms is long (hours to weeks, depending upon dose), but it may be as short as minutes if neutron doses on the order of several thousand rads (whole body dose) can be delivered. However, there is no practical way to transport enough radioactive material to provide doses this high because the amounts of isotopes necessary to inflict reasonably prompt casualties (hours to days) over a large area (square kilometers) on a foe may produce so much heat that it melts even steel bomb cases.

Because of the long latency period, radiological weapons are probably of little tactical use on the battlefield except that fear of radiation on the part of the opponent may act to deny areas to him. For area denial to be effective, the opponent's troops must be notified of the presence of the agent, because the radiation does not cause prompt casualties. Radiological weapons may have the potential for use against rear areas. The isotopes of greatest concern are those normally produced as fission products in nuclear reactors or which are copiously produced when "fertile" material is irradiated in a reactor (e.g., ^{137}Cs, ^{60}Co). More rapidly decaying, and hence more potent, radioisotopes generally have short half lives (a year or less), complicating the problem of stockpiling them for later use.

Gamma-ray and neutron-emitting isotopes in quantities needed to cause injuries to opposing troops are likely to be very dangerous for the attacker's troops to handle. The mass of the required shielding will greatly exceed that of the agent.

On the other hand, public fear of radiation is so great that small quantities of radioactive materials dispersed about a city may well induce considerable panic in the populace. Such use of radiological agents would most likely be announced by the attacking force, because the material may not otherwise be detected.

Alpha radiation (^{4}He nuclei) is normally not dangerous unless it enters the body and lodges there. Because they are massive (two neutrons and two protons) and slow moving, the particles produced in normal alpha decay stop so quickly that a single thickness of paper is usually a sufficient shield. They also carry a charge of +2, which doubles the force they exert on the electrons in target material compared to a beta ray (electron).[13] If, however, correctly sized particles containing alpha-emitting isotopes are inhaled, they tend to lodge in the tissue of the lung where they deposit their energy in a very localized region. This can lead to lung cancer, but with a decades-long latency period.

One might conceive of a long-duration radiological weapon suitable only for producing terror and forcing the evacuation of an area by exploiting the dangers of inhaled radioisotopes. Any cancers will be produced with a very long latency period (years), but the mere possibility of such personal catastrophes may be strategically important.

An alternative scenario would be to conceal a very intense radioactive gamma source such as ^{60}Co in an area to which many people return on a regular basis, such as a theater, restaurant, or mess hall. If the source were radioactive enough and remained concealed for sufficient time the extended exposures could produce direct casualties with complicated epidemiology. For this to be used as a weapon with shock value, the exposed population would have to be informed of the presence of the source.

RATIONALE

Although radiological weapons have little or no tactical importance on the battlefield, the fear of radiation has become so widespread and ingrained that if an opponent spreads even small, harmless but detectable amounts of radioactive material in rear

Highlights

- Radiological weapons are more apt to cause civil disruption than destruction.
- They can be made in almost any kind of nuclear reactor and require far less engineering and research than do nuclear explosives.
- Radiological agents in quantities great enough to cause prompt-lethal or prompt-incapacitating effects on the battlefield will likely be too thermally hot to transport.

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[13] The rate at which a heavy charged particle loses energy is proportional to the square of its charge.

echelon areas, the action may force U.S. troops to don full protective garb and attempt to operate under that handicap.

It is not possible to dispose of radiological agents by burning; they will merely be transferred to the effluent. Neither can radiological agents be “sterilized” by heat or other chemicals. Decontamination is usually accomplished by a wash-down, with the waste water becoming low-level radioactive waste. Only time—the passing of many half-lives of the isotopes in question and their radioactive daughters—can totally eliminate the hazard posed by radioactive contamination.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Radiological agents can be conveniently and secretly made in any research reactor designed to irradiate material samples. Spent fuel from any reactor can be cut up and the material dispersed without further chemical treatment. Thus, any nation with a research reactor or with civilian power reactors and the capability of discharging spent fuel from those reactors has the potential to produce material suitable for use in radiological weapons. The fundamental tool for producing radioisotopes, a nuclear reactor, can be found in very many countries. The 44 nations identified in the 1996 Comprehensive Test Ban Treaty as having safeguarded reactors and other fuel facilities provide a good start at identifying possible sources for radiological warfare agents.

Actually turning the radioisotopes into weapons may require special techniques for handling the material safely. Similarly, those crews chosen to disperse the material will require protective gear or, alternatively, must be ready to become human sacrifices. Efficient use of radiological material requires converting it from bulk form into a dust or aerosol which can be inhaled and then finding methods to spray the material. These technologies may not be present in every state which can produce radioactive isotopes. On the other hand, they are not required if the aim is merely to cause panic or to force troops to work in protective clothing.

Table 5.8-1. Radiological Weapons Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Irradiation of fertile material	Ability to make millions of curies of radioactive material	NTL A1, B1; NRC A, L	Fertile elements such as Co, Cs to be irradiated	Reactor refueling equipment; remote handling equipment. Nuclear reactor for irradiation.	Reactor design and operating software with capability to simulate presence of neutron-absorbing nonfissile material; activation cross-sections.
Transportation and handling of intensely radioactive material	Shielding against gamma photons with energies up to 3–5 MeV; ability to reduce surface field to safe levels, circa 1 mr/hr in contact with package. Ability to cool isotopes to prevent melting.	NDUL 8; CCL Cat 1A; CCL Cat 2B	Lead and borated materials for radiation shielding; hermetic seals for container; radiation-damage-resistant seals and containers. Absence of plastics likely.	None identified	Shielding software. Much of this is publicly available.
Dispersal of agent	Ability to reduce bulk material to fine powder or to liquid solution for aerosol or other spraying operation; ability to transport material in combat aircraft or UAVs.	WA ML 4; USML IV	Radioactive isotopes; shielding; spraying equipment resistant to corrosion by solvents used to dissolve radioactive compounds. Absence of unshielded plastic and rubber parts probable.	Corrosion- and radiation-resistant sprayers, pumps, etc. Absence of unshielded plastic components likely because of their rapid degradation in presence of intense photon irradiation. Personnel protection as necessary.	Plume prediction software. Much of this is publicly available.
In situ preparation of radiological agent	Neutron bomb	NTL 1	Fertile materials; SNM; tritium	Sprayers for fertile material solutions	None

Table 5.8-2. Radiological Weapons Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Reactor irradiation of fertile material	Construct reactors; extract fission products or irradiated target material	Prepare radiological agents for use in area denial	Use of high-level waste from civilian power reactors
Transport of radiological agents	Shielding; concealment; cooling of large quantities; provision of seals not affected by irradiation	Bring agent to place of employment	Accept "kamikaze" tactics for personnel delivering agent
Dispersal of agent	Aerosolization of solid agent or dissolving and then aerosolizing of liquid. Spreading of powder	Employ weapon	Accept "kamikaze" tactics for personnel delivering agent
In-situ preparation of radiological agent	Spray area with solution containing activatable material, e.g., cobalt chloride. Then detonate enhanced radiation weapon at appropriate altitude	Deny area to foe; provide inherently safe transport of agents	All other methods of obtaining radioactive material

SECTION 5.9—MANUFACTURING OF NUCLEAR COMPONENTS

OVERVIEW

This subsection describes the technologies required for the production of equipment used to manufacture nuclear weapons. In most cases, the technologies, the equipment, and the know-how are dual-use and affect civilian applications where, for example, considerations of costs, flexibility, and competitiveness have become major concerns. In some cases, the technologies described here are neither state of the art, nor is the United States the world leader in the technology. The concerns of the United States with respect to the spread of nuclear weapons are no longer directed at the technologically advanced Warsaw Pact countries, but more at developing countries that are attempting to produce weapons of mass destruction. Therefore, the United States must adjust its level of concern to the control or monitoring of that machine tool technology actually necessary to meet the U.S. antiproliferation goals, a level which is often significantly less than the state of the art.

A number of different technologies associated with a modern industrial base are addressed in this subsection, including many types of machine tools and processing equipment, certain inspection equipment, and certain robots.

Manufacturing Equipment

This section encompasses both machine tools and equipment for fabricating structures by means of various advanced manufacturing techniques. Machine tools include NC (numerically controlled) machines in which the motions of the various axes are simultaneously and continually coordinated, thereby maintaining a predetermined (programmed) path. This includes turning, milling, and grinding machines and electrical discharge machines (EDM).

Advanced manufacturing technique equipment includes spin, flow, and shear forming machines; filament-winding machines; hot isostatic presses; high-temperature furnaces and heaters; equipment for the manufacture of centrifuge rotors; vibration/shaker systems; and flash x-ray systems. It is often suggested that all or even most of these manufacturing and mensuration systems are required to build weapons of mass destruction in general and nuclear weapons in particular.

A nuclear weapon is a sophisticated device, and depending upon the complexity of the design and the constraints on the designer—such as size, weight, and amount of special nuclear materials which can be used—may or may not require very precise manufacture.

Highlights

- Computer numerically controlled (CNC) machine tools may speed construction of components of nuclear weapons and reduce the labor costs of such manufacture.
- Robotic manufacture may reduce personnel exposure to radiation.
- Precision metrology may make manufacture to tighter tolerances feasible.
- When testing is not possible, parts made as closely matched to theory as possible provide some assurance of attaining the desired results in nuclear weapons.

At the state of the art, however, factories producing the nuclear components (and some nonnuclear components) of modern devices must be capable of carrying out dimensional measurements which are both precise and accurate. Relative thicknesses must be measured to high precision, and the absolute values of those measurements must be compared to a set of standards with extreme accuracy.

It is common, of course, for the most technically advanced nuclear powers to employ all of the modern tools of computer-assisted fabrication, including computer numerically controlled (CNC) machine tools.

Shapes which can be manufactured with a modern 5-axis CNC machine tool can be approximated on a simpler machine if the work can be repositioned during machining or if the component can be made in parts which are later joined together. Significant hand work is usually required in either case. The accuracy of the approximation depends upon the precision with which the work can be repositioned or with which the separate components can be joined and in both instances, on the skills of the engineers/machinists. The history of American nuclear efforts is illustrative. The first thermonuclear bomb was produced in the 1951–1952 time frame; the first use of 3-axis machine tools occurred in 1952, and the first 5-axis machine tools were used in 1954.

Metrology

Metrology covers technologies for dimensional measuring systems and equipment needed for precise determination of the dimensions of manufactured parts, machine tools, and inspection machines. Included are systems for in-process measurement, as well as post-manufacture inspection. This technology area is of paramount importance for the construction of systems incorporating mechanical or electrical components built to exacting tolerances, whether such hardware is military or civil. It is highly dependent on sensors, positioners, feedback systems, digital computers, and associated components and hardware. Included in the list of metrology equipment are coordinate, linear, and angular measurement machines using laser, standard light, and noncontact techniques. The tolerances of parts measured range from ±1 nm (corresponding to an optical surface finish prepared by diamond turning with ion beam polishing) to ±10 µm(corresponding to more traditional metal machining).

Robots

The term “robots” covers the technology for the general category of robots, controllers, and end-effectors, which are used in conjunction with other manufacturing equipment for the production or testing of critical hardware. Robots can essentially be separated into four distinct disciplines, the robot, the controller (computer), sensors (the “eyes” of the robot), and end-effectors (the “gripper”). Robots have found a wide range of applications in manufacturing, including welders, sprayers, assemblers, loaders/unloaders, etc. They have also found use in handling hazardous or radioactive materials, transporting explosive weapons, and performing tasks in space. In this subsection, only those robots designed for use in radiation environments are addressed.

RATIONALE

Manufacturing technologies are fundamental to the national industrial base. As much as any other technology, they are vital for the manufacture of military and civil hardware, and they either enable the manufacture of vital military systems or are essential for the design and manufacture of future military systems. Without some level of manufacturing equipment capability, it would be impossible to produce the military systems used by the world’s military forces. In particular, the technologies listed in this subsection are necessary for the manufacture of modern nuclear weapons. Many listed technologies are far more advanced than those available to the first several nuclear weapon states when they built their first nuclear and thermonuclear weapons, weapons generally considered quite satisfactory for their avowed purposes of deterrence and warfighting.

Manufacturing Equipment

Modern weapon systems require a variety of processing equipment to manufacture necessary components. For example, machine tools or precision casting are used in the machining of hemi-shells for nuclear weapons; spin, flow, and shear forming machines are required for the fabrication of thin-walled, long, concentric hollow bodies, such as rotors for centrifuge devices used in uranium enrichment. Superplastic forming/diffusion bonding equipment is used for the fabrication of sheet metal structures of advanced alloys (e.g., titanium, nickel, and aluminum), in which reliability and cost are important factors, and high-temperature furnaces are used for casting uranium and plutonium, both key weapons materials.

Metrology

Modern precision manufacturing depends upon being able to make a large number of dimensional measurements precisely and accurately, and to know that measurements made at each site can be referred to a set of secondary standards which can, if necessary, be calibrated against the international standards. A centimeter measured in one laboratory must be the same as a centimeter measured with different equipment at another laboratory, and that equality must be demonstrable quickly and economically. In many ways, technological progress has been demarcated by our ability to make precision, standard measurements and to transfer this ability from the laboratory to the production floor. This is the science of metrology.

Accurate dimensional inspection is essential for the design, development, manufacture, and use of a wide range of military hardware. Dimensional inspection machines are used for the measurement of centrifuge and nuclear weapons parts; linear inspection machines are used for the measurement of bearing races or shafts (used in advanced machine tools), centrifuges, and nuclear weapons parts. Specialized measuring equipment is critical for measuring hemi-shells.

Robots

In most advanced manufacturing plants robots have replaced humans in many operations which are repetitive and do not require human intervention. Such applications include welding, painting, surveillance, and pick-and-place assembly. This type of robot is commonplace in industrial countries and is not included in this document. Robots are indispensable in many hazardous military operations, including the handling of munitions, operating in highly radioactive or electromagnetic pulse (EMP) environments, and performing tasks in space. The use of robots in these applications extends the military capability much further than what could be accomplished with “protected” humans.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Since manufacturing is so fundamental to the industrial base of any country, the availability of machines necessary to produce both military and civil hardware is worldwide. As a result, the technology level of the major industrial countries is very high, with the United States, Japan, Germany, Switzerland, Italy, France, the UK, the

Netherlands, and Sweden all having considerable expertise. The technology level in Russia and China is increasing markedly, with some rudimentary 5-axis machine tools becoming available in those countries. France, Germany, Japan, Switzerland, and the UK are the leading countries with expertise in metrology. Japan is the major competitor to the United States in robotics. France has a significant robotics capability, and Italy is a worldwide competitor.

Manufacturing Equipment

Japan, Germany, France, and Switzerland are comparable to the United States in certain machine tool capabilities. Indeed, Japan and Switzerland surpass the United States in some categories. Italy, the Netherlands, Sweden, and the UK have extensive capabilities in some of the niche areas. China has developed capabilities in 4- and 5-axis machines, although the degree of their capability, relating to quality and quantity, is still unknown.

Japan, Germany, France, and the UK are comparable to the United States in advanced manufacturing.

Metrology

A number of foreign countries have developed sophisticated metrology capabilities. Germany and the UK have capabilities across the spectrum of the technology, while France, Japan, and Switzerland have advanced capabilities in most of the technologies associated with metrology. A large number of countries have niche capabilities.

Robots

A number of other countries have developed sophisticated robotics. Japan, in particular, and Germany have emerged as world leaders in industrial robots. Most all other heavily industrialized countries have capabilities in this area. The United States and Japan are the world leaders in military/nuclear/space robotics. Russia and the Ukraine have considerable capability in robots designed for use in nuclear environments, as used for example in the monitoring of the Chernobyl nuclear plant.

Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
MANUFACTURING EQUIPMENT					
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by grinding.	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Spindles with low run-out, tilting spindles, linear and rotary position feedback units, and compound spindles and tables.	None identified	Control algorithms for the manufacture of specific items of concern.
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by turning.	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Spindles with low run-out, linear and rotary position feedback units.	None identified	Control algorithms for the manufacture of specific items of concern.
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by milling.	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Spindles with low run-out, tilting spindles, linear and rotary position feedback units, and compound spindles and tables.	None identified	Control algorithms for the manufacture of specific items of concern.
Numerically controlled turning machines or combination turning/ milling machines	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Spindles with low run-out, tilting spindles, linear and rotary position feedback units, and compound spindles and tables.	None identified	Control algorithms for the manufacture of specific items of concern.
Numerically controlled electrical discharge machines (EDM) of nonwire type	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Rotary axes	None identified	Control algorithms for the manufacture of specific items of concern.

(cont'd)

Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Numerically controlled spin, flow, and shear forming machines	Such equipment is useful, but not necessary, to enrichment devices and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	NDUL 1; MTCR 3; WA Cat 2B; CCL Cat 2B	Rotor-forming mandrels designed to form cylindrical rotors of inside diameter between 75 mm and 400 mm	None identified	Control algorithms for the manufacture of specific items of concern.
Numerically controlled composite filament winding equipment	Such equipment is useful, but not necessary, to enrichment devices and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	NDUL 3; WA Cat 1B; CCL Cat 1B	Glass and carbon fiber	None identified	None identified
Vacuum or controlled environment induction furnaces	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	NDUL 1; CCL Cat 2B	Specially designed power supplies with power output of ≥5 kW.	None identified	None identified
Vacuum or controlled atmosphere metallurgical melting and casting furnaces	Any capability for arc melting and casting, electron beam melting, plasma atomization or high temperature (>600 K) melting furnaces is a concern.	NDUL 1; CCL Cat 2B	None identified	None identified	None identified
Hot isostatic presses	Such equipment is useful, but not necessary, to build a nuclear weapon and might allow a proliferator to construct more intricate devices than would otherwise be possible. Therefore, any capability is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	None identified	Control units	None identified

(cont'd)

Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Electrodynamic vibration test system	Reliability may be of little concern to certain adversaries. However, the following capabilities would be of value in developing reliable weapons: vibrating a system at ≥15 g RMS, between 20 Hz and 2,000 Hz, imparting forces of ≥30kN (5,625 lb)	NDUL 1; CCL Cat 2B	None identified	Closed loop test equipment, digital controllers, and vibration thrusters.	Special algorithms to generate specific g levels and vibrations that corresponds to weapon system.
Digital controllers	Any capability is a concern.	NDUL 1; MTCR 15; CCL Cat 9B; WA Cat 9B	None identified	None identified	None identified
Vibration thrusters	Reliability may be of little concern to certain adversaries. However, the capability of imparting a force ≥30 kN (5,625 lb) would be a concern.	NDUL 1; MTCR 15; CCL Cat 9B; WA Cat 9B	None identified	Closed loop test equipment	Special algorithms to generate specific g levels and vibrations that corresponds to weapon system.
Rotor assembly equipment	Any capability is a concern.	NDUL 3; CCL Cat 2B	None identified	Mandrels, clamps, and shrink fit machines.	None identified
Rotor-straightening equipment	Any capability is a concern.	NDUL 3; CCL Cat 2B	None identified	Pneumatic rams	None identified
Bellows-forming mandrels and dies for producing single-convolution bellows	Any capability is a concern.	NDUL 3; CCL Cat 2B	None identified	Mandrels and dies	None identified
Centrifugal multiplane balancing machines for flexible rotors	Any capability is a concern.	NDUL 3; CCL Cat 2B	None identified	None identified	Control algorithms for the testing of specific items of concern.
Centrifugal multiplane balancing machines for hollow cylindrical rotor components	Any capability is a concern.	NDUL 3; CCL Cat 2B	None identified	None identified	Control algorithms for the balancing of specific items of concern

(cont'd)

Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Flash x-ray machines or pulsed electron accelerators	Having either of the following: an accelerator peak electron energy ≥300 keV, but <25 MeV; and with a figure of merit (K) of ≥0.25, where $K = 1.7 \times 10^3 V^{2.65} Q$; or an accelerator peak electron energy ≥15 MeV and a peak power >40 MW.	NDUL 5; CCL Cat 3A	None identified	None identified	None identified
Remote manipulators	Such equipment is useful, but not necessary for nuclear programs.	NDUL 8; CCL Cat 2B; WA Cat 2B	Able to provide mechanical translation of human operator actions by electrical, hydraulic or mechanical means to an operating arm and terminal fixture.	None identified	Control algorithms for the manufacture of specific items of concern.
METROLOGY					
Numerically controlled dimensional inspection machines	Accurate computer controlled coordinate measuring machines (CMM) would be a concern.	WA Cat 2B; NDUL 1;	Measurement probes, sensors, etc.	Accurate machine tools are required for the manufacture of such equipment, and precise metrology equipment is required to verify measurement capability.	Control algorithms for the dimensional inspection of specific items of concern.
Linear displacement (non-contact) measuring devices	Non-contact type with a resolution ≤0.5 µm within a measuring range of 0.2 mm	WA Cat 2B; NDUL 1	Measurement probes, sensors, etc.	None identified	None identified
Linear measuring machines using linear voltage differential transformer systems	Having both: linearity ≤0.5% within a measuring range up to 5 mm; and drift ≤0.2% per day at a standard ambient room temperature ±1 K.	WA Cat 2B; NDUL 1	Measurement probes, sensors, etc.	None identified	None identified

(cont'd)

Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Linear measuring machines	Having both: a laser, *and* the capability to maintain, for at least 8 hours, over a temperature range of ±1 K around a standard temperature and pressure, both: a resolution ≤0.4 µm over full scale *and* a measurement uncertainty ≤(0.2 L/2,000 µm)	WA Cat 2B; NDUL 1	Measurement probes, sensors, and lasers	None identified	None identified
Angular displacement measuring devices	Having an angular position deviation ≤0.001 deg	WA Cat 2B; NDUL 1	Measurement probes, sensors, etc.	None identified	None identified
Systems for simultaneous linear-angular inspection of hemishells	Capable of measuring hemishells with both a measurement uncertainty equal to or less than 5.0 µm per 5 mm and an angular position deviation equal to or less than 0.05 deg	NDUL 1; CCL Cat 2B	Measurement probes, sensors, etc.	None identified	None identified
ROBOTICS					
Robots (designed to operate in explosive or EMP environments), controllers, and end-effectors	Any capability of operation in an explosive environment is a concern.	WA Cat 2B; NDUL 1; CCL Cat 2B	Sensors, end-effectors, ruggedized hydraulic lines (e.g., self-sealing lines), hydraulic fluids with flash points > 839 K (565 °C) and closed or open loop servo-devices	Machine tools, inspection equipment, and all necessary equipment to manufacture sensors, cameras, etc.	Control algorithms for the motion and operation of the robots
Robots designed for nuclear environments, controllers, and end-effectors	Designed to operate in a radiation environment greater than 10^5 rad (Si)	WA Cat 2B; NDUL 1; CCL Cat 2B	Sensors, end-effectors, electronics capable of operating in radiation levels of 5×10^4 grays [5×10^6 rad (Si)] and open or closed loop servo-devices	Machine tools, inspection equipment, and all necessary equipment to manufacture sensors, cameras, etc.	Control algorithms for the motion and operation of the robots

Table 5.9-2. Manufacturing of Nuclear Components Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
MANUFACTURING			
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by grinding	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in machining nuclear materials.	NC grinding machines are an enabling technology for munitions and weapons systems. Nuclear applications include machining hardened materials used in fixturing.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by turning	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in machining nuclear materials.	NC turning machines are an enabling technology for munitions and weapons systems. Nuclear applications include the manufacture of hemishells, rotors and end-caps.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled machine tools for removing or cutting metals, ceramics, or composites by milling	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in machining nuclear materials,.	NC milling machines are a key enabling technology for munitions and weapons systems.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled turning machines or combination turning/ milling machines	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in machining nuclear materials.	NC turning/milling machines are a key enabling technology for munitions and weapons systems. Nuclear applications include the manufacture of hemishells.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled electrodischarge machines (EDM) of nonwire type	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in machining nuclear materials.	NC nonwire EDM machines are a key enabling technology for munitions and weapons systems.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled spin, flow, and shear forming machines	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in producing centrifuge tubes to the accuracies necessary for uranium enrichment.	Capability to manufacture thin-walled curvilinear or cylindrical cross-section parts for use in seamless rocket motors, nose cones, rocket launcher tubes, rotor tubes for gas centrifuge uranium enrichment systems, and contour shapes in nuclear weapons.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.
Numerically controlled composite filament-winding equipment	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in producing centrifuge tubes to the accuracies necessary for uranium enrichment.	Used in the manufacture of fiber composite rotor assemblies for gas centrifuges used in uranium enrichment.	Numerically controlled, accurate machine tools are essential for the manufacture of advanced nuclear weapons.

(cont'd)

Table 5.9-2. Manufacturing of Nuclear Components Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Vacuum or controlled environment induction furnaces	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in working with uranium and/or plutonium.	Used for casting either enriched or unenriched uranium and for processing plutonium for key weapon parts.	Some type of controlled environment furnace would be necessary to cast the nuclear materials. In lieu of an induction furnace, a plasma, e-beam, or electric furnace might be used.
Vacuum or controlled atmosphere metallurgical melting and casting furnaces	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in working with uranium and/or plutonium.	Used for casting either enriched or unenriched uranium and for processing plutonium for key weapon parts.	Some type of controlled environment furnace would be necessary to cast the nuclear materials. In lieu of an induction furnace, a plasma, e-beam, or induction furnace might be used.
Hot isostatic presses	The technical issues of general equipment use are well-known. However, proliferants would need to develop experience in working with uranium, lithium compounds and explosive materials.	Used to increase the density of uranium fuel, cladding reactor fuel rods, pressing plastic-bonded explosives (PBXs) and compacting lithium hydride and lithium deuteride.	Pneumatic presses might be used; however, the results would be much inferior.
Electrodynamic vibration test system using digital control techniques	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Testing the effects of shock and vibration is critical in developing reliable nuclear weapons, arming and safing systems.	Analog vibration systems with less stringent requirements could be used to test smaller warheads or manufacture could proceed without vibration testing.
Digital controllers	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Testing the effects of shock and vibration is critical in developing reliable nuclear weapons, arming and safing systems.	Analog equipment could be used.
Vibration thrusters	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Testing the effects of shock and vibration is critical in developing reliable nuclear weapons, arming and safing systems.	Smaller thrusters could be used for smaller loads.
Rotor assembly equipment	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	This equipment is used for the assembly of gas centriguge rotor tube sections, baffles, and end-caps.	Not applicable
Rotor-straightening equipment	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	This equipment is used for the alignment of of gas centrifuge rotor tube sections to a common axis.	Not applicable

(cont'd)

Table 5.9-2. Manufacturing of Nuclear Components Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Bellows-forming mandrels and dies for producing single-convolution bellows	While bellows, per se, are common industrial products, bellows of this design, and made of these materials, are not common. The technology to construct them is not common knowledge.	These bellows are components of the gas centrifuge equipment used for uranium enrichment.	Less sophisticated bellows could be used .
Centrifugal multiplane balancing machines for flexible rotors	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Used to balance rotors, rotor sections, and rotor assemblies used in gas centrifuges for uranium enrichment.	Although the balance of the rotors is critical, smaller and/or lower rpm balncing machines could be used.
Centrifugal multiplane balancing machines for hollow cylyndrical rotor components	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Used to balance rotors, rotor sections, and rotor assemblies used in gas centrifuges for uranium enrichment.	Although the balance of the rotors is critical, smaller and/or lower rpm balancing machines could be used.
Flash x-ray machines or pulsed electron accelerators	Flash x-ray systems have limited non-military use. However, it would not be difficult to transfer knowledge from the nonmilitary applications to nuclear uses.	Used in developing nuclear weapon implosion systems. They provide diagnostic data on non-nuclear hydrodynamic tests of the implosion system. Smaller systems are used in developing precision high-explosive implosion systems.	There may be no alternate technology to duplicate what can be done with the flash x-ray. Howver, high-speed rotating mirror cameras may perform some of the required tests.
Remote manipulators	The technical issues of equipment use are well-known. There would be no major difficulty in transferring knowledge from standard industrial experience to the nuclear arena.	Provide mechanical translation of human operator actions by electical, hydraulic or mechanical means to an operating arm and terminal fixture, used to provide remote actions in radiochemical separation operations or "hot cells."	Not applicable
METROLOGY			
Computer or stored program controlled dimensional inspection machines [coordinate measuring machines (CMMs)]	Most nuclear applications would not involve measurement of radioactive materials. Therefore, the technical issues of concern would be programming, operation, and interpretation of data, and these are well-known in the industrial world.	Allows for precision measurements of low volume, high precision components used in weapons, weapons control, etc. Nuclear applications include measurement of centrifuge and nuclear weapons parts.	Satisfactory results could be obtained using uncontrolled CMMs; e.g., they are manually operated, and they have greater uncertainty in measurement.
Linear displacement (non-contact) measuring devices	Most nuclear applications would not involve measurement of radioactive materials. Therefore, the technical issues of concern would be programming, operation, and interpretation of data, and these are well-known in the industrial world.	Essential for the measurement of very precise parts with simple geometries, such as bearing races or shafts and centrifuge and nuclear weapon parts. They also offer improved allignment of components of optical and radar system and sighting mechanisms.	Many things could be used as alternate technologies: e.g., uncontrolled CMMs, gauge blocks and indicators, height gauges, V-blocks, micrometers (including depth micrometers), bore gauges, etc.

(cont'd)

Table 5.9-2. Manufacturing of Nuclear Components Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Linear measuring machines using linear voltage differential transformer systems	Most nuclear applications would not involve measurement of radioactive materials. Therefore, the technical issues of concern would be programming, operation, and interpretation of data, and these are well-known in the industrial world.	Essential for the measurement of very precise parts with simple geometries, such as bearing races or shafts and centrifuge and nuclear weapon parts. They also offer improved allignment of components of optical and radar system and sighting mechanisms.	Many things could be used as alternate technologies: e.g., uncontrolled CMMs, gauge blocks and indicators, height gauges, V-blocks, micrometers (including depth micrometers), bore gauges, etc.
Linear measuring machines	Most nuclear applications would not involve measurement of radioactive materials. Therefore, the technical issues of concern would be programming, operation, and interpretation of data, and these are well-known in the industrial world.	Essential for the measurement of very precise parts with simple geometries, such as bearing races or shafts and centrifuge and nuclear weapon parts. They also offer improved allignment of components of optical and radar system and sighting mechanisms.	Many things could be used as alternate technologies: e.g., uncontrolled CMMs, gauge blocks and indicators, height gauges, V-blocks, micrometers (including depth micrometers), bore gauges, etc.
Angular displacement measuring devices	Most nuclear applications would not involve measurement of radioactive materials. Therefore, the technical issues of concern would be programming, operation, and interpretation of data, and these are well-known in the industrial world.	Essential for the measurement of very precise parts with simple geometries, such as bearing races or shafts and centrifuge and nuclear weapon parts. They also offer improved allignment of components of optical and radar system and sighting mechanisms.	Many things could be used as alternate technologies: e.g., uncontrolled CMMs, gauge blocks and indicators, height gauges, V-blocks, micrometers (including depth micrometers), bore gauges, rotary heads, etc.
Systems for simultaneous linear-angular inspection of hemishells	Although this is specialized equipment, the operation and interpretation would be straightforward. The imposing technical issue would be the know-how and interpretation of test results.	Specialized device used in the manufacture of nuclear weapon components	Alternate technologies could include uncontrolled CMMs and rotary heads and measuring indicators.
ROBOTICS			
Robots designed to operate in explosive or EMP environments, controller and end-effectors	Since robots, per se, are universally used, the operation of such equipment would be straightforward. The main technical issue would be either the difficulty in procuring such robots or the having technology to design and build them.	Such robots can be used both as replacements for military forces or in hot cells.	There are two alternatives to the use of these robots: (1) using commercial type robots, with the understanding that there will be a short mean time to failure, or (2) using humans, with the understanding that they would be expendable.
Robots designed for nuclear environments	Since robots, per se, are universally used, the operation of such equipment would be straightforward. The main technical issue would be either the difficulty in procuring such robots or the having technology to design and build them.	Such robots are used in nuclear reprocessing and nuclear production reactor facilities. they may also be used in nuclear facilities to reduce occupational radiation exposure.	There are two alternatives to the use of these robots: (1) using commercial type robots, with the understanding that there will be a short mean time to failure, or (2) using humans, with the understanding that they would be expendable.

SECTION 5.10—NUCLEAR WEAPONS DEVELOPMENT TESTING

OVERVIEW

Nuclear weapons, to quote Sidney D. Drell, are “sophisticated but not complicated.” That is, the working principles are straightforward, although the equipment needed to make a device function, and function reliably, is quite sophisticated and requires high-quality engineering to design and build. Although it is generally believed that a proliferator need not test a conservatively designed device at full yield to have confidence in it, some experimentation and testing along the way is necessary to demonstrate the behavior of the non-nuclear components including the firing set, detonators, and neutron generators. If there is not to be a full-yield nuclear test, then the non-nuclear experiments must be carried out with greater care and competence.

One reason for believing that a full-yield nuclear test is unnecessary is that each of the six states known to have tested nuclear devices has achieved a nuclear detonation on the first try.

The term “nuclear testing” as used here encompasses all experiments in which special nuclear material (or a simulant) is placed in contact with high explosives, which are then detonated, or with a propellant, which is ignited. This limitation deliberately excludes activities which are more scientific in nature and not intimately connected with the progression from fissile material and/or fusion fuel to a nuclear explosive device.[14] This definition is far broader than that of the Comprehensive Test Ban Treaty (CTBT) of 1996, which prohibits only nuclear weapon test explosions and other nuclear explosions.[15] Many states of concern for nuclear proliferation[16] have subscribed to the CTBT, and may, therefore, find it difficult to conduct full-yield tests either underground or in the atmosphere. India, however, has served notice that it will not sign the CTBT; in 1974 India detonated what it *called* a “peaceful nuclear explosive device.”

Even under the CTBT, most non-nuclear *hydrodynamic* implosion testing[17] will be permitted. At the lowest end of the nuclear yield distribution from *hydronuclear* tests, some states might reckon that the knowledge gained from a small explosive release of nuclear energy would be worth the risk of getting caught. Generally, within the U.S. Government, the condition of prompt nuclear criticality distinguishes, under the CTBT, a prohibited test of an explosively assembled device from one which is allowed.

Highlights

- It is possible to make a credible nuclear weapon without ever testing the nuclear parts of the device or producing any nuclear energy release.
- Hydrodynamic nuclear experiments using flash x-ray cameras to image the imploding material that simulates plutonium or uranium are necessary.
- American-style underground nuclear testing requires some sophisticated equipment, but bare bones experiments are also feasible and useful.
- The 1996 Comprehensive Test Ban Treaty prohibits the testing of nuclear weapons. Signatories include all five declared nuclear weapons states, Israel, and Iran. India, Pakistan, North Korea, Iraq, and Libya have not signed the Treaty.

The spectrum of nuclear devices which a proliferant organization could field potentially spans everything from simple devices which scatter radioactive waste (see Section 5.8, Radiological Weapons) to sophisticated weapons incorporating boosted primaries and adjustable yield secondaries. The device actually built by any given proliferator depends on the technological sophistication; size; available budget; availability of special nuclear materials; time scale; strategic or tactical intent; and a host of other exogenous and endogenous considerations, political, economic, and social.

There is little doubt that technologically sophisticated nations with well-educated populations and large GDPs, and having an indigenous reactor industry as well as

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[14] For example, laser and particle beam fusion.

[15] The CTBT, signed by President Clinton on 24 September 1996, obligates each signatory not to conduct “nuclear weapons test explosions” or “any other nuclear explosions” on any territory under its control.

[16] India, Iraq, and Pakistan are not CTBT signatories; all five nuclear weapons states are.

[17] In a *hydrodynamic* test, inert material (e.g., ^{238}U or a simulant for plutonium) is imploded to determine how well the high-explosive system functions. In a *hydronuclear* test, fissile material is imploded, but a supercritical mass is not maintained for a long enough time to permit the device to deliver “full” nuclear yield. Depending upon the conditions of the test, nuclear energy releases may range from the unmeasurably small (milligrams or less) to kilograms or even metric tons of TNT equivalent yield.

enrichment and reprocessing facilities, could produce nuclear weapons in a very short time. The strategic or tactical doctrine for their use would be vastly different from those of a subnational group developing nuclear capability and probably different from a third world proliferator.

The general design of a gun-assembled device is straightforward and based on well-understood principles of artillery weapons; however, the technology for obtaining enriched uranium is complex. On the other hand, implosion-assembled devices using plutonium—which could be extracted simply using chemical techniques from reactor rods—are more difficult to manufacture.[18] If a nation had an indigenous reactor industry, such extraction would be straightforward.

The testing programs required to accomplish the goals of proliferators spread out along the spectrum of technical sophistication and available resources are as diverse as the goals of the proliferant states themselves and the programs to develop the weapons. At the most primitive end of the spectrum, if the device were stolen, yield testing would not be required, but circumvention of possible use controls would be. If the weapon were "legitimately" acquired from a nuclear power, presumably use control information would be passed on to the purchaser. In neither case is testing required. If, however, a nuclear device is indigenously designed and built, the question to be answered by a full-scale nuclear test is likely to be *how much* nuclear yield a specific device will deliver, and not necessarily *whether* it will produce nuclear yield.

RATIONALE

Fundamentally, test programs can be divided into two major categories: those for an HEU-fueled, gun-assembled device and those for an implosion device using either plutonium or HEU. The first Chinese test was of an HEU implosion device, Iraq intended to develop just such a weapon, and the South Africans conducted no nuclear tests of their gun-assembled devices.

Gun-Assembled Devices

The testing program for a gun-assembled device is moderately complex, but it is essential to realize that nothing nuclear need be tested to verify the probable operation of such a device—only its conventional components. The design of Little Boy, the bomb dropped on Hiroshima, had not been proof tested before the war shot.

Implosion Devices

The testing program for a simple fission device using plutonium must be more extensive than that for a gun-assembled device using enriched uranium. For example, the constructor must know that his fissile "pit" will be uniformly compressed and that the compression will be rapid enough to minimize the chances for a pre-initiation "fizzle," that any neutron generator present will fire at the correct moment, and that compression is likely to be maintained long enough to result in significant nuclear yield.

A proliferator hoping to demonstrate its technical prowess may elect to pursue an implosion device despite the availability of enriched uranium. Alternatively, it may choose implosion to achieve greater efficiency in the use of special material. It can be presumed that this type of proliferator will forego the development of thermonuclear weapons.

Hydrodynamic Testing

The testing program for an unboosted implosion device primarily ensures that the hydrodynamic behavior of the implosion (particularly of a hollow pit) is correct.

The simplest way to do hydrodynamic testing is to implode inert pits made of a simulant for fissile material (e.g., natural uranium instead of HEU) while using any of several "old fashioned" means to observe the behavior of the heavy metal. One such technique is to use a pin-dome, essentially nothing more than a precisely machined insulating "champagne cork" with a large number of protruding radial pins of different distances placed at the center of the implosion region.

Pin dome experiments are probably the easiest hydrodynamic diagnostics available. However, backlighting the pit with a flash x-ray or neutron source to obtain an actual picture of the imploding material is also a possibility. Generally, the flash x-ray source needed has to have very high peak power available in a single pulse, and the timing and firing of the source in concert with the implosion of the device requires very sophisticated system design. Backlighting the imploding system with a neutron source is a bit more straightforward, but requires very sophisticated neutron optics and imaging capability, which could be difficult to obtain. Iraq used flash x-ray diagnostics.

The Radio Lanthanum (RaLa) method, which does permit time-dependent measurements of the symmetry of an implosion, should be mentioned because of its conceptual simplicity. RaLa was used extensively during the Manhattan Project, but has probably not been employed very often since then. An intensely radioactive sample of the element lanthanum was prepared in an accelerator or reactor and then quickly inserted into the center of the implosion test device. Highly collimated Geiger-Mueller counters observed the behavior of the material as it imploded. The RaLa technique is inherently fairly crude in its ability to detect asymmetries and environmentally unappealing because the radioactive material is scattered about the test stand. However, the

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[18] Some analysts believe that the difficulties of enriching uranium are offset by the simpler weapon designs which enriched uranium allows. In the United States, HEU is considered less expensive to use in a weapon than plutonium. Operation of a reactor to produce plutonium requires the extraction and purification of uranium and, in some cases, at least modest enrichment. Given international safeguards on reactors using enriched uranium obtained from another nation or heavy water moderated reactors, a proliferant may be forced in any case to construct an enrichment facility. The choice is likely to be determined by the indigenous availability of uranium and the national surplus (or shortage) of electricity.

isotopes have half lives of only a few hours to a few days, so the residual radioactivity decreases significantly in a week or so.

Hydronuclear Testing

Hydronuclear experiments, as distinguished from hydrodynamic ones, use actual fissile material assembled to form a supercritical mass in which a chain reaction begins. Normally, hydronuclear experiments are designed to use nuclear devices modified in one of several ways, including substituting inert material or less-fissile material for some of the HEU or plutonium in the pit, so that very little nuclear energy release occurs. Yields in experiments described as "hydronuclear" by various countries have ranged from much less than 1 kg TNT equivalent to many tons.

Nuclear Yield Testing

The CTBT has created a new international norm against the testing of nuclear weapons. Nonetheless, it has not yet entered into force, and some of the states of greatest concern are unlikely to sign it in the near future. Therefore, the possibility of a proliferant state carrying out a nuclear explosion with a significant yield remains moderately high.

From 1945 through much of 1991, the United States detonated more than 1,200 nuclear devices with yields from a few pounds to about 15 megatons. Until the middle of 1963, most U.S. (and Soviet) tests took place in the atmosphere; some were conducted underground, a few were below the surface of the ocean, and roughly a dozen American shots took place at altitudes above 10 km. The largest test ever conducted, that of a 60-megaton device, was carried out in the Arctic by the USSR. Since the Limited Test Ban Treaty (LTBT) was signed in 1963, all U.S., UK, and Soviet nuclear detonations have been underground. The French and Chinese, while not parties to the LTBT, gradually moved their testing from the open atmosphere to subterranean sites—in boreholes, mine shafts, and in drill holes beneath the ocean floor.

Atmospheric tests are easier to carry out—although impossible to conceal—and for technically less-sophisticated powers provide more information in a more direct manner than do underground explosions. A weapon detonated from a several hundred foot high tower or suspended from a tethered balloon permits photography of the evolution of the nuclear fireball and the cloud. The shock wave in air can be observed, and one can determine the effects of the weapon on real targets such as structures and vehicles.

It appears likely that the drilling technology needed to emplace nuclear devices and instruments at the bottom of a deep borehole is the most difficult for a proliferator to acquire and use. Such boreholes are frequently a kilometer or more deep and 2 meters or more in diameter. The specialized drilling machinery required for such construction is not commonly available and exceeds what is found in the oil industry.

The development of the fireball and the propagation of a shock wave proceed quite differently when the device is tightly tamped at the bottom of a borehole than when it is detonated in free air. However, when the borehole or mine shaft have been properly stemmed,[19] underground experiments have the advantage of not releasing significant amounts of radioactive debris. It is also simpler to place large masses of experimental apparatus close to an underground shot than to locate the same hardware next to a balloon gondola or on the platform of a slender tower, either of which has a limited carrying capacity. In any event, very few atmospheric tests have been carried out during the last three decades, and even the French and Chinese abandoned their atmospheric test programs.

Only with a large collection of data derived from yield tests of different types of devices can a weapons designer be confident that he understands the behavior of different possible designs within what is termed the nuclear weapons "design space," and only then can he be confident that the computer programs used to predict device performance deliver reliable results. This may be the strongest motivation for a proliferator to test at full yield. However, even a series of full-yield tests may not provide all of the information needed for weapons design.

Rudimentary Testing

Most nuclear weapon states have constructed underground testing facilities similar to the U.S. Nevada Test Site. That is, weapons development and proof tests are usually carried out in vertical shafts stemmed to prevent the escape of radioactive debris. Power and signal cables for the device are routed up the shaft and fanned out to several instrumentation trailers outside the probable cratering zone. Nuclear weapons effects tests are primarily carried out in horizontal mine shafts sealed to prevent the escape of debris; instrumentation cables are connected to the surface through a vertical bore hole. In both cases, the tests are characterized by the large amount of electronic instrumentation used to study the details of the functioning of the implosion assembly and of the nuclear phases of the explosion. A beginning nuclear power opting for simpler weapons may well choose not to employ sophisticated diagnostic instrumentation, selecting instead to determine the approximate yield with seismographs.

The most accurate measurement of yield is through the radio-chemistry studies of device debris—the radioactive isotopes produced in the detonation. No electronics are used to gather the data for such analyses; it is only necessary to drill back into the device chamber and to extract samples for lab examination. A faster but less accurate yield determination can be done using seismographs to measure ground motion, but

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[19] Radioactive debris from an atmospheric test or from an underground shot which vents can be analyzed by other nations. Much information about the design and performance of the test device can be inferred from the debris.

such a test would not collect a large quantity of data usually considered desirable by U.S. weapon designers and testers.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

All five nuclear weapons states have tested nuclear devices and presumably retain the technologies needed to conduct underground nuclear explosions should the CTBT be abandoned. **South Africa** prepared two boreholes in which it could have tested its nuclear devices; those shafts have been filled and the site abandoned. **India** conducted one instrumented underground nuclear explosion and is believed to have been readying a site for additional tests during 1996. That effort may have been abandoned, but India has the technologies needed to conduct nuclear yield tests. **Brazil** drilled a borehole for a nuclear test, but that shaft was closed with great ceremony. The country has the capability to instrument a nuclear explosion to some degree. **Sweden** carried out some planning for a nuclear test in the 1960's, but apparently those plans were abandoned along with its nuclear weapons program. Most advanced industrial nations have the technology to conduct underground nuclear weapons tests which could be instrumented well enough to aid a weapons program.

Very little advanced technology is required by a proliferator wishing to conduct useful atmospheric nuclear tests, but virtually all nations of concern are States Parties to the LTBT banning tests except those conducted underground.

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters*

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
HYDRODYNAMIC TESTING					
Pin domes	Positioning to better than .001 in. ; time resolution to 10 ns	CCL EAR 99	Steel domes, pins	None identified	None identified
HE pressure, temperature, and shock transducers	Pressure upper limit on the order of 2–5 megabar; temperature on the order of 3,000 K. Rise time <<1 microsec.	CCL EAR 99	Semiconductor grade quartz; manganin metal	Clean room environments common in semiconductor assembly, most transducers available off the shelf (OTS).	Understanding of device assembly dynamic range and timing from model predictions
Pulse generators to calibrate cables, etc.	Output voltages >6 V into <55 ohm resistive load with pulse transition times less than 500 ps (defined as the time interval between 10% and 90% voltage amplitude).	CCL EAR 99	None identified	None; these instruments can be manufactured domestically with advanced understanding of high-speed circuits or be purchased OTS.	None, although computer modeling codes for high speed circuit performance would be advantageous (SPICE Code, for example)
Coaxial cables	Satellite TV technology. Cables with 1–5 dB attenuation per 100 ft at 1 GHz readily available.	CCL EAR 99	None identified	None; cables will be procured from the open market. Continuity testers and fast pulse generators used to calibrate	None identified
Cable connectors	Satellite TV technology. N, C, HN, or LC series connectors standard.	CCL EAR 99	None identified	None; connectors will be procured from the open market. Continuity testers used to quality check.	None identified
Fast oscilloscopes, usually with storage features	For hydro testing subnanosecond scopes are not required. Many types of digitizing scopes with 1–10 ns recording times are available.	NDUL 7; CCL Cat 3A	None identified	None; available commercially OTS	None, but ability to forecast device performance from models to set dynamic range of data acquisition is critical.
Oscilloscope cameras	Standard OTS cameras with triggerable shutters.	CCL EAR 99	None identified	None identified	None, but ability to forecast device performance from models to set trigger times is critical.

* Values identical to those in the NDUL do not necessarily reflect the normal TWG process.

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Transient recorders (flash digitizers)	100 MHz digitizer speed with 10–100 microseconds of memory and 8 bits of dynamic range sufficient for hydro testing.	NDUL 7; CCL Cat 3A	None identified	None; available commercially OTS	None identified
Time delay generators	Available OTS, but single cable lengths would be sufficient.	CCL EAR 99	None identified	None identified	None identified
Flash X-ray generators	Peak energy of few hundred KeV and a figure of merit, $K = 1.7 \times 10^3 \times V^{2.65} Q$ greater than about 0.25. Special equipment to halt the propagation of physical bomb debris.	NDUL 5; CCL Cat 3A	Oxygen-free copper for linear accelerator (mega-volt operation); low loss capacitors. For smaller units marx generator and cables. Dielectric oils, pref. PCB-free.	For megavolt machines based on linear accelerators, ability to machine special copper to near optical finish.	Solutions of Poisson's equation in two or three dimensions, validated against experiments. Radiation shielding codes.
X-ray recording systems (photo)	Medical x-ray technology scaled up to suit size of image.	CCL EAR 99	Medical x-ray phosphors available from several suppliers.	None identified	None identified
Mechanical framing cameras	Framing rates greater than 250,000 per second	NDUL 5; CCL Cat 3A	None identified	None identified	None, but ability to forecast device performance from models to set trigger times is critical.
Mechanical streak cameras	Writing speeds greater than 0.5 mm per microsecond.	NDUL 5; CCL Cat 3A	None identified	None identified	None, but ability to forecast device performance from models to set trigger times is critical.
X-ray recording systems (digital)	Arrays of photodiodes coupled to inorganic crystals or fiber optic coupled to CCD if imaging is required. Large inorganic crystals for flux measurements.	CCL EAR 99	Inorganic crystals, such as CsI, BGO, LSO or equivalent	None; crystals and PD arrays available commercially. Photomultiplier tubes for big crystals also available.	Data acquisition system capable of reading 1,000+ channels of data to form an image. Some systems commercially available if imaging is required.
X-ray recording systems (analog)	Heavy gas proportional chambers	CCL EAR 99	Heavy gases such as xenon.	None identified	None identified

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Multistage light gas guns or other high-velocity gun systems (coil, electromagnetic, electrothermal or other advanced systems).	Acceleration of projectiles to 2 km per second or greater	NDUL 5; CCL Cat 2B	None identified	None identified	None identified
HYDRONUCLEAR TESTING (up to few ton yield range)					
Neutron pinex (pinhole) photography	None available	CCL EAR 99	Machinable tungsten alloy for pinhole fabrication. Standard fluors for detectors.	Ability to machine tungsten to high precision at small dimensions, electro machining, for example. Fast video cameras for image recording.	Ability to forecast device performance for dynamic range and timing and shock propagation in local geology for stand-off time for data acquisition.
Gamma pinex (pinhole) photography	None available	CCL EAR 99	Machinable tungsten alloy for pinhole fabrication. Inorganic crystals for detectors.	Ability to machine tungsten to high precision at small dimensions, electro machining, for example. Fast video cameras for image recording.	Ability to forecast device performance for dynamic range and timing and shock propagation in local geology for stand-off time for data acquisition.
Gamma detectors (e.g., sodium iodide, GeLi, etc.)	Standard OTS detectors used in well logging or basic research	CCL EAR 99	Large inorganic crystals	None; detectors are commercially available. Calibration by use of standard radioactive sources.	None identified
Compton current gamma detectors	Pulsed power design techniques	CCL EAR 99	None identified	None identified	Ability to forecast device performance for dynamic range and timing and basic pulsed power codes for modeling instrument response characteristics.

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Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Neutron detectors, standard nuclear approaches	Standard OTS detectors used in basic research	CCL EAR 99	None identified	None; detectors are commercially available. Calibration by use of standard neutron sources or generators.	None identified
Cable crush yield measurement	Standard drilling techniques and time domain reflectometry with fast pulsers.	CCL EAR 99	None identified	None identified	None, but ability to forecast device performance from models and understanding of shock propagation in local geology is critical.
X- and gamma-ray detectors	Standard OTS detectors used in basic research.	CCL EAR 99	None identified	None; detectors are commercially available. Calibration by use of standard radioactive sources.	None identified
Photomultiplier tubes	On the order of few ns rise time; tube face larger than 20 cm^2	CCL EAR 99	None identified	None identified	None identified
Coaxial cables	Satellite TV technology. Cables with 1–5 dB attenuation per 100 ft at 1 GHz readily available.	CCL EAR 99	None identified	None identified	None, but ability to carry higher currents is essential.
Cable connectors	Satellite TV technology. N, C, HN, or LC series connectors standard	CCL EAR 99	None identified	None identified	None, but ability to support connections at higher currents is essential.
Transient recorders (flash digitizers)	100 MHz digitizing speed sufficient if local data buffering of high-speed events is available in instrumentation	CCL EAR 99	None identified	None identified	None, but ability to forecast device performance from models to set trigger times is critical.

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
NUCLEAR YIELD TESTING (Underground)					
Drilling machinery	Capability to drill holes approximately 2 m in diameter to depths on the order of several hundred meters to 2 kilometers	CCL EAR 99	Hardened drill bits of large diameter. Drill string material capable of function- in deep holes.	Bits, shaft casing, drill rigs capable of drilling large diameter holes to great depths. The combination of diameter and depth is larger than common in the oil business.	Validated codes to simulate pressures and stresses on very deep shafts.
Hole stemming technologies to ensure acceptable containment	Knowledge of soil permeability; ability to seal boreshaft gas-tight even after the passage of the shockwave from the nuclear explosion.	CCL EAR 99	None, although near device and detector package special material like magnetite with known neutron absorption cross sections could be required.	None identified	Validated models of the mechanical and thermodynamic properties of the shaft and its stem during the passage of the nuclear shockwave.
Neutron detectors	Standard OTS detectors as used in basic nuclear physics research, but with larger standoff distance and dynamic range.	CCL EAR 99	None identified	None; detectors are commercially available. Calibration by use of standard neutron sources or generators.	None identified
Gamma detectors (e.g., sodium iodide, GeLi, etc.)	Standard OTS detectors used in well logging or basic research.	CCL EAR 99	Large inorganic crystals	None; detectors are commercially available. Calibration by use of standard radioactive sources.	None identified
Compton current gamma detectors	Pulsed power design techniques	CCL EAR 99	None identified	None identified	Ability to forecast device performance for dynamic range and timing and basic pulsed power codes for modeling instrument response characteristics.
Photomultiplier tubes	Rise time order of 5 ns or better; area > 20 cm^2	NDUL 7; CCL Cat 6A	None identified	None identified	None identified
Microchannel plates	Rise time order of 1 ns or faster; area > 20 cm^2	WA Cat 6A; CCL Cat 6A	None identified	None identified	None identified

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Fast frame-rate vidicon	Vidicon cameras or equivalent with 4-ms frame times or faster.	CCL EAR 99	None identified	None, but cameras are special order commercially	Detailed understanding of device performance from modeling calculations
Fiber-optic cables	Standard OTS cables from many suppliers.	WA Cat 5A P1; CCL Cat 5A P1	None identified	Optical assembly and test equipment common in communication industry.	None identified
Gamma and X-ray scattering stations	Set-up as for basic research experiment. Precision alignment for lines of sight. Fast data acquisition.	CCL EAR 99	None identified	Precision alignment survey equipment, calibration sources for detector performance.	Detailed modeling understanding of device performance and scattering cross sections for modeling detector response.
Neutron scattering stations	Set-up as for basic research experiment. Precision alignment for lines of sight. Fast data acquisition.	CCL EAR 99	None identified	Precision alignment survey equipment, calibration sources for detector performance.	Detailed modeling understanding of device performance and scattering cross sections for modeling detector response.
Neutron pinex (pinhole) photography	Spatial resolution 4–10 times smaller than expected pit diameter at maximum compression. Time resolution on the order of 20 ns. Longer stand-off range than for hydronuclear testing.	CCL EAR 99	None identified	Precision alignment survey equipment, calibration sources for detector performance.	Detailed modeling understanding of device performance for dynamic range. Detailed understanding of local geology for shock stand-off distance.
X-ray pinex (pinhole) photography	Spatial resolution 4–10 times smaller than expected pit diameter at maximum compression. Time resolution on the order of 10 ns. Longer stand-off range than for hydronuclear testing.	CCL EAR 99	None identified	Precision alignment survey equipment, calibration sources for detector performance.	Detailed modeling understanding of device performance for dynamic range. Detailed under–standing of local geology for shock stand-off distance.
Fireball cameras (including special 3-layer films)	Ability to coat film with three layers with different sensitivities and to embed color couplers in each layer. Sensitivities range from the order of ISO .0001 to ISO 100. Most useful with atmospheric testing but possible underground.	CCL EAR 99	None identified	Modern photographic emulsions useful but not necessary.	None identified

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Streak cameras	Cameras capable of 50 ns or better time resolution.	NDUL 5; CCL Cat 3A	None identified	None identified	None, but ability to forecast device performance from models to set trigger times and dynamic range is critical.
Framing cameras	Cameras capable of 50 ns or better frame resolution time.	NDUL 5; CCL Cat 3A	None identified	None identified	None, but ability to forecast device performance from models to set trigger times and dynamic range is critical.
Local seismic systems	Basic seismographs and recording instruments for ground motion.	CCL EAR 99	None identified	None identified	None, but ability to forecast device performance from models and understanding of shock propagation in local geology is critical.
Radiochemical tracer isotopes	Basic radiochemistry laboratory equipment common in reactor analysis institutions. Some materials available from medical radioisotopes.	CCL EAR 99	Special isotopes, some commercially available but rare.	Hot cell handling capability and detailed radiochemistry instrumentation.	None, but detailed understanding of neutron fluxes at distances from device from model pre–dictions and neutron cross sections for rare isotopes.
Analysis of uncontained gases	Basic radio and analytic chemistry laboratory equipment	CCL EAR 99	None identified	None identified	None identified
Oscilloscopes	Many types of digitizing scopes with 1–10 ns recording times; bandwidths greater than 1 GHz will give better alpha data.	NDUL 7; CCL Cat 3A	None identified	None; available commercial OTS	None, but ability to fore–cast device performance from models to set dynamic range of data acquisition is critical.
Coaxial cables	Satellite TV technology using cables with 15 dB attenuation per 100 ft at 1 GHz, but higher current capability than satellite TV cable may prove necessary.	CCL EAR 99	None identified	None identified	None identified

(cont'd)

Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Cable connectors	Satellite TV technology. N, C, HN or LC series connectors appropriate, but with higher current capability than normal in satellite TV receiving equipment.	CCL EAR 99	None identified	None identified	None identified
Analog-to-digital converters	100 MHz digitizer rates sufficient if down hole buffering of data is available in instrumentation package.	MTCR 14; CCL Cat 3A; WA Cat 3A	None identified	None identified	None, but detailed device performance characteristics from model is essential for dynamic range and timing specification.

Table 5.10-2. Nuclear Weapons Development Testing Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
HYDRODYNAMIC TESTING			
Pin domes	Electrical connections, readouts. Uncertainty of timing after HE initiation	Assuring proliferator that implosion system works.	Simplest diagnostic currently used; radio-lanthanum may be substituted. Also the electro-magnetic technique could be used.
HE pressure, temperature, and shock transducers	Speed, reliability, accuracy	Verifying operation of complex implosion designs	None, although primitive arrays of crushable or frangible materials could be used for coarse measurements
Pulse generators to calibrate cables, etc.	Repeatability	Facilitating analysis of experiments by allowing detailed calibration of cable performance and delays	None, pulse generators are readily available or could be manufactured domestically
Coaxial cables	Low loss over very long runs; consistent impedance; low dispersion. Cables with 1–5 dB attenuation over 100ft	Required to bring signal from test apparatus to data recording	None, but older type cables may be satisfactory in some cases, particularly if the cable length is kept small.
Cable connectors	Low loss at connections; low dispersion; repeatability	Required to link cables	None, but older connectors may provide adequate performance if the number of joints is minimized.
Fast oscilloscopes, usually with storage features	Sweep speed, sensitivity, rise time	Principal extreme speed data recording device	Modern oscilloscopes are necessary for precision testing of advanced design weapons, but it must be remembered that most weapon types ever manufactured were tested using oscilloscopes which are no better than those found in commercial applications today.
Oscilloscope cameras	Triggerable shutter with film cassette	Data recording of fast transient events from scope screen	Flash digitizers or storage scopes
Transient recorders (flash digitizers)	Speed, memory capability, computer data acquisition system	Data recording of fast transient events using digital recording	Scope cameras
Time-delay generators	Accuracy, predictability, and repeatability	Synchronizing recording devices	None, but adequate generators are found in TV stations. In some cases simple cable lengths could be used

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Table 5.10-2. Nuclear Weapons Development Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Flash x-ray generators	Photon energy and spectrum; power output; rise time; pulse length; repeatability	Observing interior of imploding system	Energy below the 500 KeV of the NDUL will probably be satisfactory
X-ray recording systems (photo)	Sensitivity; uniformity of response over film surface	Observing interior of imploding system	Digital radiographic arrays of scintillating crystals with photo-diodes attached
Mechanical framing cameras	Speed; repeatability; frame-to-frame uniformity	Recording one or more frames from x-ray burst.	Fast video recorders with MCP gating for time elapsed images
Mechanical streak cameras	Speed; repeatability	Observing high speed phenomena	Electronic streak cameras
X-ray recording systems (digital)	Linearity of response; response time	Observing interior of imploding systems and recording information for computer analysis	Photographic approaches
X-ray recording systems (analog)	Linearity of response; response time	Observing interior of imploding systems and recording information for off-line analysis	Fast video recorders with MCP gating for time elapsed images or framing cameras
Multistage light gas guns or other high velocity gun systems (coil, electromagnetic, electrothermal, or other advanced systems).	"Muzzle" velocity; repeatability; precision of adjustment; sensors in or on test samples.	Determining the equation of state of fissile materials at values of pressure, temperature and density found in nuclear explosive devices.	EOS data for uranium were published in open literature in 1947.
HYDRONUCLEAR TESTING (up to few ton yield range)			
Neutron pinex (pinhole) photography	Pinhole size, location from device, data recording system and shuttering	Observing onset of nuclear reactions in imploding device and imaging the imploding system to assess uniformity and deviations from symmetry	None identified
Gamma pinex (pinhole) photography	Pinhole size, location from device, data recording system and shuttering	Observing onset of nuclear reactions in imploding device and imaging the imploding system to assess uniformity and deviations from symmetry	None identified
Gamma detectors (e.g., sodium iodide, GeLi, etc.)	Size (large enough to prevent escape of photons); crystal quality; coupling of output signal from detector to photomultiplier or other light-to-electrical transducer.	Observing onset of nuclear reactions in imploding device	Triggered wire proportional chambers; spark chambers. If the yield is large enough simple Compton current detectors can be used
Compton current gamma detectors	Yield must be high enough for significant Compton currents to be generated	Observing time development of gamma rays from nuclear event	Crystal gamma detectors

(cont'd)

Table 5.10-2. Nuclear Weapons Development Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Neutron detectors, standard nuclear approaches	Efficiency, uniformity, repeatability, high-speed response	Determining rate of multiplication of chain reaction in order to assess degree of implosion and probable yield.	None. If the yield is big enough, simple faraday cups measuring the proton current from (n,p) reaction in a CH foil could be used
Neutron detectors, faraday cup approach	Efficiency, uniformity, repeatability, high-speed response	Determining rate of multiplication of chain reaction in order to assess degree of implosion and probable yield.	Neutron detectors, standard nuclear approaches
Cable crush yield measurement	Time domain reflectometry of cable during event.	Measurement of shock-wave propagation in material near event site	Neutron measurements or rad-chem techniques
X- and gamma-ray detectors	Size (large enough to prevent escape of photons); crystal quality; coupling of output signal from detector to photomultiplier or other light-to-electrical transducer.	Determining rate of multiplication of chain reaction in order to assess degree of implosion and probable yield. (n,gamma) reactions may be easier to measure than direct neutrons. Determine temperature of nuclear reaction.	Triggered wire proportional chambers; spark chambers. If the yield is large enough, simple Compton current detectors can be used
Photomultiplier tubes	Rise time, transit time, noise level, UV sensitivity; reliability in high radiation environment	Sensor used in many of the detectors used for particle counting	None, but satisfactory PM tubes are commonly available, most from Japan.
Coaxial cables	Low loss over very long runs; consistent imepdance low dispersion. Cables with 1–5 dB attenuation over 100 ft	Link test device to electronic data recording instruments.	Older cables with poorer dielectric properties, particularly if cable lengths can be minimized. Fiber-optic cables.
Cable connectors	Low loss at connections; low dispersion; repeatability.	Link cables to one another and to device and recording instruments	Older connectors may be used.
Fast oscilloscopes, usually with storage features	Sweep speed, sensitivity, rise time	Principal extreme speed data recording device	Modern oscilloscopes are necessary for precision testing of advanced design weapons, but most weapon types ever manufactured were tested using oscilloscopes which are no better than those found in commercial applications today.
Transient recorders (flash digitizers)	Speed, memory capability, computer data acquisition system	Data recording of fast transient events using digital recording	Scope cameras

(cont'd)

Table 5.10-2. Nuclear Weapons Development Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
NUCLEAR YIELD TESTING (Underground)			
Drilling machinery	Bit diameter; ability to drill to great depths.	Prepare site for installation of nuclear test device	Convert existing mines; use dedicated horizontal shafts excavated with conventional techniques
Hole stemming technologies to ensure acceptable containment	Gas tightness; ability to withstand ground shock and effects of device on base of the stem. Ability to contain debris for extended period.	Close borehole so that debris from nuclear test does not escape. Preventing the escape of radioactive debris denies adversaries a valuable look at the performance of the test device. Needed to comply with Limited Test Ban Treaty.	Many types of stemming will probably be reasonably effective. This is a civil construction issue, and has been moderately well documented in the open literature. Fundamental technologies are not exotic.
Neutron detectors	Efficiency, uniformity, repeatability, high speed response; calibration and calibration stability	Determining rate of multiplication of chain reaction in order to assess degree of implosion and probable yield.	None; if the device yield is great enough simple faraday cups measuring the proton current from (n,p) reactions in a polyethylene (CH) foil could be used.
X- and gamma-ray detectors	Size (large enough to prevent escape of photons); crystal quality; coupling of output signal from detector to photomultiplier or other light-to-electrical transducer.	Determining rate of multiplication of chain reaction in order to assess primary performance. (n,gamma) reactions may be easier to measure than direct neutrons. Determine temperature of nuclear reaction. Estimate ability of primary to drive secondary.	Triggered wire proportional chambers; spark chambers. If the yield is large enough, simple Compton current detectors can be used.
Photomultiplier tubes	Rise time, size of output pulse, linearity of output pulse size vs. input signal.	Sensor used in many of the detectors used for particle counting	Older-design tubes with >1 ns risetime may be useful, particularly for unboosted fission devices. Interstage timing requires higher speed.
Microchannel plate	Rise time, size of output pulse, linearity of output pulse size vs. input signal.	Faster-responding photomultiplier	PM tubes with slower responses
Fast frame-rate vidicon	Phosphor type for persistence, readout electronics	Obtaining images of exploding device	CCD or CID cameras
Fiber-optic cables	Loss; dispersion, band width of transmitters and receivers	Transmitting large amounts of data from down-hole to recording facility. Also for direct transmission of optical output of detectors for up-hole recording.	Coaxial cables

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Table 5.10-2. Nuclear Weapons Development Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Gamma and x-ray scattering stations	Fluxes, detector response for dynamic range and bandwidth.	Observing developing radiation without overloading sensors. Scatters small fraction of primary radiation to a sensor which cannot “see” device directly.	Not needed for many types of tests. Increasing standoff distance of detector package allows for other approaches
Neutron scattering stations	Fluxes, detector response for dynamic range and bandwidth.	Observing developing radiation without overloading sensors. Scatters small fraction of primary radiation to a sensor which cannot “‘see” device directly.	Not needed for many types of tests. Increasing standoff distance of detector package allows for other approaches
Neutron pinex (pinhole) photography	As above, but for much larger neutron fluences	Image device during nuclear explosion period	X-ray pinex
X-ray pinex (pinhole) photography	As above, but for much larger photon fluences	Image device during nuclear explosion period	Neutron pinex
Fireball cameras (including special 3-layer films)	Shutter; film advance mechanism	Photograph fireball for conventional viewing. Special film has 3 layers with different sensitivities, typically between ISO 0.001 and 1,000 so that both early and late stages of explosion can be recorded on the same film.	None, but most underground tests do not photograph fireball
Streak cameras	Device performance forecast	Photograph high-speed events during explosion	None, but commercial hardware may suffice
Framing cameras	Device performance forecast	Photograph high-speed events during explosion	None, but commercial hardware may suffice
Local seismic systems	Understanding of local geology	Make first determination of yield	None. Standard seismographic techniques
Radiochemical tracer isotopes	Placement of tracers, drill back technology, radiological hazard handling of materials	Make most accurate determination of yield	Neutron or photon flux measurements
Analysis of uncontained gases	Placement of sample collecting devices	Supplements radiochemical analysis and may give details of the performance of a complex device.	Radiochemical analysis of debris in shot hole

(cont’d)

Table 5.10-2. Nuclear Weapons Development Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Fast oscilloscopes, usually with storage features	Sweep speed, sensitivity, rise time	Principal extreme speed data recording device	Modern oscilloscopes are necessary for precision testing of advanced design weapons, but most weapon types ever manufactured were tested using oscilloscopes which are no better than those found in commercial applications today.
Coaxial cables	Low loss over very long runs; consistent impedance low dispersion. Cables with 1–5 dB attenuation over 100 ft.	Link test device to electronic data recoridng instruments.	Older cables with poorer dielectric properties, particularly if cable lengths can be minimized. Fiberoptic cables.
Cable connectors	Low loss at connections; low dispersion; repeatability.	Link cables to one another and to device and recording instruments.	Older connectors may be used.
Analog-to-digital converters	Time response, dynamic range, event performance forecast	Convert readily made analog measurements to digital values for post-shot computer analysis.	Scopes with scope cameras and digitizing of film

SECTION 5.11—NUCLEAR WEAPONS CUSTODY, TRANSPORT, AND CONTROL

OVERVIEW

The enormous destructive power and the small physical size of many modern nuclear weapons has led to the development of stringent measures to ensure against theft or unauthorized use. In addition, much effort has gone into the development of safe and secure methods of transporting nuclear weapons and into the development of training and operational concepts so that, if needed, nuclear weapons will be used to the greatest effect. Generally, these technologies and related processes are not unique to nuclear weapons or necessarily lie on a path to nuclear weapons. The technologies for the custody, transport, and control of nuclear weapons are all commercially available.

DoD's approach to maintaining the physical security of nuclear weapons is manpower intensive. Large numbers of security personnel accompany the vehicle(s) actually transporting nuclear weapons. Civil law enforcement personnel lead the convoy, while a considerable number of military vehicles—on the land and in the air—are added to handle physical security. Constant secure radio contact is maintained with a home base that is ready to respond with additional security personnel should the need arise. With routings varied and classified, and with massive amounts of physical security, DoD ensures that each nuclear weapon is kept safe and secure while en route to be mated with its corresponding delivery system. Once mated, DoD provides multiple layers of protection, often including roving patrols for nuclear-loaded aircraft. In addition, when missiles were not in hardened silos, multiple guards were required for missiles carrying nuclear weapons. The DoD requires more than one guard for any maintenance actions on nuclear-loaded missiles.

Two-man control and no-lone zones apply in nuclear-weapon-related activities; in U.S. practice such operations are unique to nuclear operations. Increased security is also the rule when dealing with nuclear weapons. When moving nuclear weapons on DoD sites, the routes are typically swept and "sanitized" before the move.

RATIONALE

As noted previously, all of the technologies involved are commonly available industrial technologies fundamental to security operations worldwide. The entire spectrum of sensor technology and communications technology—both secure and nonsecure—can be included in the custody, transport, and control of nuclear weapons. Monitoring many of these technologies is difficult, and their acquisition only means that the acquiring state or subnational group has something very important to protect—but it does not have to be a nuclear weapon. Also, procedural changes in security forces which identify uniquely nuclear operations are equally difficult to determine.

Since the new proliferant or subnational actor will most likely have a very limited number of nuclear weapons, increased security would be required for protection of the weapons as well as to prevent the use of the weapon

Highlights

- Nuclear weapons must be protected against theft or damage during transport; this function is frequently accomplished by an adequate guard force.
- Technologically based security is provided by a mix of technologies, no one of which is extremely sensitive. Taken in the aggregate, the methods of securing nuclear weapons are highly sensitive. Most of the technologies themselves are unclassified.
- Standing up of elite forces to deliver and secure nuclear weapons might be an intelligence indicator that a proliferant was on the verge of obtaining nuclear weapons.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

The fundamental technologies for custody, transport, and control of nuclear weapons can be found in essentially every military in the world, for they simply involve the provision of a well-disciplined guard force in adequate strength to defend against any likely threat. The assessed security requirement will depend upon the country in question.

The United States has a long lead over most other countries in technology-intensive ways of protecting nuclear weapons.

Table 5.11-1. Nuclear Weapons Custody, Transport, and Control Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Motion Detection Sensors/Alarms	Any level which impedes the operations of EOD teams seeking access to IND.	None identified	None identified	None identified	None identified
Laser Detection Systems	Any level which delays or denies access to IND.	None identified	None identified	None identified	None identified
Temperature Sensitive Sensors/Alarms	Any level.	None identified	None identified	None identified	None identified
Radios and Transceivers. Systems, subsystems or equipment developed or modified for security communications networks or C^4I systems that perform integrated C^4I system security communications network functions	Systems engineered to be difficult to detect or which do not transmit in plain language and where decrypting cannot be done in real time.	None identified	Encryption chip manufacture	None identified	None identified
Acoustic detection sensors/alarms	Any level which impedes the operations of EOD teams seeking access to IND.	None identified	None identified	None identified	None identified
Pressure sensitive detectors/alarms	Any level which impedes the operations of EOD teams seeking acess to IND.	None identified	None identified	None identified	None identified

Table 5.11-2. Nuclear Weapons Custody, Transport, and Control Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Motion Detection Sensors/Alarms	None identified	Security and defensive only. May be used to protect emplaced devices.	None identified
Laser Detection Systems	None identified	Security and defensive only. May be used to protect emplaced devices.	None identified
Temperature Sensitive Sensors/ Alarms	None identified	Security and defensive only. May be used to protect emplaced devices.	None identified
Radios and Transceivers. Systems, subsystems or equipment developed or modified for security communications networks or C^4I systems that perform integrated C^4I system security communications network functions.	Encryption level required to gain tactical security (decrypt time circa 2–4 hours for someone not in possession of the key).	For this application, security and defensive only. However, any C^4I capability can be used offensively to coordinate attacks. Encryption used to gain tactical OPSEC.	None identified
Acoustic Detection Sensors/ Alarms	None identified	Security and defensive only. May be used to protect emplaced devices.	None identified
Pressure Sensitive Sensors/ Alarms	None identified	Security and defensive only. May be used to protect emplaced devices.	None identified

SECTION 5.12—HEAVY WATER PRODUCTION

OVERVIEW

Heavy water, D_2O, is water in which both hydrogen atoms have been replaced with deuterium, the isotope of hydrogen containing one proton and one neutron. It is present naturally in water, but in only small amounts, less than 1 part in 5,000. Heavy water is one of the two principal moderators which allow a nuclear reactor to operate with natural uranium as its fuel. The other moderator is reactor-grade graphite (graphite containing less than 5 ppm boron and with a density exceeding 1.50 gm/cm^3). The first nuclear reactor built in 1942 used graphite as the moderator; German efforts during World War II concentrated on using heavy water to moderate a reactor using natural uranium.

The importance of heavy water to a nuclear proliferator is that it provides one more route to produce plutonium for use in weapons, entirely bypassing uranium enrichment and all of the related technological infrastructure. In addition, heavy-water-moderated reactors can be used to make tritium.

Although one speaks of "making" heavy water, deuterium is not made in the process; rather, molecules of heavy water are separated from the vast quantity of water consisting of H_2O or HDO (singly deuterated water), and the "dross" is discarded. Alternatively, the water may be electrolyzed to make oxygen and hydrogen containing normal gas and deuterium. The hydrogen can then be liquefied and distilled to separate the two species. Finally, the resulting deuterium is reacted with oxygen to form heavy water. No nuclear transformations occur.

RATIONALE

The production of heavy water in significant amounts requires a technical infrastructure, but one which has similarities to ammonia production, alcohol distillation, and other common industrial processes. One may separate heavy water directly from natural water or first "enrich" the deuterium content in hydrogen gas.

It is possible to take advantage of the different boiling points of heavy water (101.4 °C) and normal water (100 °C) or the difference in boiling points between deuterium (–249.7 °C) and hydrogen (–252.5 °C). However, because of the low abundance of deuterium, an enormous amount of water would have to be boiled to obtain useful amounts of deuterium. Because of the high heat of vaporization of water, this process would use enormous quantities of fuel or electricity. Practical facilities which exploit chemical differences use processes requiring much smaller amounts of energy input.

Highlights

- Heavy water is separated from ordinary water by enrichment cascades.
- The separation factor at each stage is higher for heavy water than for uranium, but heavy water must be enriched far more than uranium.
- Practical heavy water plants use chemical exchange processes such as H_2S/H_2O (Girdler Sulfide) or NH_3/H_2.
- Distillation columns to "finish" heavy water enrichment to >99.75% are similar to those used in distilling brandy from wine.

Separation methods include distillation of liquid hydrogen and various chemical exchange processes which exploit the differing affinities of deuterium and hydrogen for various compounds. These include the ammonia/hydrogen system, which uses potassium amide as the catalyst, and the hydrogen sulfide/water system (Girdler Sulfide process).

Separation factors per stage are significantly larger for deuterium enrichment than for uranium enrichment because of the larger relative mass difference. However, this is compensated for because the total enrichment needed is much greater. While ^{235}U is 0.72 percent of natural uranium, and must be enriched to 90 percent of the product, deuterium is only .015 percent of the hydrogen in water and must be enriched to greater than 99 percent.

If the input stream has at least 5 percent heavy water, vacuum distillation is a preferred way to separate heavy from normal water. This process is virtually identical to that used to distill brandy from wine. The principal visible difference is the use of a phosphor-bronze packing that has been chemically treated to improve wettability for the distillation column rather than a copper packing. Most organic liquids are non-polar and wet virtually any metal, while water, being a highly polar molecule with a high surface tension, wets very few metals. The process works best at low temperatures where water flows are small, so wetting the packing in the column is of particular importance. Phosphor-bronze is an alloy of copper with .02–.05 percent lead, .05–.15 percent iron, .5–.11 percent tin, and .01–.35 percent phosphorus.

The Bruce Heavy Water Plant in Ontario, Canada, is the world's largest producer of D_2O. It uses the Girdler Sulfide (GS) process which incorporates a double cascade in each step. In the upper ("cold," 30–40 °C) section, deuterium from hydrogen sulfide preferentially migrates into water. In the lower ("hot," 120–140 °C) section, deuterium preferentially migrates from water into hydrogen sulfide. An appropriate cascade arrangement actually accomplishes enrichment.

> In the first stage the gas is enriched from 0.015% deuterium to 0.07%. The second column enriches this to 0.35% , and the third column achieves an enrichment between 10% and 30% deuterium. This product is sent to a distillation unit for finishing to 99.75% "reactor-grade" heavy water. Only about one-fifth of the deuterium in the plant feed water becomes heavy water product. The production of a single pound of heavy water requires 340,000 pounds of feed water.[20]

Proliferation Implication Assessment

Heavy water is the key to one type of reactor in which plutonium can be bred from natural uranium. As such, the production of heavy water has always been monitored, and the material is export controlled. In addition, a source of deuterium is essential for the production of tritium and ^{6}LiD, two ingredients of thermonuclear weapons. A nation seeking large quantities of heavy water probably wishes to use the material to moderate a reactor, and may be planning to produce plutonium. However, CANDU (CANadian Deuterium Uranium) reactors designed and built in Canada are used for commercial electric power production.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

Heavy water is produced in Argentina, Canada, India, and Norway. Presumably, all five declared nuclear weapons states can produce the material. The first commercial heavy water plant was the Norsk Hydro facility in Norway (built 1934, capacity 12 metric metric tons per year); this is the plant which was attacked by the Allies to deny heavy water to Germany. As stated above, the largest plant, is the Bruce Plant in Canada (1979; 700 metric tons/year). India's apparent capacity is very high, but its program has been troubled. Accidents and shutdowns have led to effective limitations on production.

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[20] *Isotope Enrichment*, Office of Nonproliferation and National Security, U.S. Department of Energy, Nuclear Nonproliferation Workshop. K/NSP-121/PT 5/R3, May 1996 (Unclassified).

Table 5.12-1. Heavy Water Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Pumps for potassium amide/liquid ammonia	Hermetically sealed; capacity >8.5 cubic meters per hour. Concentrated potassium amide (>1%) operating at 15–600 atm. Dilute potassium amide (<1%) operating at 200–600 atm.	NDUL 4; NRL-K	Forgings to withstand pressure	All parts contacting solutions must be free of hydrocarbons and fluorocarbons	None identified
Water-hydrogen sulfide exchange tray columns	Effective assembled diameter of 1.8 m or greater. Fabricated from fine carbon steel (e.g., ASTM A516) with diameters from 6 m to 9 m capable of operating at pressures greater than or equal to 2 MPa (200 atm) and with a corrosion allowance of 6 mm or more. Note that a “sufficient” tower may be smaller but probably must operate in a similar pressure range.	NTL B6; NRC-K; NDUL 4; CCL Cat 1B	Blowers and compressors for H_2S circulation. Throughput capacity greater than or equal to 56 cubic meter/s while operating at pressures greater than or equal to 1.8 MPa (260 psi) suction with seals designed for wet H_2S service. Note that “sufficient” pumps may have less capacity but probably operate in a similar pressure range.	None identified	None identified
Ammonia-hydrogen exchange towers	35 m or more in height with diameters of 1.5–2.5 m capable of operating at pressures >15 MPa (2,225 psi). These towers have at least one flanged axial opening of the same diameter as the cylindrical part of the tower in order to insert or withdraw tower internals.	NRL-B6; NRC-K	Stage pumps and contactors to promote intimate gas/liquid contact. Pumps must be submersible.	None identified	None identified
Infrared absorption analyzers	On-line analysis of hydrogen/deuterium ratios where deuterium concentrations are greater than or equal to 90%	NTL-B6; NRC-K	None identified	None identified	None identified

(cont’d)

Table 5.12-1. Heavy Water Production Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Catalytic burners for conversion of deuterium gas into heavy water especially following the ammonia-hydrogen exchange process	Possession of catalysts; alternatively, can use simple combustion	NTL-B6; NRC-K	None identified	None identified	None identified
Phosphor-bronze mesh packings for use in vacuum distillation of heavy water and chemically treated to improve wettability	Possession	NDUL 4; CCL Cat 1A	None identified	None identified	None identified
Cryogenic distillation towers	Operate at temperatures <35 K and at pressures of 0.5–5 MPa (5–50 atm). Generally >1 m in diameter and with effective length of at least 5 m.	NDUL 4; CCL Cat 1B	Fine-grain austenitic stainless steel with an ASTM or equivalent standard grain size number of 5 or greater	None identified	None identified
Ammonia converters or synthesis units	Operating pressure of 20–60 MPa, typically 3–5 m in diameter and 9–12 m long.	NDUL 4; CCL Cat 1B	Stainless steel lining	None identified	None identified

Table 5.12-2. Heavy Water Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Pumps for potassium amide/liquid ammonia	None identified	Preparation of heavy water for plutonium or tritium production reactors	Hydrogen sulfide process; vacuum distillation
Water-hydrogen sulfide exchange tray columns	None identified	Preparation of heavy water for plutonium or tritium production reactors	Ammonia hydrogen exchange process; vacuum distillation
Ammonia-hydrogen exchange towers	None identified	Preparation of heavy water for plutonium or tritium production reactors	Hydrogen sulfide process; vacuum distillation
Infrared absorption analyzers	None identified	Analysis of products from heavy water plants	None identified
Catalytic burners for conversion of deuterium gas into heavy water especially following the ammonia-hydrogen exchange process.	None identified	Preparation of heavy water for plutonium or tritium production reactors	Conventional burning
Phosphor-bronze mesh packings for use in vacuum distillation of heavy water and chemically treated to improve wettability	None identified	Preparation of heavy water for plutonium or tritium production reactors	Ammonia-exchange or hydrogen sulfide processes
Cryogenic distillation towers	None identified	Preparation of heavy water for plutonium or tritium production reactors	Ammonia-exchange or hydrogen sulfide processes
Ammonia converters or synthesis units	None identified	Preparation of heavy water for plutonium or tritium production reactors	None identified

SECTION 5.13—TRITIUM PRODUCTION

OVERVIEW

Tritium (^{3}H) is essential to the construction of boosted-fission nuclear weapons. A boosted weapon contains a mixture of deuterium and tritium, the gases being heated and compressed by the detonation of a plutonium or uranium device. The D-T mixture is heated to a temperature and pressure such that thermonuclear fusion occurs. This process releases a flood of 14 MeV neutrons which cause additional fissions in the device, greatly increasing its efficiency.

The tritium beta decay to ^{3}He (mean beta particle energy 5.7 keV; decay energy 18.6 keV) can be easily detected or can cause some other compound to fluoresce. Tritium is therefore used as a radioactive tracer element in biological research in the form of tritiated water (HTO or T_2O) and also used in capsules surrounded by a fluorescing compound (e.g., zinc sulfide) to provide illumination which must be independent of the electricity supply. For example, it is used in emergency exit signs, self-luminous airport runway and helicopter pad lights, and light wands for use in directing traffic. The amounts of tritium in runway lights, helipad lights, and light wands are sufficiently great that they meet the NSG Dual-Use Annex specifications. Emergency exit signs and aircraft emergency exit lights do not contain sufficient tritium to meet the NDUL specifications for control.

The low energy of the beta decay means that tritium is not an *external* radiation hazard because the charged decay products are stopped by 0.2 mil of water or a similar shield. However, tritium can pose an *internal* radiation hazard if *tritiated water vapor* is inhaled or absorbed through the skin. Because of its higher mass and consequent lower chemical activity, tritium gas is less strongly absorbed by the body, whether through the lungs or the skin.

Nuclear physics experiments in which tritium is compared to ^{3}He have been important to our understanding of fundamental properties of the nuclear force.

RATIONALE

Tritium is rare in nature because of its 12.4-year half-life. It is produced by cosmic radiation in the upper atmosphere where it combines with oxygen to form water. It then falls to earth as rain, but the concentration is too low to be useful in a nuclear weapons program.

Highlights

- Tritium is essential for producing boosted-fission weapons.
- Practical quantities of tritium must be produced in a nuclear reactor or in an electronuclear breeder.

Most tritium is produced by bombarding ^{6}Li [^{6}Li(n, a)^{3}H] with neutrons in a reactor; it is also produced as a byproduct of the operation of a heavy-water-moderated reactor when neutrons are captured on the deuterons present. It has been suggested that it may be feasible to produce tritium in an accelerator (electronuclear breeder) in which protons bombard an appropriate target.

Tritium can be stored and shipped as a gas, a metal hydride (e.g., of titanium) or tritide, and trapped in zeolites (hydrated aluminum silicate compounds with uniform size pores in their crystalline structure). Stainless-steel cylinders with capacities up to 5.6×10^7 GBq (1.5 MCi) of tritium gas are used for transportation and storage and must be constructed to withstand the additional pressure which will build up as tritium gradually decays to ^{3}He.

Tritium is used in boosted fission devices and in some designs for thermonuclear weapons.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 5.0-2)

All five declared nuclear weapon states must have the underlying capability to manufacture and handle tritium, although the United States has shut down its production reactors due to safety considerations. Canada manufactures tritium as a byproduct of the operation of CANDU reactors. In principle, limited amounts of tritium could be made in any research reactor with the ability to accept a target to be irradiated.

Table 5.13-1. Tritium Production Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Elemental tritium	Any pure quantity	NDUL 8; NRC L	^{6}Li for production target; heavy water	Production reactor or electronuclear breeder.	None identified
Storage and shipping	Stainless steel cylinders capable of withstanding at least twice the initial tritium fill pressure. Also metal hydride storage cylinders.	None identified	Stainless steel; titanium or uranium for hydriding tritium.	None identified	None identified
Production reactor	Nuclear reactor operating with a surplus of neutrons suitable for irradiating a target. Frequently heavy-water-moderated.	NTL B1; NRC A	^{6}Li targets for irradiation	None identified	Nuclear reactor codes specially modified to take into account neutron absorption in a fertile target.
Electronuclear breeder	High current proton accelerator (>1 mA continuous at >100 MeV)	None identified	High-purity copper or superconducting (usually niobium) accelerator cavities); ^{6}Li	Special accelerator; equipment for construction and test of (usually niobium) superconducting RF cavities; extremely rapid-acting vacuum valves. Cooled lithium neutron target; neutron production target.	Accelerator design and operating software specially adapted to the case of high current operation

Table 5.13-2. Tritium Production Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Elemental tritium	Production; transport; use; weaponization	Thermonuclear and boosted fission weapons	None identified
Storage and shipping	Hydriding of metals; pressure vessels; knowledge of properties of hydrogen and hydrides; pressure-testing equipment	Gas storage and handling for weapons	None identified
Production reactor	Operation of research or production reactors with fertile targets	Production of materials for TN and boosted fission weapons	Electronuclear breeder
Electronuclear breeder	Design, development, and test of accelerator and target systems; supply of electricity; fabrication of copper components or superconducting cavities; target design and construction.	Production of materials for TN and boosted fission weapons	Reactor; usually heavy-water-moderated

SECTION VI

NUCLEAR WEAPONS EFFECTS TECHNOLOGY

SECTION 6—NUCLEAR WEAPONS EFFECTS TECHNOLOGY

Scope

Highlights

- NWE technologies enable a country to harden more effectively its offensive and defensive systems against a nuclear weapon.
- Physical simulators that mimic the environments generated by a nuclear explosion and validated computer codes that can predict the NWE on systems are both used to evaluate the vulnerabilities of potential targets or delivery systems.
- Each type of nuclear weapons effect—blast and shock, thermal radiation, transient nuclear radiation, and EMP—requires its own set of physical simulators and validated codes. Few simulators are able to replicate more than one NWE.
- Both physical simulators and validated codes require large financial investments.

BACKGROUND

A nuclear detonation creates a severe environment including blast, thermal pulse, neutrons, x- and gamma-rays, radiation, electromagnetic pulse (EMP), and ionization of the upper atmosphere. Depending upon the environment in which the nuclear device is detonated, blast effects are manifested as ground shock, water shock, “blueout,” cratering, and large amounts of dust and radioactive fallout. All pose problems for the survival of friendly systems and can lead to the destruction or neutralization of hostile assets.

Although some nuclear weapons effects (NWE) such as blast and cratering have analogs in the effects of conventional weapons, many NWE are unique to nuclear use. In addition, blast and other “common” weapons effects are likely to be much more powerful in the nuclear case than in the realm of conventional weapons. NWE are so severe that combinations of two or more simultaneously (as in a real event) may not add linearly, complicating the design and construction of physical simulators or the writing and validation of computer simulation codes.

OVERVIEW

Some NWE can be modeled mathematically using powerful computers; others, and in particular the combination of several effects, are beyond valid analytic or numerical assessment. The only way to know if friendly systems or target assets will endure a given nuclear attack may be to expose representative equipment to real nuclear explosions or to construct complex simulators which reproduce a part of the spectrum of NWE. Until the conclusion of the Limited Test Ban Treaty (LTBT) in 1963, the United States conducted atmospheric tests of nuclear weapons, and it was relatively simple to include effects testing in the experiment. By signing the 1963 accord, the United States, the UK, and the Former Soviet Union agreed to discontinue atmospheric testing, testing in outer space, and testing under water. The only environment in which nuclear devices could be detonated was underground in circumstances where radioactive debris did not drift beyond national boundaries.

In the years between 1963 and 1992 the States Parties to the LTBT conducted underground tests to study NWE. As a result of congressional action the United States unilaterally entered a testing moratorium, which was made permanent with the signing of the Comprehensive Test Ban Treaty (CTBT) in 1996. Because it is no longer considered acceptable for the United States to conduct any nuclear explosions for any reason, future U.S. assessments of the vulnerability of its systems or of potentially hostile systems will have to rely upon the use of simulation and analysis validated by comparison with the results from almost 50 years of testing.

Combinations of nuclear weapons effects pose particularly difficult simulation problems. The thermal pulse can weaken or ignite a target, permitting the blast wave to be more effective than against a “cold” object. X-ray radiation can damage electronics and protective systems, making the target more vulnerable to neutrons. EMP and transient radiation effects in electronics (TREE) can operate synergistically. Thermal effects could conceivably damage some components designed to harden a system against EMP. Low-energy x-rays absorbed by a target in space can heat surface material to the vaporization point, causing it to explode away from the system, producing shock effects within the target. The effects produced and the ranges at which they are effective depend upon the yield of the nuclear weapon and the height of burst (HOB) and may depend upon the design of the device itself.

Potential proliferators will not have their own data from atmospheric and underground testing of nuclear weapons to use in validating simulation and analysis. If a proliferator decides that detailed knowledge of weapons effects is necessary for developing either a targeting or a survival strategy, it will need to gain a useful increment of information beyond that in the open literature (e.g., in Glasstone and Dolan’s *The Effects of Nuclear Weapons* and in more technical publications) to justify the expense of simulation. It will also have to acquire a detailed knowledge of the mechanisms by which nuclear weapons produce their physical effects. Should a proliferator actually carry out an NWE test despite international norms against such testing, one can infer that the testing state can produce significantly more special nuclear material (SNM) than it requires for its war stocks.

Theoretical predictions of NWE based on computer codes and algorithms that have not been compared with experiments may not be accurate, and the details of such experiments are not generally available. Those codes and algorithms which have been validated by experiment usually contain adjustable parameters and are much more reliable predictors of NWE. Such codes are termed “substantiated.” Physical simulation provides more confidence in predicting NWE because it does not rely upon the mathematical approximations of codes and algorithms but uses physical phenomena closely related to those produced by a nuclear detonation to test the behavior of real systems. But physical simulation remains “second best” compared to testing against a real nuclear detonation.

The technologies to be discussed at length in this section are briefly described in the following paragraphs.

1. Underground Nuclear Weapons Testing

Underground testing (UGT) can provide much insight into weapon design, radiation effects (gammas, neutrons, x-rays) on military systems, selected aspects of shock and blast, thermal effects, and source region EMP (SREMP). Countries with limited defense budgets are less likely than the major nuclear powers to have had exhaustive underground testing programs.

2. Blast and Shock Effects From Nuclear Detonations

Although thermal radiation, EMP, and ionizing radiation from a nuclear blast are all damage producing, at yields below about a megaton the blast and shock produced by a nuclear weapon are the predominant means of damaging a target. For some targets, such as underground bunkers and missile silos, blast and shock are virtually the only effective destructive mechanisms.

3. Nuclear Thermal Radiation Effects

The intensity of thermal radiation decreases only as the inverse square of the distance from a nuclear detonation, while blast, shock, and prompt ionizing radiation effects decrease more rapidly. Thus, high-yield weapons are primarily incendiary weapons, able to start fires and do other thermal damage at distances well beyond the radius at which they can topple buildings or overturn armored vehicles.

4. TREE and System-Generated Electromagnetic Pulse (SGEMP) Effects

An understanding of TREE and SGEMP is of critical importance in designing and building equipment that can survive a nuclear attack. It is not clear, however, that a nation having limited financial and technical resources could develop unique radiation-hardened devices and/or systems. These countries could, however, test a few critical subsystems or systems in an established foreign simulation facility. Although there are certain aspects of TREE and SGEMP technology that are of general scientific interest, for nations which have interests in the acquisition of nuclear weapons, the desire to evaluate and test systems at SGEMP and TREE dose rate levels typical of nuclear weapons is a useful indicator that they plan on nuclear combat, whether as a user or as a victim of the weapon. While TREE and SGEMP may indeed be effective, a nuclear planner without the benefit of extensive simulation and substantiated codes will probably rely on the gross NWE such as blast, shock, and thermal radiation.

5. Nuclear Effects on Electromagnetic Signal Propagation

Nuclear effects on electromagnetic signal propagation, which affects command, control, communications, computers, and intelligence (C^4I), are of concern to countries expected to use nuclear weapons, particularly those which intend to explode a weapon at great altitudes or those which expect to have to defend against such a nuclear attack. C^3I technology is primarily affected by high-altitude nuclear effects that could interrupt satellite-to-satellite communications, satellite-to-aircraft links, or satellite-to-ground links. Most nations will hope that signals from Global Positioning System (GPS) satellites and ground-based differential GPS transmitters will be usable shortly after a nuclear explosion, as well as traditional communications channels which must be protected.

6. *High-Altitude Electromagnetic Pulse (HEMP) Effects*

The electromagnetic pulse generated by the detonation of a *single* nuclear weapon at high altitudes can be a threat to military systems located as much as a thousand miles away. HEMP can disable communications systems and even power grids at enormous distances from the burst. This type of threat could be used by a third world country that has the capability to launch a rocket carrying a high-yield device (about 1 megaton or more) a few hundred kilometers into the upper atmosphere and a few thousand kilometers from its own territory (to avoid damaging its own systems).

Nuclear weapons effects simulators, particularly for HEMP, require high-energy, terawatt-class power conditioning. Parts of these systems have significantly advanced energy storage, switching, and power-control technologies in the submicrosecond, multimegajoule regime. These technologies directly map into support for the power technologies needed for advanced weapons such as high-power microwaves.

7. *Source Region Electromagnetic Pulse (SREMP) Effects*

This technology is specifically concerned with nuclear detonations that occur at very low altitudes down to ground level and that are usually targeted at military installations. Interest in this technology is uniquely associated with interest in using or *defending against* the use of nuclear weapons. SREMP produces an environment characterized by a combination of electromagnetic and ionizing radiation caused by a low-altitude nuclear detonation.

8. *Pulsed-Power Nuclear Weapons Effects Simulation*

Although this technology is focused on developing simulators which produce pulsed electromagnetic and particle radiation resembling that arising from a nuclear weapon, it is shared by many nations. Certain aspects of this technology have relevance for non-nuclear directed-energy weapons devices and thermonuclear power technology. Countries that have an interest in acquiring in-house capability in this technology could possibly have a long range interest in nuclear weapons. The financial investment required "for admission" is, however, very large.

RATIONALE

Nuclear detonations are the most devastating of the weapons of mass destruction. To make this point one need only recall the pictures from Hiroshima or the international furor over the accidental but enormous radiation release from the Chernobyl power plant. The contamination from Chernobyl was significantly larger than would have been expected from a nuclear detonation of about 20 kT at ground level, but was comparable in extent to what might result from a "small" nuclear war in which a dozen or so weapons of nominal yield were exploded at altitudes intended to maximize blast damage. Hence, for those nations which are concerned about being the victims of a nuclear attack, the requirement for understanding and implementing ways of mitigating NWE is important. It is just as important for the user of a nuclear weapon to understand (and be able to mitigate) NWE on his own forces, not merely on the delivery vehicle, unless he can be certain that there will be no nuclear retaliatory strike.

Some important nuclear weapons effects are subtle in their action, producing no obvious visible damage to targeted systems. If these effects are to be employed deliberately, the using state must understand them well. To do so requires simulation and substantiated computation codes.

In the absence of nuclear testing, simulation equipment, numerical simulation, and theoretical analysis of NWE are the only means states can verify how NWE will affect their own forces and those of their opponents in a nuclear environment. NWE simulation, as well as survivability and hardening programs, have both offensive and defensive aspects, and may be desired by both nuclear possessor states and those with neither nuclear weapons nor plans to build them.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

Most of the relevant equipment and specialized software has been developed in parallel by many countries including Russia, China, the UK, and France, as well as Japan, Germany, Switzerland, Sweden, Canada, and members of the former Warsaw Treaty Organization. Although the simulation, survivability, and hardening equipment available from non-Western countries is inferior to that produced in the West ("years behind" in the case of HEMP simulation), it may be good enough to permit a nuclear aspirant to understand how to make its own equipment more survivable than otherwise. The most advanced capabilities usually only are necessary when one is trying to design equipment to be the lightest, most effective, and most efficient; when one backs away from the edge of the envelope, less-detailed analysis and testing may suffice. After all, the NATO allies operated acceptably survivable equipment decades ago.

Country	Sec 6.1 Underground Testing	Sec 6.2 Blast and Shock	Sec 6.3 Thermal Radiation	Sec 6.4 TREE and SGEMP	Sec 6.5 Signal Propagation	Sec 6.6 HEMP	Sec 6.7 SREMP	Sec 6.8 Pulsed Power
Australia		♦♦		♦♦		♦♦		
Canada	♦	♦♦	♦	♦♦		♦♦♦		
China	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦	♦♦	♦♦	♦♦
Egypt		♦	♦			♦		
France	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
Germany	♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦	
India	♦♦	♦♦	♦♦	♦♦	♦♦♦	♦	♦	
Iran		♦	♦			♦		
Iraq		♦				♦		
Israel	♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦	♦♦♦	♦♦
Italy	♦	♦♦	♦♦	♦♦	♦♦♦	♦♦	♦♦	
Japan	♦	♦♦	♦♦	♦♦♦	♦♦	♦♦	♦♦	♦♦
Libya		♦	♦			♦		
North Korea		♦	♦			♦		
Pakistan						♦	♦♦	
Russia	♦♦♦	♦♦♦	♦♦♦	♦♦♦		♦♦♦	♦♦♦	♦♦♦
South Africa	♦	♦	♦			♦		
UK	♦♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦	♦♦♦
United States	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦	♦♦♦♦

Legend: Sufficient Technologies Capabilities: ♦♦♦♦ exceeds sufficient level ♦♦♦ sufficient level ♦♦ some ♦ limited

Because two or more countries have the same number of diamonds does not mean that their capabilities are the same. An absence of diamonds in countries of concern may indicate an absence of information, not of capability. The absence of a country from this list may indicate an absence of information, not capability.

Figure 6.0-1. Nuclear Weapons Effects Foreign Technology Assessment Summary

SECTION 6.1—UNDERGROUND NUCLEAR WEAPONS EFFECTS TESTING

OVERVIEW

This section concentrates on those additional and specific technologies needed for nuclear weapons effects testing. The technologies for underground nuclear testing in general are covered in Section 5.10. Underground nuclear weapons effects tests (UGWETs) provide nuclear environments for demonstrating the hardness and survivability of military equipment and materials as well as for studying basic nuclear effects phenomenology.

The UGWET-specific technologies include horizontal emplacement of the device, the provision of evacuated horizontal line-of-sight (HLOS) tubes for viewing the detonation, and mechanical closures to prevent debris from traveling through the HLOS tube to the experiment station that measures the radiation and shock environment and the response of systems. Also included are scattering station design and the computer codes necessary to understand the results of the experiments. Technologies to contain the release of radiation are only covered to the extent that they differ from those used in nuclear weapon development tests.

For effects testing, horizontal emplacement tests (HET) are preferred over vertical emplacement tests because the emplacement of device and test equipment is simplified. Horizontal tunnels provide greater experiment flexibility and access. Vertical shaft tests are less expensive but only provide limited exposure area because of the risk associated with containment when the crater is formed. The need to excavate large cavities for the placing of “test samples” and the construction of appropriate environments for those samples (for example, a vacuum for reentry bodies) drives the conductor of HLOS tests to seek suitable terrain such as a mesa or mountainside. Effects tests could also be conducted inside a deep mine.

HETs can incorporate large cavities so that shock and SREMP from a low-yield device actually have space to develop to the point where they are representative of similar effects in the open air from a large-yield weapon. The minimum burial depth is:

$$D = 400\ \mathbf{Y}^{1/3}\ \text{feet,}$$

and the radius of the cavity formed by the detonation is:

$$R = 55\ \mathbf{Y}^{1/3}\ \text{feet,}$$

where linear dimensions are measured in feet and yield in kilotons.

The object of an HET is often to allow nuclear radiation to reach the test object while preventing it from being destroyed by the other effects. Indeed, scientists expect to be able to recover the test instrumentation. Such a test requires redundant containment vessels: the first around the device, a second around all of the experiment to protect the tunnel system if the inner vessel fails and the experimental equipment is lost, and a third to ensure that no radiation escapes into the atmosphere even if the experimental equipment is lost and the tunnel system contaminated.

The HET-HLOS configuration is most often used for radiation effects tests, but the HLOS configuration must withstand the blast and shock waves produced by the device. The HLOS pipe is tapered from about 6 inches in diameter at the “zero room” (the device emplacement cavity) to about 30 feet in diameter at the experimental area 1,500 to 1,800 feet away and provides a clear line of sight to the device for those test subjects which need to see direct radiation.

Highlights

- Full-yield nuclear tests are the only way to produce all relevant nuclear weapon effects simultaneously.
- Underground nuclear weapons effects tests can provide insight into weapon performance, nuclear radiation effects, shock and blast, thermal effects, and source region EMP (SREMP).
- Signatories of the 1996 Comprehensive Test Ban Treaty (CTBT), including all five declared nuclear weapon states and Israel, are no longer permitted to conduct nuclear test explosions. For those states physical simulation combined with validated computer codes provides the most reliable way to evaluate NWE.
- Even when it was allowed, underground testing was a very expensive way to garner the needed information. It was used by countries with significant economic bases and which were also committed to the development of nuclear offensive and defensive capabilities.
- Complete containment of radioactive debris is probably essential if a nation wishes to conduct a clandestine nuclear test. In any underground nuclear weapons effects test (UGWET), fast-acting mechanical closures to prevent debris from reaching the test objects are unique and critical equipment.

Not all experiments require “direct” nuclear radiation; many are suitable for use with a scattered (lower intensity) beam produced in a scatter station—typically made with appropriate nuclear and atomic properties to deflect the correct wavelength and intensity of radiation. The design of these scatter stations requires both technical skill and experience so that the scattered radiation is properly tailored for its intended use. An incorrectly designed station could mean that the test object is exposed to incorrect radiation types or intensities, which could significantly reduce the value of the test.

A number of techniques are used in parallel to ensure that the HLOS pipe is closed before nuclear debris reaches the experiment. X- and gamma-rays travel *at* the speed of light, and electrons (beta particles) and neutrons are not much slower. The debris, however, moves much more slowly, at hydrodynamic velocities. [A “modified auxiliary closure” (MAC) or, when lower-yield weapons are used, a “fast acting closure” (FAC), positioned close to the device location—the working point—is able to shut the pipe in about 1 ms and to withstand pressures of about 30,000 psi.] A gas seal auxiliary closure (GSAC) farther along the HLOS pipe can close in less than 30 ms, and the tunnel and pipe seal (TAPS) will shut the pipe off in 300–700 ms. The TAPS is considerably farther from the working point than the FAC and therefore (a) has more time to function and (b) must close a larger aperture due to the taper of the HLOS pipe. These closure technologies are likely to require significant experience to develop to the point of reliable operation.

Other instrumentation to measure device performance, delivered shock, thermal pulse, electromagnetic pulse, and radiation is essentially similar to that used in a device development test (see Section 5.10).

RATIONALE

Emplacement canisters, fast-acting closures for HLOS tunnels, and containment technology are the keys to preventing the release of radioactive debris into the atmosphere, allowing UGWET tests to be conducted without their being detected off-site. Mechanical closure designs and materials unique to underground tests in general and UGWET in particular include mechanical and cable gas-flow blocking designs and techniques that operate up to a pressure difference of 1,000 psi for up to an hour and specialized explosive and/or mechanically driven devices capable of isolating portions of the HLOS pipe during or within the first 100 ms after exposure to radiation.

Because the experimental area is often quite large and is at a considerable distance from the working point, the vacuum systems needed to evacuate air from them to simulate a space environment are unusual. Required are specially designed diffusion or cryogenic pumps capable of maintaining a pressure much less than 10^{-3} Torr over a pipe system as long as 1,800 feet and varying in diameter from as small as 1 inch to as large as 30 feet. The crystals used to determine the energy spectrum of the radiation are unusual as well, and must be specially designed and fabricated to measure x-ray fluences at levels >0.1 cal/cm^2 in a time <50 ns and to operate in the UGT environment.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

Some foreign vendors can manufacture digitizers, measurement systems, and fiber-optic equipment comparable to those used in U.S. UGWET. France manufactures digitizing oscilloscopes; Japan, South Korea, and Taiwan manufacture the electronic components for measurement and recording systems; and Germany manufactures cryogenic vacuum pumps of the large size required for HLOS events. For an FTA covering equipment generally usable in a nuclear test, see Section 5.10.

Table 6.1-1. Underground Nuclear Weapons Effects Testing Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
UGWET Testbed that Contains the Nuclear Radiation Generated in the Explosion	Contain radioactive release that concurrently complies with environmental constraints and detection using mechanical and cable-gas-flow blocking designs that withstand up to 1,000 psi for up to 1 hour, or mechanical devices that isolate portions of the line-of-site pipe within 100 ms after exposure to radiation; techniques for recording analog signals with frequency content >250 MHz; timing and firing systems that provide a probability of failure less than 0.01%. Systems that permit measurement and recording of x-ray fluence >0.1 cal/cm^2 and time-resolved spectra in the photon energy range 50 eV to 500 keV measure and record neutron spectrum at flux levels $>10^{19}$ n/cm^2-5 of 14 MeV neutrons; measure the complete time-dependent flux of gamma rays.	USML XVI	Stemming materials	Specially designed: mechanical closures that prevent the uncontrolled release of gas or debris, diffusion or cryogenic pumps that maintain less than 1 Torr over a total pipe system more than 500 feet in length, manufacturing equipment that can maintain 2-dimensional uniformity <1%, detectors that measure X-ray fluence >0.1 cal/ cm^2, stress and particle motion gauges capable of measuring stress greater than 1 kilobar and velocities >10 m/s, airblast gauges with <2 ms risetime.	Substantiated computer codes and algorithms for computing: coupled radiation hydrodynamics flow (especially in 2- or 3-dimensional geometry), high-temperature opacity, x-ray deposition and material response, shock propagation and equation-of-state, stress waves in and around nuclear explosive cavities, Maxwell's equations in ionized air; and evaluate x-ray blow-off.
Scattering Station Design	Design parameters and design rules for scatter station design that facilitate the acquisition of information on system response to the nuclear and electromagnetic radiation generated in UGWETs.	USML XVI	Lithium hydride	None identified	Substantiated computer codes and algorithms that facilitate the design of scatter stations and collectively incorporate the effects of electromagnetic and x-ray environments.

(cont'd)

Table 6.1-1. Underground Nuclear Weapons Effects Testing Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Codes and Related Algorithms for Computing Coupled Radiation-Hydrodynamics Flow	Radiation/hydrodynamic flow parameters that have been derived from UGT environments that improve the ability to design UGWETs.	USML XVI	None identified	None identified	Substantiated computer codes and algorithms that compute radiation-hydrodynamics flow for the range of parameters relevant to an underground nuclear test environment.
Computer Codes and Related Algorithms for Computing High-Temperature Opacity	Opacities of materials of atomic number greater than 71 and for photon energies from 50 to 20,000 electron volts.	USML XVI	None identified	None identified	Substantiated computer codes and algorithms that compute high-temperature opacity (including ionized gas contributions), and multi-group opacity libraries created by such codes.
Computer Codes and Related Algorithms for Computing x-ray Deposition and Material Response	Thermal conduction and electron transport parameters theoretically derived and/or empirically deduced from UGWETs that can accurately predict the response of thin-film optical systems to nuclear weapon generated x-rays.	USML XVI	None identified	None identified	Substantiated computer codes and algorithms that can predict x-ray deposition and material response of thin-film optical systems.
Computer Codes and Related Algorithms for Computing Shock Propagation and Equation of State	Substantiated parameters for shock propagation and equation of state at high pressures and temperatures that can be used in the prediction of these entities.	USML XVI	None identified	None identified	Substantiated computer codes and algorithms for computing shock propagation that contain equation of state information at high pressures and temperatures.

Table 6.1-2. Underground Nuclear Weapons Effects Testing Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
UGWET Testbed that Contains the Nuclear Radiation Generated in the Explosion	Containing the large overpressures generated by nuclear detonation while allowing the transport of nuclear radiation through the various test chambers, and preventing the residual gases from reaching the atmosphere. Developing instrumentation and integrated electronic systems that can operate acceptably in the presence of the high level ionizing radiation and strong shock waves that are generated by the nuclear detonation.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, thermal radiation, or shock waves.	Above-ground radiation testing techniques, computer codes, and related algorithms for determining system response to nuclear weapons.
Scattering Station Design	Methods of obtaining sufficient energy from the main nuclear radiation beam using suitable scattering materials in conjunction with placement of measurement instrumentation to obtain a large amount of information on the radiation response of subsystems. Typical radiation levels at the experiment are 1 cal/cm^2 of x-rays, 10^{12} neutrons/cm^2.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, or neutrons.	Above-ground radiation testing techniques, computer codes, and related algorithms for determining system response to nuclear weapons.
Codes and Related Algorithms for Computing Coupled Radiation-Hydrodynamics Flow	Incorporating experimental data into theoretical models that give accurate results for coupled radiation-hydrodynamics flow.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, or neutrons.	None identified
Computer Codes and Related Algorithms for Computing High-Temperature Opacity	Incorporating experimental data into theoretical models that give accurate results for x-ray and gamma ray energy absorption and transmission through materials	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, or neutrons.	None identified
Computer Codes and Related Algorithms for Computing x-ray Deposition and Material Response	Incorporating experimental data into theoretical models that give accurate results for the energy deposition and response of thin films to x-rays.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, or shock waves.	None identified
Computer Codes and Related Algorithms for Computing Shock Propagation and Equation of State	Incorporating experimental data into theoretical models that provide insight into the equation of state at extremely high pressure and temperature.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, or shock waves.	Gas guns and flyer-plate tests.

(cont'd)

Table 6.1-2. Underground Nuclear Weapons Effects Testing Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Computer Codes and Related Algorithms for Computing Stress Waves from Nuclear Explosive Cavities	Incorporating experimental data into theoretical models that give predictable and repeatable results for the stress waves produced by underground nuclear detonations.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, thermal radiation, or shock waves.	None identified
Computer Codes and Related Algorithms for Computing x-Ray Induced Blow-Off	Incorporating experimental data into theoretical models that give predictable and repeatable results for the blow-off of materials produced by incident x-rays.	All military systems that must operate in a nuclear detonation environment involving gamma rays, x-rays, thermal radiation, or shock waves.	None identified

SECTION 6.2—BLAST AND SHOCK EFFECTS FROM NUCLEAR DETONATIONS

Highlights

- Blast and shock effects are the primary damage-producing mechanisms for soft targets such as cities and are often the only effective mechanism for destroying underground structures such as missile silos.
- Nuclear weapons with yields below about one megaton are particularly identifiable as blast/shock weapons.
- Nuclear blast and shock phenomena differ from those produced by conventional chemical explosives because of their long duration and large overpressures.
- There is considerable overlap between the pressure regime of nuclear-produced blast and shock and that of air drag produced in strong hurricanes.

OVERVIEW

As pictures of Hiroshima, Nagasaki, and of the test structures erected at the Nevada Test Site in the 1950’s amply demonstrate, the blast and shock waves produced by nuclear explosions are the principal means for destroying soft targets. Ground shock from a low-altitude, surface, or underground burst may be the only way to destroy hardened underground structures such as command facilities or missile silos.

In the absence of atmospheric and underground nuclear testing to determine the survivability of structures, means must be found to simulate the phenomena associated with a nuclear explosion. For blast and shock this can be done either in a large-scale, open-air test employing chemical explosives or in a specially designed test facility which can also produce thermal fluxes comparable to those from a nuclear weapon.

The air blast from a nuclear explosion is, however, different from that produced by conventional explosives. Because of the intense thermal pulse, the surface and near-surface air mass surrounding ground zero is heated rapidly. Within this heated region the blast wave travels more rapidly than it does in the cooler air above. As a result, blast waves reflected from the ground travel outwards and merge with the direct blast wave from the explosion. This produces a nearly vertical shock front called the Mach stem, which is more intense than that from the direct blast. To simulate the Mach stem with tests using high explosives, scientists employed helium-filled bags at ground level surrounding the high explosives used in the test. Because such tests can only be scaled and do not replicate the actual effects of a nuclear explosion, only scale models of test objects could normally be used.

More recently, U.S. attention has focused on a higher pressure regime than can be attained in open-air testing and on the construction of large simulators capable of reproducing simultaneously the blast *and* the thermal pulse from a nuclear detonation. These simulators typically employ a fuel-oxygen mixture, for example, liquid oxygen and finely powdered aluminum, and consist of long semicircular tubes. These simulators can even approximate the effects of soil type on blast wave propagation as well as the entraining of dust in the blast wave.

RATIONALE

Proliferators could conduct nuclear simulations to obtain quantitative data about the behavior of blast and shock waves interacting with real structures. The actual combination of overpressure, dynamic pressure, lift, and diffraction effects on a target is exceedingly difficult to model analytically or to simulate numerically, particularly without actual data. Military interest in the effects of dynamic loading on systems is in the survivability of tracked and wheeled vehicles, towed vehicles, C^3 shelters, etc., in the pressure regime characteristic of nuclear weapons. Civilian interest is in the survivability of similar systems and structures subjected to storm winds. The two are not completely distinct interests because the dynamic pressure from strong hurricanes may be comparable to that from nuclear blasts. Military interest also focuses on shock loading, a dynamic process which differs from the nearly steady-state effects of storm winds. As a rule of thumb, a 30 kPa pressure threshold corresponding to a 60 m/s particle velocity in the shock, or a drag force equivalent to that produced by about 210 km/hr (130 mph) steady winds, distinguishes the military and civilian applications. A frequently used design objective for civil structures is survivability in 190 km/hr (120 mph) winds.

Technologies for simulation include not only the ability to produce strong shocks and air blasts but also those used to measure shock wave values, dynamic pressure in a dusty environment, and deflections or other motions of the test structure. Dust-loaded shock tubes are unique to NWE testing. Similarly, combining both blast and thermal pulse would be unique to the nuclear situation. Explosives which are diluted or mixed with inert materials such as dilute explosive tiles produce more uniform detonations that more closely resemble a nuclear detonation; such explosives would also be critical to NWE testing.

Simple software for computing nuclear blast, shock, and thermal effects is already uncontrolled, but codes which have been compared with nuclear detonations and which have been improved as a result are critical.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

U.S. capability in numerical simulations of nuclear blast effects is probably unsurpassed, but France, Canada, the UK, and Germany are making rapid progress in the field. Note that neither Canada nor Germany possesses nuclear weapons and that neither is believed to have any program to acquire such arms. Israel has some capability in numerical simulation. Most likely, Russia does as well.

The French had the most advanced Western blast simulator, a compressed-air-driven facility with a 70 m^2 cross section that is large enough to test full-sized military vehicles. The United States now has the Large Blast/Thermal Simulator with a larger cross section (about 300 m^2), a greater operating envelope than the French installation, and the capability to perform combined synergistic blast and thermal simulations (thermal pulse up to 8 cal/cm^2).

Germany has a blast simulator with a cross-section of 76 m^2 and is acquiring thermal radiation simulators. The Germans are good at shock wave photography in small laboratory-scale shock tubes. The UK has a smaller explosively driven blast simulator with a smaller cross-section and smaller operating envelope than any of the above-listed facilities. The UK also operates lamp-type thermal radiation simulators.

Canada, Australia, Sweden, Switzerland, Norway, Israel, and the Netherlands have had active blast simulation programs in the past. Italy, Japan, India, and Pakistan have capabilities in some critical elements of survivability and hardening to nuclear blast and thermal radiation. Japan has been conducting high-quality, laboratory-scale shock-tube research. Russia and some Eastern European states have above-ground blast simulators comparable to those of the United States and other NATO nations. Most of the countries with blast simulation capabilities do not possess nuclear weapons and likely acquired the technologies to study the survivability of their own assets.

Table 6.2-1. Blast and Shock Effects from Nuclear Detonations Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Nuclear Airblast Simulator	Overpressure and/or dynamic pressure levels exceeding 3 kPa, dust generated by nuclear burst with scaled HOB below 250m/(KT)$^{1/3}$, and all high-yield bursts at higher HOB for high humidity layers below 3,000 m above sea level.	USML XVI	Explosives or explosives mixed with inert materials (dilute explosives) specially designed for nuclear weapons simulation.	Miniaturized gauges that can measure pressure and structural response; shock tubes or other devices that can simulate the non-ideal nuclear airblast environment.	Substantiated computer codes and algorithms that predict the pressure waveform generated by a nuclear airblast that can be used for designing the simulator and for calibration.
System Level Thermal/ Blast Simulators for Low-Altitude Nuclear Detonations	3,000 K e.b.b. source, pulse-length 0-10 s, surface emittance >8 cal/cm^2-s, that can test subsystems and systems against combined thermal and blast effects of a low-altitude nuclear detonation.	USML XVI	Liquid oxygen, powdered aluminum	Instrumentation for measuring response of systems and materials for flux levels >8 cal/cm^2-s, cameras with spectral resolution <0.25 nm, sampling rate >120/s, and with 10-bit resolution.	Substantiated computer codes and algorithms that can interpret and extrapolate the results from simulation to real systems; and include: the response of materials at elevated temperature and temperature gradients in the presence of shock waves.
Nuclear Ground Shock Simulator	Peak overpressures from 0.1 MPa surface flush and shallow-buried structures that extend from the surface to several meters below the surface.	USML XVI	Explosives or explosives mixed with inert materials (dilute explosives) specially designed for nuclear weapons simulation. All-weather materials that can protect RVs, launch vehicles, and aircraft against dust.	Instruments for measuring effects resulting from stresses ≥10 MPa, gauges that measure stresses and strains in underground detonations.	None identified
Underwater Nuclear Detonation Simulator	Overpressures greater than 100 psi and having impulse sufficient to degrade the operational capability of sea-based assets resulting from an underwater nuclear detonation.	USML XVI	None identified	None identified	None identified

(cont'd)

Table 6.2-1. Blast and Shock Effects from Nuclear Detonations Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Thermostructural Shock Simulator	Generate time history (1 to 100 ns pulse duration) of soft x-ray induced shock wave on space platforms.	USML XVI	None identified	Optical measuring systems that exhibit less than 10 mm per meter change in lateral or longitudinal dimensions when exposed to levels of x-ray generated pressures and impulses necessary to degrade the operational effectiveness of space assets.	None identified

Table 6.2-2. Blast and Shock Effects from Nuclear Detonations Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Nuclear Airblast Simulator	Ability to maintain sufficiently high pressure for sustained period of time using high explosives so as to adequately simulate the effect of a nuclear blast.	Above-ground communication nodes, jeeps, trucks, tanks, artillery; RVs, boost vehicles, and aircraft.	Substantiated computer codes and related algorithms that predict: overpressure and impulse on surface platforms, and dust lofting and atmospheric transport; laboraory scaled experiments of airblast over non-ideal grounds using laser beam facilities.
System Level Thermal/Blast Simulator for Low-Altitude Nuclear Detonations	Achieving synchronization of blast and thermal radiation waveforms.	Above-ground communication nodes, jeeps, trucks, tanks, artillery; RVs, boost vehicles, and aircraft.	Substantiated computer codes and related algorithms that predict combined effects of blast and thermal radiation.
Nuclear Ground Shock Simulator	Disposable simulation techniques that produce ground-shock shocks >5 MPa and coupled energy >10 KT of TNT.	Buried communication nodes, bunkers, underground missile silos that may either be simply covered or structurally reinforced.	Substantiated computer codes and related algorithms that predict any of the following: airblast, ground shock, loads on flush-mounted, shallow-buried, or deeply buried structures that may include the effect of non-ideal terrain.
Underwater Nuclear Detonation Simulator	Engineering of conventional high-explosive shaped charges to simulate nuclear detoanation pressure-time history of underwater detonation.	Combat and combat-related surface ships, submarines.	Substantiated computer codes and algorithms that predict overpressure and impulse on surfce ships and submarines due to nuclear-produced underwater detonations out to ranges where the pressures fall to 100 psi.
Thermostructural Shock Simulator	Tailoring of shock overpressure and impulse (pulse width 1 to 100 ns) on irregular surface of space structures and RVs.	Satellites, ICBMs	Substantiated computer codes and algorithms that can predict the mechanical and structural response of missile/spacecraft structures due to nuclear weapon generated x-rays.

SECTION 6.3—NUCLEAR THERMAL RADIATION EFFECTS

OVERVIEW

Thermal radiation decays only as the inverse square of the distance from the detonation. Thus, weapons in the megaton class and above are primarily incendiary weapons, able to start fires and do other thermal damage at distances well beyond the radius at which they can topple buildings or overturn armored vehicles.

The effect of thermal radiation on unprotected human beings is likely to be very serious, producing flash burns over large areas of the body. However, the Hiroshima and Nagasaki bombings demonstrated that once the victim is beyond the radius at which light-colored fabrics are directly ignited, even simple precautions can greatly reduce the extent and seriousness of thermal injuries. Many examples exist of people severely burned on their faces and arms, but unburned beneath even a thin shirt or blouse.

Thermal effects on structures are equally complex. The response of a structure to the thermal pulse from a nuclear weapon depends upon its composition (wood, masonry, concrete); the type and albedo of any exterior paint; the transparency of any windows facing the burst; the type, texture, and composition of roofing; and even the presence or absence of awnings and shades. For weapons in the 1 to 200-kiloton region used against structures commonly found in the West, blast effects are likely to predominate; larger weapons will have the ability to start fires at distances far greater than they can inflict significant blast damage. Films of tests conducted in Nevada in the 1950's confirm that at the extreme distance at which wood-frame houses can be ignited by lower yield weapons, the buildings are blown apart seconds later by the blast wave, while structures which survive the blast do not ignite after the blast. Tests conducted in the Pacific using megaton-class weapons show the opposite effect. Secondary fires started by broken gas mains, electrical short circuits, etc., are not considered here.

To fight on the modern electronic battlefield, one must understand the effects of nuclear weapons on sensors which function in the ultraviolet, optical, and infrared wavelength regions. Much less information about the response of such instruments is available openly, simply because no modern sensors were operating in Japan in 1945, and few were tested above ground before the LTBT went into effect. Thus, a state seeking to harden its sensors against the "light" flash from a nuclear weapon must determine the spectrum of the radiation from the weapon, simulate that spectrum at appropriate intensity levels and for representative durations, and then expose sensors to the flash. This probably could be done for small systems and sensors in a facility of modest size using commercially available non-nuclear technology; it is much more difficult to test large systems. Note that the spectrum of interest is a function of the yield of the attacking weapon, the time after detonation, and the distance the sensor is from the burst (because the atmosphere is not uniformly transparent at all wavelengths of interest).

Highlights

- The thermal flash from nuclear weapons in the megaton class is able to ignite structures at distances greater than the blast wave from the same weapons can destroy them. Ignition of wood, etc., takes place at fluences of about 5 cal/cm^2, while many modern structures can withstand overpressures of at least a few psi.
- Thermal radiation can produce flash burns on unprotected human beings, but at distances beyond that at which clothing is ignited by the flash even simple precautions can greatly reduce injuries.
- Thermal radiation from a nuclear weapon can adversely affect sensors in the infrared through the ultraviolet regions of the electromagnetic spectrum.
- A country seeking to harden its sensors against the "light" flash from a nuclear weapon must determine the spectrum from the weapon as affected by atmospheric absorption and then simulate that spectrum at appropriate intensity levels for representative duration.
- High-temperature blackbody radiation sources are used for simulation of the nuclear thermal radiation.

RATIONALE

The fireball from a nuclear explosion reaches blackbody temperatures greater than 10^7 K, so that the energy at which most photons are emitted corresponds to the x-ray region of the electromagnetic spectrum. For detonations occurring below 30,000 m (100,000 ft) these X-rays are quickly absorbed in the atmosphere, and the energy is reradiated at blackbody temperatures below 10,000 K. Both of these temperatures are well above that reached in conventional chemical explosions, about 5,000 K. For detonations below 100,000 feet, 35 percent to 45 percent of the nuclear yield is effectively radiated as thermal energy.

In addition to the high temperature of the nuclear fireball, the blackbody radiation is emitted in a characteristic two-peaked pulse with the first peak being due to the radiating surface of the outrunning shock. As the shock front temperature drops below 6,000 K, thermal radiation decreases when the shock front becomes transparent to radiation from the interior. This occurs between 10^{-5} and 10^{-2} seconds after detonation.

At about 0.1 second after detonation, the shock front becomes sufficiently transparent that radiation from the innermost, hottest regions becomes visible, producing a second thermal peak. Before the second peak begins the fireball has radiated only about one quarter of its *total* energy. About 99 percent of the total *thermal* energy is contained in the second pulse. The duration of this pulse depends on the yield of the weapon and the height of burst (HOB); it ranges from only about 0.4 s for a 1 kT airburst to more than 20 s for a 10 MT explosion.

Both theory and experiment indicate that the dominant thermal pulse can be adequately represented by a blackbody at a temperature between 6,000 and 7,000 K, which places the peak of the spectrum near the boundary between the ultraviolet and the visible regions of the spectrum. The shape of the Planck spectrum is such that most of the radiation is contained in the visible and infrared regions.

The response of any given system to the thermal pulse depends on the absorption properties of the test subject but also to the distance from the burst and the atmospheric conditions between fireball and target such as clouds, snow, aerosols, and dust. The atmosphere is not equally transparent at all wavelengths, so the spectrum of the radiation incident on a target must be correctly calculated and then simulated.

By the same token, known atmospheric absorption effects can be used by a system incorporating sensors at different distances from a nuclear explosion to establish the characteristics of the explosion itself and, therefore, the weapon type. Such information would be very useful in selecting appropriate responses. Sensors used to deliver information on which decision makers can rely, however, must be calibrated against simulated nuclear fireballs under a wide range of atmospheric conditions.

Mixing and ignition facilities with surface emittance rates on the order of 150 cal/cm^2-s at blackbody temperatures of ≥ 3,000 K are critical to some simulators. Such mixer facilities should mix fuel and oxidizer before ignition to avoid the production of smokes and particulate clouds. Instrumentation designed to function at flux levels above about 150 cal/cm^2-s is specialized to the nuclear simulation role; this intense radiation environment can easily melt all known materials over the duration of a full thermal pulse. These conditions are not found in any commercial applications.

Other processes and technologies such as plasma discharges with arc diameters >1.0 cm and arc lengths >10 cm for current greater than 1,000 Å and more than 300 kW input power are unique to nuclear simulation and have no commercial applications. Software is to be validated against nuclear detonations or simulations and intended to model the characteristics of the fireball as functions of the characteristics of the nuclear source, burst environment, and atmospheric conditions.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

The new U.S. Large Blast/Thermal Simulator (LBTS) is the most advanced facility of its type in the West, having a larger operating envelope (blast) than the comparable French instrument plus the capability to perform simultaneous blast and thermal testing, also a capability lacked by the French.

The United States and France lead in full-scale, thermal pulse simulation technology. Large-area, chemically driven, thermal-radiation simulators were developed in the United States but have been sold to France, the UK, and Germany. The United States operates flash and continuous-lamp facilities and uses solar furnaces on small targets. France and Germany have made incremental improvements to the simulators purchased from the United States. Russia and some Eastern European countries have thermal simulators comparable to those of the United States and other NATO nations.

Table 6.3-1. Nuclear Thermal Radiation Effects Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
High Intensity Thermal Radiation Chemical Energy Sources	3,000 K e.b.b. sources, pulse length >1 sec, that can provide a flux >7 cal/cm^2-s to test objects with volumes >100 cubic feet.	USML XVI	Liquid oxygen, powdered aluminum	Movable asymptotic calorimeters for measuring thermal flux, cameras with spectral resolution <0.25 nm, digital sampling rate >120/s, and with 10-bit resolution.	No special commercial software is required for power control.
Solar Power Tower (Central Receiving Tower with Mirror Field)	Heliostats and receiver that produce 3,000 K e.b.b., provide ≥5 MW total thermal power, peak fluxes ≥260 W/cm^2, illuminate targets as large as 27 m^2, and simulate thermal nuclear transient in second range.	USML XVI	None identified	Instrumentation including photometers and flux gauges that can accurately measure incident flux densities in the 10's of W/cm^2 range (temperature and flux are inferred from power density measurement)	No special commercial software is required for power control. Programming effort is challenging but straightforward.
Solar Parabolic Dish/ Parabolic Trough Systems	Parabolic dish that generates solar thermal power by tracking the sun and provides ≥75 kW total thermal power, peak flux ≥1500 W/cm^2 over a 15-in. diameter circular area, and can control pulse duration in millisecond range.	USML XVI	None identified	Instrumentation including photometers and flux gauges that can accurately measure incident flux densities in the 10's of W/cm^2 range (temperature and flux are inferred from power density measurement)	No special commercial software is required for power control. Programming effort is challenging but straightforward.
Solar Furnace Systems	Heliostat that tracks and directs sunlight into parabolic dish and can provide ≥ total thermal power, and peak flux ≥400 W/cm^2, and can control power to simulate nuclear thermal transients.	USML XVI	None identified	Instrumentation including photometers and flux gauges that can accurately measure incident flux densities in the 10's of W/cm^2 range (temperature and flux are inferred from power density measurement)	No special commercial software is required for power control. Programming effort is challenging but straightforward.

(cont'd)

Table 6.3-1. Nuclear Thermal Radiation Effects Technology Parameters (cont'd)

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Thermal Effects Simulators for IR Detectors	Peak energy density from 1 to 10^3 J/cm^2; peak power density from 10^3 to 10^6 W/cm^2; laser irradiation pulses from 10^{-7} to 1 sec; uncertainty in damage threshold <35%.	USML XVI	Photovoltaic Detectors (PV): HgCdTe, PbSnTe; Pyroelectric Detectors: TGS, SBN; Thin-film Photoconductors (PC): PbS, PbSe; bulk HgCdTe	Laboratory lasers having following capabilities: peak energy density from 1 to 10^3 J/cm^2; peak power density from 10^3 to 10^6 W/cm^2; pulse width from 10^{-7} to 1 sec.	None identified
Thermal Effects Simulators for Optical Semiconductors	Pulse length between 10^{-9} to 10^{-4} sec, power density from 10^5 to 10^8 W/cm^2.	USML XVI	Ge, Si, InSb, GaAs, SiGa, SiAs, InAs, InGaSb, PbSnSe, $LiTaO_3$	Laboratory lasers having following range of capability: pulse length between 10^{-9} to 10^{-4} sec, power density from 10^5 to 10^8 W/cm^2.	None identified
Thermal Radiation Effects Soft x-Ray Simulators Using Plasma Radiation Source	Soft x-ray (photon energies between 1 to 10 keV) radiation spectrum for on-target fluences ≤4.5 cal/cm^2 over an area > fraction of a centimeter in under 100 ns; capability of generating peak pressures in 10 s of kbar (few GPa) range.	USML XVI	None identified	Plasma Radiation Source	None identified
Magnetic Driven Flyer Plates Simulator for Soft x-ray Thermal Radiation Effects	Magnetic driven flyer plates that simulate thermally generated pressures at the surface of space platforms as high as 10 kbar, and impulses as low as ~ 5 ktap (500 Pa-s).	USML XVI	None identified	Pulsed power system for magnetic field	None identified
Explosive Loading Simulators for Soft x-ray Thermal Radiation Effects	Explosively driven flyer plates that simulate thermally generated pressures and impulses at the surface of generic shaped space platforms of moderate size (e.g., RVs) with pressures <1 kbar to 70 kbar (7 GPa) for fiber-reinforced organic ablators and up to 13 GPa for metal targets; and impulses ranging from several hundred taps to >7,000 taps (700 Pa-s).	USML XVI	High Explosives	None identified	None identified

Table 6.3-2. Nuclear Thermal Radiation Effects Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
High Intensity Thermal Radiation Chemical Energy Sources	Generate nuclear thermal radiation for testing and evaluation of materials, components, subsystems, and systems for military application.	Systems that must survive the thermal effects from a low altitude nuclear detonation	Substantiated computer codes and algorithms that can predict the response of systems to the thermal radiation generated by a nuclear detonation; solar simulation methods.
Solar Power Tower (Central Receiving Tower with Mirror Field)	Precise computer control of reflector field to simulate thermal nuclear pulse; design and focus of mirrors; techniques for determining incident flux. These must work in combination with high speed shutter to produce the leading edge of the thermal pulse.	Systems that must survive the thermal effects from a low altitude nuclear detonation	Substantiated computer codes and algorithms that can predict the response of systems to the thermal radiation generated by a nuclear detonation; chemical energy sources
Solar Parabolic Dish/Parabolic Trough Systems	Design and fabrication of facets; tailor power level by facet alignment; control of transients, in conjunction with high speed shutter, to replicate nuclear thermal pulse (especially leading edge); techniques for determining incident flux.	Systems that must survive the thermal effects from a low altitude nuclear detonation	Substantiated computer codes and algorithms that can predict the response of systems to the thermal radiation generated by a nuclear detonation; chemical energy sources
Solar Furnace Systems	Design and fabrication of facets; tailor power level by facet alignment; control of transients, in conjunction with high speed shutter, to replicate nuclear thermal pulse (especially leading edge); techniques for determining incident flux.	Systems that must survive the thermal effects from a low altitude nuclear detonation	Substantiated computer codes and algorithms that can predict the response of systems to the thermal radiation generated by a nuclear detonation; chemical energy sources
Thermal Effects Simulators for IR Detectors	Determination of damage thresholds for detectors including vaporization and melting in photoconductors, cracking caused by thermal stress in pyroelectric detectors, and junction degradation in photodiodes.	Sensor systems that must survive the thermal effects from either a low or high altitude nuclear detonation.	Substantiated computer programs and algorithms that can predict melting and vaporization, cracking caused by thermal stress, and junction degradation, taking into account laser beam parameters and geometry.
Thermal Effects Simulators for Optical Semiconductors	Theoretical models for: optical and carrier transport, depth of heated material, coupled diffusion equations for temperature and excess carrier density, non-linear processes including two-photon absorption, free-carrier absorption, dynamic Burstein shift.	Sensor systems that must survive the thermal effects from either a low- or high-altitude nuclear detonation.	Substantiated computer programs that can predict optical and carrier transport; depth of heated region; coupled diffusion equations for temperature and excess carrier density; two-photon absorption, free-carrier absorption, and dynamic Burstein shift.

(cont'd)

Table 6.3-2. Nuclear Thermal Radiation Effects Reference Data (cont'd)

Technology	Technical Issues	Military Applications	Alternative Technologies
Thermal Radiation Effects Soft x-Ray Simulators for High-Altitude Nuclear Detonations Using Plasma Radiation Source	Simulation: of impulse, material blow-off, spallation and surface damage caused by vaporization and/or ablation, buckling of thin-walled structures, brittle fracture, delamination, nucleation and growth of flaws.	RVs and space platforms that must survive a high-altitude NUDET.	Substantiated multidimensional shock wave computer programs that incorporate constitutive models of composite materials, blow-off, fracture, nucleation, growth of flaws; buckling, brittle fracture, and delamination.
Simulation of Soft x-ray Thermal Radiation Effects Produced by High-Altitude Nuclear Detonations Using Magnetic Driven Flyer Plates	Increasing the size of the energy source >500 kJ for applying magnetic pressures >10 kbar (1 GPa) to large targets.	RVs and space platforms that must survive a high-altitude NUDET.	Substantiated multidimensional shock wave computer programs that incorporate constitutive models of composite materials, blow-off, fracture, nucleation, growth of flaws; buckling, brittle fracture, and delamination.
Explosive Loading Simulator for Soft x-ray Thermal Radiation Effects	Methods for concurrent simulation of peak pressure, impulse, and angular distribution of shock waves produced by soft x-rays on moderate to large space platforms or segments of space platforms using a combination of the: Sheet-Explosive Loading Technique (SELT), Light-Initiated High Explosive (LIHE) technique, and methods for spraying explosive on complex targets such as the Spray Lead at Target (SPLAT) technique. Specific issues are: SELT—accounting for finite velocity and oblique shock wave instead of uniform detonation time over surface and nonperpendicular shock, especially at low stress, reducing the minimum explosive thickness to permit reduction of impulse to threat levels, and adjusting the peak pressure and impulse using attenuators; LIHE—produce impulses <1,000 taps (100 Pa-s) using short-duration blast waves, reduce sensitivity of explosives and improve handling capabilities, and apply to complex target shapes; SPLAT—generate low-impulse simulation for large test objects.	RVs and space platforms that must survive a high-altitude NUDET.	Substantiated multidimensional shock wave computer programs that incorporate constitutive models of composite materials, blow-off, fracture, nucleation, growth of flaws; buckling, brittle fracture, and delamination.

SECTION 6.4—TRANSIENT RADIATION EFFECTS IN ELECTRONICS (TREE) AND SYSTEMS-GENERATED ELECTROMAGNETIC PULSE (SGEMP) EFFECTS

OVERVIEW

Many military systems (and, increasingly, civilian systems such as communications and weather satellites) must be capable of operating in environments containing sources of both natural and man-made radiation. In this context "radiation" refers to particle-like effects caused by neutrons, photons, and charged particles. When energetic radiation passes through matter, many complex processes occur including Compton scattering, photoelectric excitation, Auger electron emission, and pair production caused by photons; ionization caused by charged particles; and various nuclear processes caused by neutrons. Neutron-induced reactions can stimulate the release of charged particles and photons.

As the level of integration of modern electronics increases, and as the size of individual devices on chips shrinks, electronic systems become increasingly vulnerable to any unwanted charge deposition or atomic displacement within the silicon base of the semiconductors. Effects which are generally short-lived are classed as transient radiation effects in electronics (TREE). EMP generated within the system by the passage of radiation through cases, circuit boards, components, and devices is called systems-generated EMP or SGEMP.

The quantification of both phenomena is critical to the design of optical and electronic packages which can survive these effects. Ideally, such subsystems should be produced without significant increases in either cost or weight. Because the radiation which causes TREE and SGEMP is relatively strongly absorbed in the atmosphere, both phenomena are of primary importance to space systems exposed to high-altitude, high-yield nuclear detonations.

RATIONALE

Survivability analysis of semiconductor electronics requires quantitative understanding of at least the following:

- Ionization effects (both total dose and dose rate) which produce enhanced photocurrents in the transient state and can also cause permanent trapping of free charge in metal oxide semiconductor (MOS) devices.
- Displacement effects (displacement of lattice atoms leading to changes in the bandgap energy levels) and thermomechanical shock induced by the rapid deposition of energy from the nuclear detonation.

These effects depend not merely on total dose but also on dose rate. Naturally occurring effects include total dose from electrons and protons trapped in the Van Allen belts and single-event upset (SEU) or even single-event burnout. SEU results when enough ionization charge is deposited by a high-energy particle (natural or man-produced) in a device to change the state of the circuit—for example, flipping a bit from zero to one. The effect on a power transistor can be so severe that the device burns out permanently.

Large x- and gamma-ray dose rates can cause transient upset and permanent failure. These dose rates are delivered over a 10–100 ns time period.

Delayed gammas in a 1–10 microsecond period at the same dose rate can cause latchup and burnout of devices. Latchup is the initiation of a high-current, low-voltage path within the integrated circuit and causes the circuit to malfunction or burnout by joule heating.

Neutron fluences of greater than 10^{10} n/cm^2 can cause permanent damage. A nuclear weapon will typically deliver this dose in a period from 0.1 to 10 ms.

Total ionization greater than 5,000 rads in silicon delivered over seconds to minutes will degrade semiconductors for long periods. As device sizes decrease, the threshold for damage may go down.

Highlights

- Radiation can damage or destroy microelectronic integrated circuits by a number of mechanisms.
- Although high doses and dose rates are more predictably effective at damaging microcircuits, single-event upsets are becoming increasingly more common and devastating as individual device size decreases.
- TREE and SGEMP are primarily problems for space-based systems. Natural radiation can do similar damage over a period of years.
- It is difficult to predict the details of system survivability using computation, and it is also very expensive to build adequate simulators.
- Many foreign powers have the ability to produce radiation-hardened or radiation-resistant microcircuits.

It is inherently difficult to predict the effects of TREE and SGEMP from first principles. Because components, circuit boards, cases, connectors, and everything else within a system can be arranged in many ways, and because radiation can come from any direction, only a detailed simulation (perhaps involving Monte Carlo calculations) can do the job. The task of prediction is made more complex because the effects of the radiation pulse can depend on the operating state of the system at the moment the radiation passes through it.

A series of tests with conditions chosen to reach design dose and dose rate limits during many different phases of system operation is probably preferable. Such testing, however, requires simulators which can reproduce the extreme conditions produced by nuclear weapon detonation, typically $>10^{11}$ rads (Si)/s. Simulators of this environment typically include high-current, short-pulse electron linear accelerators irradiating a primary target to produce an appropriate flux of secondary radiation.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

Many nations have the capability to produce radiation-hardened microelectronic and electro-optical devices and to use these devices in military systems. These states include the UK, France, Germany, Sweden, Japan, Russia, Taiwan, and South Korea. Many of these nations do not possess nuclear weapons. The UK, France, Sweden, and Russia have demonstrated their ability to produce radiation-hardened systems.

All nations which can produce radiation-hardened components and systems may be presumed to have the ability to verify by experiment that such systems function correctly. Those countries which did not conduct nuclear effects tests must have some simulation capability. Nuclear weapon states must also have the capability to simulate TREE and SGEMP since all have signed the CTBT.

Table 6.4-1. Transient Radiation Effects in Electronics (TREE) and Systems-Generated Electromagnetic Pulse (SGEMP) Effects Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
TREE/SGEMP Effects Simulators	Pulsed gamma ray, x-ray, electron beam, and ion beam sources that simulate a nuclear weapons radiation environment with dose rates $>10^{11}$ rads(Si)/s over a volume that is large enough to test military subsystems/systems; diagnostic and test equipment that can operate in dose rates $>10^{11}$ rads(Si)/s.	USML XVI	Optical fibers and semiconductor materials that can operate in dose rates $>10^{11}$ rads(Si)/s.	Substantiated multi-dimensional shock wave computer programs that incorporate constitutive models of composite materials, blow-off, fracture, nucleation, growth of flaws; buckling, brittle fracture, and delamination. that can operate and evaluate the performance of components, subsystems and systems in a nuclear weapon generated environments $>10^{11}$ rads(Si)/s.	None identified
TREE/SGEMP Hardening	Systems, subsystems, and components that are hardened against nuclear weapon generated environments that exceed 10^{11} rad(Si)/s	USML XVI	None identified	Specially designed test systems that can evaluate the performance of components, subsystems, and systems that are required to operate in a radiation environment $>10^{11}$ rads(Si)/s.	Substantiated radiation computer codes and algorithms that: perform TREE/SGEMP hardening assessments and trade-off studies at either the component, subsystem and system level; can evaluate “operate-through capability.”

Table 6.4-2. Transient Radiation Effects in Electronics (TREE) and Systems-Generated Electromagnetic Pulse (SGEMP) Effects Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
TREE/SGEMP Effects Simulators	Computer implemented analytical models of gamma ray, x-ray, electron and ion transport in multilayered and multidimensional structures. Development of testing procedures and related measurement systems that can operate at dose rates exceeding 10^{11} rad (Si)/s.	Mission critical military systems that must operate in the TREE and SGEMP threat environment such as satellites, C3 nodes, RVs, etc.	Substantiated radiation (gamma ray, x-ray, electron beam, and ion beam transport) computer codes and algorithms that predict TREE/SGEMP effects in subsystems or systems.
TREE/SGEMP Hardening	Methods for circumventing and mitigating the effects of prompt nuclear radiation induced electrical signals. Minimizing sensor degradation from debris gammas. Developing radiation-hardened components and circuits.	Mission critical military systems that must operate in the TREE and SGEMP threat environment such as satellites, C3 nodes, RVs, etc.	None identified

SECTION 6.5—NUCLEAR EFFECTS ON ELECTROMAGNETIC SIGNAL PROPAGATION

OVERVIEW

The large quantities of ionizing radiation produced by a high-altitude, high-yield nuclear detonation can severely change the environment of the upper atmosphere, producing heavily ionized regions which can disrupt electromagnetic waves passing through those zones. These disturbed regions can easily be the size of North America and can persist for tens of hours. The trapping mechanism for these high-energy electrons may be similar to that which produces the Van Allen radiation belts.

The actual degree of communications interruption is dependent upon the scenario and includes weapon yield and HOB, time of day, cloud cover, latitude and longitude of the burst, the specific communications path, and the time after the detonation. Other systems which may be affected by nuclear weapons effects on electromagnetic wave propagation include sensors in the IR, visible, and UV regions, and laser communications which may be affected by the background IR. A very hot (but transparent) region of the atmosphere can act as a lens to refract a laser communications beam off of its intended receiver.

Radar beams are both attenuated and refracted when passing through a nuclear fireball at altitudes below 25 km. At these altitudes the mean free path is small, and it is reasonable to speak of the fireball as being in local thermal equilibrium. Under these circumstances it is difficult to track incoming reentry vehicles (RV). Optical systems will suffer increased noise levels both because of ionized regions and from blackbody radiation from the fireball, and long-wave infrared (LWIR) systems may be unable to see through the fireball to an RV in the distance and may not be able to see an RV nearer to the sensor than the fireball because of the background.

No high-altitude nuclear tests have been carried out by the United States since the ratification of the 1963 Limited Test Ban Treaty (LTBT). Apparently, few IR data were obtained from the CHECKMATE, KINGFISH, ORANGE, and STARFISH high-altitude tests, so the visual information from those tests has been extrapolated to the IR regime. The main sources of high-altitude IR which would produce clutter include plasma emission, molecular and atomic emission from excited states, and emission from uranium oxide. All of these are functions of electron density.

At frequencies above about 300 MHz (UHF, SHF, and EHF), signals may be disrupted by scintillation, primarily characterized by intermittent fading and multipath transmission. These effects may persist for long periods and can degrade and distort a signal almost beyond recognition (for example, the plasma clouds are dispersive so that the speed of all frequencies of electromagnetic radiation are not equal in the cloud). Temporal and frequency coherence can both be destroyed.

Highlights

- Trans-satellite and satellite-to-ground communications are frequently interrupted.
- Operational effects include lower signal-to-noise ratio, fading, and reduced information rate for communication channels.
- Simulation of these effects uses hardware-in-loop.

RATIONALE

The vast majority of information relating to the propagation of electromagnetic radiation in a nuclear environment is pure science, primarily ionospheric and auroral physics including such phenomena as whistlers between northern and southern hemisphere locations. It requires no protection, but information on the mitigation of the effects may be classified because of considerations applicable to specific systems. Two areas require special mention as critical technology:

- The process of calculating the evolution of the nuclear-produced plasma in the Earth's atmosphere and magnetic field.
- Certain aspects of propagation simulators that reproduce the nuclear environment.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

All five of the declared nuclear weapon states, the United States, Russia, the UK, France, and China may have some capability to determine the effects of nuclear environments on electromagnetic signal propagation. All have access to and/or have contributed to the unclassified literature on RF propagation through structured media. The United States and the UK have provided models for calculating line-of-sight communications effects; the status of similar models in the other three nations is unknown.

Table 6.5-1. Nuclear Effects on Electromagnetic Signal Propagation Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Fading Dispersive Communication Channel Simulators	Simulate RF propagation through disturbed ionosphere generated by high altitude nuclear detonations, compute: frequency-selective bandwidth, coherence time, signal-to-noise ratio, bit error rate; frequency-selective band >100 kHz	USML XVI	None identified	None identified	Substantiated computer codes and algorithms integrated with hardware in the loop that predict the space-time ionospheric plasma concentration, frequency-selective bandwidth, and coherence time in nuclear disturbed ionosphere.
Optical and Infrared Simulators	Simulate propagation of IR (0.8–30 microns), VIS (0.4–0.8 microns), UV (0.01–0.4 microns) waves in backgrounds generated by nuclear detonations.	USML XVI	None identified	None identified	Substantiated computer codes and algorithms integrated with hardware-in-the-loop that calculate high-altitude nuclear environments and predict propagation for IR/VIS/UV signals.

Table 6.5-2. Nuclear Effects on Electromagnetic Signal Propagation Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Fading Dispersive Communication Channel Simulators	Predict generation of ionic species, plasma concentration, coherence bandwidth, coherence time, propagation delay, and probability of correct message resulting from a high altitude nuclear detonation.	Military communication systems and radars that must operate in nuclear disturbed propagation paths.	None identified
Optical and Infrared Simulators	Predict generation of ionic species, plasma concentration, and propagation characteristics such as attenuation, refraction, etc., in IR/VIS/UV region resulting from a high altitude nuclear detonation.	IR/VIS/UV systems that must operate in nuclear disturbed propagation paths.	None identified

SECTION 6.6—HIGH-ALTITUDE ELECTROMAGETIC PULSE (HEMP) EFFECTS

OVERVIEW

A high-altitude nuclear detonation produces an immediate flux of gamma rays from the nuclear reactions within the device. These photons in turn produce high energy free electrons by Compton scattering at altitudes between (roughly) 20 and 40 km. These electrons are then trapped in the Earth's magnetic field, giving rise to an oscillating electric current. This current is asymmetric in general and gives rise to a rapidly rising radiated electromagnetic field called an electromagnetic pulse (EMP). Because the electrons are trapped essentially simultaneously, a very large electromagnetic source radiates coherently.

The pulse can easily span continent-sized areas, and this radiation can affect systems on land, sea, and air. The first recorded EMP incident accompanied a high-altitude nuclear test over the South Pacific and resulted in power system failures as far away as Hawaii. A large device detonated at 400–500 km over Kansas would affect all of CONUS. The signal from such an event extends to the visual horizon as seen from the burst point.

The EMP produced by the Compton electrons typically lasts for about 1 microsecond, and this signal is called HEMP. In addition to the prompt EMP, scattered gammas and inelastic gammas produced by weapon neutrons produce an "intermediate time" signal from about 1 microsecond to 1 second. The energetic debris entering the ionosphere produces ionization and heating of the E-region. In turn, this causes the geomagnetic field to "heave," producing a "late-time" magnetohydrodynamic (MHD) EMP generally called a heave signal.

Initially, the plasma from the weapon is slightly conducting; the geomagnetic field cannot penetrate this volume and is displaced as a result. This impulsive distortion of the geomagnetic field was observed worldwide in the case of the STARFISH test. To be sure, the size of the signal from this process is not large, but systems connected to long lines (e.g., power lines, telephone wires, and tracking wire antennas) are at risk because of the large size of the induced current. The additive effects of the MHD-EMP can cause damage to unprotected civilian and military systems that depend on or use long-line cables. Small, isolated, systems tend to be unaffected.

Military systems must survive all aspects of the EMP, from the rapid spike of the early time events to the longer duration heave signal. One of the principal problems in assuring such survival is the lack of test data from actual high-altitude nuclear explosions. Only a few such experiments were carried out before the LTBT took effect, and at that time the theoretical understanding of the phenomenon of HEMP was relatively poor. No high-altitude tests have been conducted by the United States since 1963.[1]

Highlights

- HEMP is generated by electric currents in the atmosphere produced by Compton scattering of the gamma radiation from a high-altitude nuclear detonation.
- The electromagnetic waves from EMP can degrade the performance of ground and airborne systems more than 1,500 km from the burst.
- The technologies used to harden against HEMP are essentially those used in the area of electromagnetic compatibility and electromagnetic interference; they are internationally available.

The "acid test" of the response of modern military systems to EMP is their performance in simulators, particularly where a large number of components are involved. So many cables, pins, connectors, and devices are to be found in real hardware that computation of the progress of the EMP signal cannot be predicted, even conceptually, after the field enters a real system. System failures or upsets will depend upon the most intricate details of current paths and interior electrical connections, and one cannot analyze these beforehand. Threat-level field illumination from simulators combined with pulsed-current injection are used to evaluate the survivability of a real system against an HEMP threat.

The technology to build simulators with risetimes on the order of 10 ns is well known. This risetime is, however, longer than that of a real HEMP signal. Since 1986 the United States has used a new EMP standard which requires waveforms at threat levels having risetimes under a few nanoseconds.

Threat-level simulators provide the best technique for establishing the hardness of systems against early-time HEMP. They are, however, limited to finite volumes (air-

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[1] In addition to the more familiar high-yield tests mentioned above, three small devices were exploded in the Van Allen belts as part of Project Argus. That experiment was intended to explore the methods by which electrons were trapped and traveled along magnetic field lines.

craft, tanks, communications nodes) and cannot encompass an extended system. For these systems current injection must be used.

RATIONALE

HEMP can pose a serious threat to U.S. military systems when even a single high-altitude nuclear explosion occurs. In principle, even a new nuclear proliferator could execute such a strike. In practice, however, it seems unlikely that such a state would use one of its scarce warheads to inflict damage which must be considered secondary to the primary effects of blast, shock, and thermal pulse. Furthermore, a HEMP attack must use a relatively large warhead to be effective (perhaps on the order of one megaton), and new proliferators are unlikely to be able to construct such a device, much less make it small enough to be lofted to high altitude by a ballistic missile or space launcher. Finally, in a tactical situation such as was encountered in the Gulf War, an attack by Iraq against Coalition forces would have also been an attack by Iraq against its own communications, radar, missile, and power systems. EMP cannot be confined to only one “side” of the burst.

Because actual nuclear tests can no longer be performed, and because above-ground explosions have been prohibited since 1963, the only ways to determine the results of attacks utilize simulators, theoretical models, and the data from earlier U.S. nuclear tests. The integrated use of this information in computer models which can predict the HEMP environment as a function of weapon parameters and explosion geometry is a critical technology requiring protection. In contrast, basic theoretical models lacking actual test results should not be controlled.

Theoretical models of HEMP coupling to *generic* systems such as cables and antennas are of general scientific interest. Codes associated with the *generic* coupling of HEMP to systems and which do not reveal specific features of military systems and their responses, performance, and vulnerabilities to HEMP need not be controlled. These codes are similar to those used in electromagnetic compatibility and electromagnetic interference and the study of lightning. Interest in the synergism between lightning and HEMP will continue.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

The United States has been the world leader in HEMP technology since the first articles on the subject appeared in the early 1960’s. These scientific papers appeared in the open literature, which allowed the Soviet Union to become active in the field. The general consensus is that Soviet (now Russian) capabilities lag years behind those of the United States. Nonetheless, Soviet interest in pulsed-power, which began under A.D. Sakharov, should call attention to the possibility that some of the Soviet HEMP program was very closely held.

HEMP capabilities have been acquired by the European nations, including Sweden and Switzerland. Many of these countries have developed active programs that include the use of simulators operating nearly at the threat level.

Papers presented at recent unclassified conferences by participants from the countries of the former Warsaw Pact indicate that they lag significantly behind the West in both simulation and theoretical understanding.

Several foreign vendors produce equipment comparable to that available from U.S. sources. France manufactures pulse generators, field sensors, fiber-optic links, transient digitizers, and measurement systems; England manufactures 1-GHz bandwidth fiber-optic links used mainly in HEMP and conducts high-power microwave research. Switzerland and Israel have also developed test/simulation equipment of high quality.

Table 6.6-1. High-Altitude Electromagnetic Pulse (HEMP) Effects Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
System Threat Level HEMP Simulators	Generate peak electric fields exceeding 5 kV/m, risetime <10 ns, and pulse duration <1 µs over volumes that are large enough to test complete military systems.	USML XVI	None identified	Pulsers capable of delivering rates of voltage rise greater than 100 kV/ns into less than 100 ohms, or rates of current rise greater than 1 kA/ns into impedances greater than 100 ohms into a port on a system.	Substantiated computer programs and related algorithms for computing the on-test-target electric field generated by the pulser.

Table 6.6-2. High-Altitude Electromagnetic Pulse (HEMP) Effects Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
System Threat Level HEMP Simulators	Developing plane wave EM fields for horizontal and vertical polarization with peak electric field >5 kV/m, risetime <10 ns, and pulse duration <1 µs over volumes that can test complete military systems. The development of plane wave EM fields is extremely difficult. In all tests, configuration effects due to the simulation must be removed to develop the system response in a plane wave EM environment. These codes are critical for an adequate test. The use of current injection techniques adds risk because nonlinear effects due to arcing and sparking cannot be taken into acount, so results can be misleading.	Subsystems and systems that must complete their mission in the presence of the HEMP threat.	Current injection techniques, theoretical computations

SECTION 6.7—SOURCE REGION ELECTROMAGNETIC PULSE (SREMP) EFFECTS

OVERVIEW

SREMP is produced by low-altitude nuclear bursts. An effective net vertical electron current is formed by the asymmetric deposition of electrons in the atmosphere and the ground, and the formation and decay of this current emits a pulse of electromagnetic radiation in directions perpendicular to the current. The asymmetry from a low-altitude explosion occurs because some electrons emitted downward are trapped in the upper millimeter of the Earth's surface while others, moving upward and outward, can travel long distances in the atmosphere, producing ionization and charge separation. A weaker asymmetry can exist for higher altitude explosions due to the density gradient of the atmosphere.

Within the source region, peak electric fields greater than 10^5 V/m and peak magnetic fields greater than 4,000 A/m can exist. These are much larger than those from HEMP and pose a considerable threat to military or civilian systems in the affected region.

The ground is also a conductor of electricity and provides a return path for electrons at the outer part of the deposition region toward the burst point. Positive ions, which travel shorter distances than electrons and at lower velocities, remain behind and recombine with the electrons returning through the ground. Thus, strong *magnetic* fields are produced in the region of ground zero.

When the nuclear detonation occurs near to the ground, the SREMP target may not be located in the electromagnetic far field but may instead lie within the electromagnetic induction region. In this regime the electric and magnetic fields of the radiation are no longer perpendicular to one another, and many of the analytic tools with which we understand EM coupling in the simple plane-wave case no longer apply.

The radiated EM field falls off rapidly with increasing distance from the deposition region (near to the currents the EMP does not appear to come from a point source). As a result, the region where the greatest damage can be produced is from about 3 to 8 km from ground zero. In this same region structures housing electrical equipment are also likely to be severely damaged by blast and shock. According to the third edition of *The Effects of Nuclear Weapons,* by S. Glasstone and P. Dolan, "the threat to electrical and electronic systems from a surface-burst EMP may extend as far as the distance at which the peak overpressure from a 1-megaton burst is 2 pounds per square inch."

One of the unique features of SREMP is the high late-time voltage which can be produced on long lines in the first 0.1 second. This stress can produce large late-time currents on the exterior shields of systems, and shielding against the stress is very difficult. Components sensitive to *magnetic* fields may have to be specially hardened.

Highlights

- SREMP is generated by electric currents produced by ionizing radiation from nuclear bursts below 20 km in altitude and can be effective within a radius of 3 to 8 km from the burst point, depending on weapon yield.
- SREMP adversely affects communications facilities and power grids and may be effective against electronic systems in blast-hardened targets such as missile launchers.
- It is difficult to simulate SREMP because the electromagnetic and radiation environments must be produced simultaneously.

SREMP effects are uniquely nuclear weapons effects.

RATIONALE

During the Cold War, SREMP was conceived primarily as a threat to the electronic and electrical systems within hardened targets such as missile launch facilities. Clearly, SREMP effects are only important if the targeted systems are expected to survive the primary damage-causing mechanisms of blast, shock, and thermal pulse.

Because SREMP is uniquely associated with nuclear strikes, technology associated with SREMP generation has no commercial applications. However, technologies associated with SREMP measurement and mitigation are commercially interesting for lightning protection and electromagnetic compatibility applications. Only those aspects of SREMP involving intense ionizing radiation or extremely large current pulses are militarily critical.

Basic physics models of SREMP generation and coupling to generic systems, as well as numerical calculation, use unclassified and generic weapon and target parameters. However, codes and coupling models which reveal the response and vulnerability of current or future military systems are militarily critical.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

Several NATO countries including the UK, France, and Germany can perform the calculations of the SREMP environment and coupling to systems. More extensive capabilities for SREMP testing exist in Russia, France, and the UK.

Table 6.7-1. Source Region Electromagnetic Pulse (SREMP) Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Source Region Electromagnetic Pulse(SREMP) Simulators	Systems that can generate simultaneously a radiation environment that exceeds 10^9 rad(Si)/s, and an electromagnetic environment for a nuclear weapon detonation ≤ 5 km in altitude.	USML XVI	None identified	Current generators that produce an action $>2 \times 10^7$ A^2-s, or currents that exceed 20 kA, or rates of current change $>2 \times 10^{10}$ A/s; current generators that simulate SREMP induced long line currents at high voltages with the following combined characteristics: load current $>2 \times 10^4$ A, load voltage >100 kV, FWHM greater than or equal to 30 microseconds.	None identified

Table 6.7-2. Source Region Electromagnetic Pulse (SREMP) Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Source Region Electromagnetic Pulse (SREMP) Simulators	Substantiated computer codes and related algorithms that can predict the SREMP waveform and coupling to military systems.	Military systems and subsystems that must operate in the SREMP threat environment.	Substantiated computer codes and algorithms for predicting SREMP that include: neutron inelastic scattering and capture, radiation induced electric properties of fireballs; models of electrical discharges in soil

SECTION 6.8—PULSED-POWER NUCLEAR WEAPONS EFFECTS SIMULATION

OVERVIEW

The large amount of commonality among the various pulsed-power schemes used to simulate TREE, HEMP, and SREMP makes it reasonable to discuss those technologies in a single subsection. However, the enormous amount of detail required to discuss even one technology thoroughly means that this section can only sketch the machines used to produce, tailor, and control the physical processes which produce the effects.

Radiation, as commonly used in the nuclear weapons arena, applies to neutrons, gamma rays, and x-rays alike. It can also include high-energy beta particles (electrons). All of these types of radiation show corpuscular behavior when interacting with matter—the high-energy photons because of their extremely short wavelength. Describing these interactions quantitatively requires the full machinery of relativistic quantum mechanics including the computation of the relevant Feynman diagrams.

The particle energies involved range from the upper energy limit of the ultraviolet band, 0.124 keV, to the MeV and tens of MeV associated with the gamma rays and neutrons emitted from a fissioning or fusioning nucleus. Figure 6.8-1 shows the nuclear effects and the radiation sources for simulation.

Figure 6.8-1. Simulation of Nuclear Effects Using Pulsed-Power Radiation Sources

Nuclear Effect	Radiation Sources for Simulation
TREE	gamma rays, hard x-rays, neutrons
SGEMP	gamma rays, hard x-rays
SREMP	gamma rays
IEMP (internal EMP)	gamma rays, hard x-rays
Thermomechanical shock (TMS)	soft x-rays, electrons, ions
Thermostructural shock (TSR)	soft x-rays, ions

The distinction between x-rays and gamma rays is not fundamentally based on photon energy. Normally, one speaks of gamma rays as having energies between 10 keV and 10 MeV and thinks of even hard x-rays as having lower energies. In fact, the difference between the two phenomena lies in their origin: gamma rays are produced in nuclear reactions while x-rays are an atomic phenomenon produced by electron transitions between discrete atomic levels or by blackbody (thermal) radiation from a heated object. A reasonable upper bound for “x-ray energy” in discussing nuclear phenomenology would be a few hundred keV, associated with the initial stages of fireball formation.

The upper limit to the frequency of the electromagnetic radiation attributed to HEMP is in the range of a few GHz. Thus, the interactions of the HEMP pulse with systems can be computed using classical electromagnetic theory without the need to include quantum effects.

Off-the-shelf equipment suffices for the simulation of HEMP in small volumes. The peak electric field is about 50 kV/m, with a pulse width of several nanoseconds. However, producing equivalent fields over an entire military system such as a tank requires a very large radiating system with feed-point driving voltages in the megavolt range. The combination of antenna feed-point voltage and nanosecond rise time is what gives rise to the connection between HEMP pulsed-power technology and the technology needed to produce appropriate gamma- and x-rays.

The production of pulses of neutrons corresponding to those generated by a nuclear weapon is primarily of interest for simulating TREE.

Flash x-ray (FXR) techniques are used to produce hard and soft x-rays. Typically, a high-energy electron beam is dumped onto a target to produce *bremsstrahlung* (“breaking radiation”) photons over a broad range of energies up to the kinetic energy of the incident particles. Calculating the actual spectrum produced in a given target is difficult because thick targets, in which the electrons may interact several times, are

Highlights

- Pulsed-power technologies are critical to the simulation of NWE caused by gamma rays, x-rays, neutrons, SREMP, and HEMP.
- Many of the identified energy storage, pulse formation, and switching techniques are relevant for particle accelerators, possible thermonuclear power production, particle-beam weapons, and laser weapons.
- Some of the identified pulsed-power techniques are also used in the design and testing of civilian power distribution systems.
- Pulsed-power generators for NWE simulation are very expensive.

required to obtain the desired intensities. This, in turn, raises the importance of nonlinear terms. Ideally, an FXR device should produce the same photon spectrum distributed identically over time as the spectrum from a nuclear device. This is not possible at the present time, but existing simulators provide useful approximations.

Specific technologies used to provide the power pulse include the Z-pinch; Blumlein or coaxial cable pulse-forming and transmission lines; large banks of very high-quality, low-loss capacitors; fast opening and closing gas and liquid switches with very low resistance in the closed state; Marx generators to produce the actual high-voltage pulse, and even Van de Graaff electrostatic generators with high current (for the class of accelerator) output.

The switches used are unusual and have few other uses. One, for example, must conduct with a low resistance over a period of 0.4 to 1.0 microsecond, but must open to a high resistance state in times of the order of 10 ns.

RATIONALE

Pulsed-power generating and conditioning systems and their associated loads (e.g., vacuum diodes) which convert the pulsed system's electrical output pulse to a photon or particle beam are valuable tools to study the hardness and survivability of critical military systems. The required fidelity of the simulation *increases* as the size of tested hardware increases because it is important to maintain the correct conditions over the aggregate of components which must function together. Some aspects of systems used in simulators are unclassified, and some border on the classified world. Some devices which may be used to simulate nuclear effects (e.g., the National Ignition Facility to be built at Livermore, or the Particle Beam Fusion Accelerator operating at Sandia National Lab) are also important research tools for the broader scientific community.

Of particular importance are NWE simulators that can produce pulses with peak power greater than 25 TW from sources with impedance <0.1 ohm and having vacuum power flow and conditioning that can couple to a radiating load having a circular area less than 500 cm^2. These performance levels exceed the publicly available figures for the SATURN and HERMES III accelerators at Sandia National Laboratory.

FOREIGN TECHNOLOGY ASSESSMENT (See Figure 6.0-1)

Russia has demonstrated strong NWE simulation capabilities, comparable to those of the United States. The UK and France have extensive programs, but less ambitious than Russia's. China has an NWE simulation program, but little is known about its capabilities. Germany has always been a leader in pulsed-power conditioning for basic research applications.

Pulsed-power conditioning has been developed in Sweden, primarily to support kinetic energy and particle beam weapons research; in Switzerland, to investigate protection against EMP; and in Israel, primarily for basic research at the Weizmann Institute of Science and for kinetic-energy weapons research at Israel's SOREQ Nuclear Research Center. Germany and Japan use similar technology primarily in support of light ion beams for inertial confinement fusion.

For HEMP simulation, the principal advanced technologies developed in the United States for risetimes less than 2 ns are multiple channel gas switches and multistage circuits in which the last stage charges very rapidly to increase the breakdown field of the output switch and decrease its inductance. The existence of triggered multichannel switches and the use of multistage circuits has been reported widely, but not in the context of EMP simulations. Countries with substantial pulsed-power capabilities (e.g., the UK, France, Russia, and Japan) could easily develop EMP simulators using such technologies.

Table 6.8-1. Pulsed-Power Nuclear Weapons Effects Simulation Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Production, and Inspection Equipment	Unique Software and Parameters
Plasma Radiation Sources for Soft x-Ray Effects Simulation	X-rays under 15 keV produced by Z-pinches or other devices that can be used to approximate the soft x-ray spectrum produced by a high altitude nuclear detonation.	USML XVI	None identified	None identified	None identified
Bremsstrahlung Sources for Hard x-Ray and Gamma Ray Simulation	X-rays produced by electrons with energies >100 keV hitting a high-Z target, and can approximate either the gamma rays or hard x-rays generated by a nuclear detonation.	USML XVI	None identified	None identified	None identified
Neutron Beam Sources for Simulation	Neutron beam sources capable of generating $>10^{13}$ neutrons/ sq-cm that approximate the spectrum generated by either a fission or fusion device.	USML XVI	None identified	None identified	None identified
Ion Beam Sources for Soft x-Ray Simulation	Ion beam sources that can be used to approximate the soft x-ray deposition in materials generated by a nuclear detonation.	USML XVI	None identified	None identified	None identified
Vacuum Power Flow	Transport electrical power to a vacuum load at levels >2.5 TW.	USML XVI	None identified	None identified	None identified

Table 6.8-2. Pulsed-Power Nuclear Weapons Effects Simulation Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Plasma Radiation Sources for Soft x-Ray Effects Simulation	Development of: sources >40 kJ using 1–10 keV x-rays and >.5 kJ using 5–20 keV x-rays in under 100 ns over an area >1 sq. cm; debris mitigation techniques; x-ray optic components with reflectivity >20%; methods for collecting and focusing x-rays.	All military systems that must survive the soft x-ray threat	Substantiated computer programs and related algorithms that can predict the effects of soft x-ray penetration in materials; magnetic flyer plate or high explosive simulators.
Bremsstrahlung Sources for Hard x-Ray and Gamma Ray Simulation	Development of: electron beam currents >2.5 MA in rise or fall time <100 ns, an assembly of multiple-series diodes and components capable of operation at power levels >0.6 TW; debris shields that maintain a vacuum seal over areas >10 sq. cm.	All military systems that must survive the gamma ray or hard x-ray threat	Substantiated computer programs and related algorithms that can predict the effects of hard x-ray penetration in materials.
Neutron Beam Sources for Simulation	Neutron sources that can generate the required fluence and energy spectrum over a large area in under 10 ms.	All military systems that must survive the neutron irradiation threat	Substantiated computer programs and related algorithms that can predict the effects of neutron penetration in materials.
Ion Beam Sources for Soft x-Ray Simulation	Match ion beam energy deposition profile in various materials.	All military systems that must survive the soft x-ray threat	Substantiated computer programs and related algorithms that can predict the effects of ion beam penetration in materials.
Vacuum Power Flow	Transporting and conditioning the electrical power through the vacuum interface and vacuum region to a vacuum load at power levels >2.5 TW.	None identified	None identified

APPENDIX A
1996 DOD MCTL MASTER LOCATOR

APPENDIX A
DoD MCTL MASTER LOCATOR*

MCTL Parts

This master locator lists the 18 MCTL technology sections for Part I and their included technology areas and indicates for Parts II and III where supporting data are located. The Locator also lists additional technology areas which are addressed only for Parts II and III. A short description of the three MCTL parts is shown below.

Part I *Weapons Systems Technologies (WST)*
Contains a list of technologies critical to the development and production of superior weapons.

Part II *Weapons of Mass Destruction (WMD) Technologies*
Contains a list of technologies required for development, integration, or employment of nuclear, biological, or chemical weapons and their means of delivery.

Part III *Developing Critical Technologies (DCT)*
Contains a list of technologies which, when fully developed and incorporated into a military system, will produce increasingly superior performance or maintain a superior capability more affordably.

	PART		
	I WST	II WMD	III DCT
AERONAUTICS SYSTEMS TECHNOLOGY			
Advanced Concept Turbine Engines			X
Aircraft, Fixed Wing	1.1	1.4	X
Aircraft, Rotary Wing			X
Air Vehicles, Unmanned		1.3	X
Full Authority Digital Electronic Controls (FADEC)			X
Gas Turbines Engines	1.2		X
Guidance, Navigation, and Controls		1.4	X
Human (Crew) Systems Interfaces	1.3		X
Ramjet and Scramjet		1.3	X
Systems Integration		1.3,1.4	X
Test Facility, Propulsion System			X

	PART		
	I WST	II WMD	III DCT
ARMAMENTS AND ENERGETIC MATERIALS TECHNOLOGY			
Air-Dispersed Explosives Systems			X
Ammunition, Small and Medium Caliber	2.1		X
Ballistic Missiles		1.1, .2	X
Bombs, Warheads, and Large-Caliber Projectiles	2.2	1.5,3.2, 4.2	X
Cruise Missiles		1.3	X
Energetic Materials	2.3	4.2	X
Gun and Artillery Systems	2.5	1.5	X
Mines, Countermines, and Demolition Systems	2.6		X
Non-Lethal Weapons			X
Penetrators			X
Regenerative Liquid Propellant Gun			X
Safing, Arming, Firing, and Fuzing	2.4	5.7	X
Survivability, Armor and Warhead Defeat			X

***These listings are subject to change as Part III is developed. Technology areas may be added or deleted.**

		PART	
	I	II	III
	WST	WMD	DCT
BIOLOGICAL SYSTEMS TECHNOLOGY			
Biological Defense Systems	3.1	3.4	X
Biological Dispersion		3.2	
Biological Detection, Warning, and Identification	3.2	3.3	X
Biological Material Production		3.1	X
CHEMICAL SYSTEMS TECHNOLOGY			
Chemical Defense Systems	3.1	4.4	X
Chemical Dispersion		4.2	
Chemical Material Production		4.1	
Chemical Detection, Warning, and Identification	3.2	4.3	X
DIRECTED AND KINETIC ENERGY SYSTEMS TECHNOLOGY			
Coil Gun and Railgun			X
Electrothermal and Electrothermal Chemical Gun			X
High-Power Microwaves			X
Lasers, Gas Dynamic and Pulsed Electrical Atomic and Molecular			X
Lasers, High Energy Chemical	4.1		X
Lasers, High Energy Excimer			X
Lasers, High Energy Free Electron			X
Lasers, High Energy Optically Pumped Gas and Solid State			X
Lasers, High Energy Solid State			X
Lasers, High Energy Transfer			X
Lasers, Short Wavelength			X
Particle Beam, Charged			X
Particle Beam, Neutral			X
Supporting Technologies for Directed Energy (DE) Systems	4.2		X

		PART	
	I	II	III
	WST	WMD	DCT
ELECTRONICS TECHNOLOGY			
Electronic Components	5.1		X
Electronic Materials	5.2		X
Fabrication Equipment	5.3		X
General Purpose Electronic Equipment	5.4		X
Microelectronics	5.5		X
Opto-Electronics	5.6		X
ENVIRONMENT TECHNOLOGY			
Camouflage			X
Control of Combat Environment			X
Micrometerology			X
Obscurants			X
Particle Dispersion, Coagulation, Recyling, and Reverse Disposal			X
GROUND SYSTEMS TECHNOLOGY			
Advanced Diesel Engines	6.1		
Human Systems Interfaces for Ground Systems			X
Hybrid-Electric Propulsion Systems			X
Sensors for Ground Systems			X
Signature Control for Ground Systems			X
Structures for Ground Systems			X
Systems Integration for Ground Systems		1.1	X
Vetronics	6.2		X
GUIDANCE, NAVIGATION, AND VEHICLE CONTROL TECHNOLOGY			
Aircraft and Vehicle Control Systems	7.1	1.3,1.4	X
Inertial Navigation Systems and Related Components	7.2	1.1,1.2, 1.3	X
Radio and Data-Based Referenced Navigation Systems	7.3	1.1,1.3	

		PART	
	I WST	II WMD	III DCT
INFORMATION SYSTEMS TECHNOLOGY			
Command, Control, Communications, Computing Intelligence and Information Systems	8.1	2.1, .5	X
Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM)	8.2		X
High-Performance Computing	8.3		X
Human Systems Interfaces	8.4		X
Information Security	8.5	2.4	X
Intelligent Systems	8.6		X
Modeling and Simulation	8.7		X
Networks and Switching	8.8	2.6	X
Signal Processing	8.9	2.3	X
Software	8.10		X
Transmission Systems	8.11	2.2	X
INFORMATION WARFARE TECHNOLOGY			
Combat Identification			X
Electronic Attack	9.1		X
Electronic Deception			X
Electronic Protection	9.2		X
Optical Countermeasures	9.3		X
Optical Counter-Countermeasures	9.4		X
Psychological Operations			X
MANUFACTURING AND FABRICATION TECHNOLOGY			
Advanced Fabrication and Processing	10.1	5.9	X
Bearings	10.2		X
Computer-Aided Design, Manufacturing, Engineering, Test, and Maintenance			X
Metrology	10.3	1.1,5.9	X
Non-Destructive Inspection and Evaluation	10.4	1.1	X
Production Equipment	10.5	1.1	X
Robotics	10.6	5.9	X

		PART	
	I WST	II WMD	III DCT
MATERIALS TECHNOLOGY			
Armor and Anti-Armor Materials	11.1		X
Biomaterials			X
Electrical Materials	11.2		X
Magnetic Materials	11.3		X
Optical Materials	11.4		X
Signature Control Materials			X
Special Function Materials	11.6		X
Structural Materials, High Strength and High Temperature	11.5		X
MARINE SYSTEMS TECHNOLOGY			
Advanced Hull Forms			X
Human Systems Interfaces			X
Ocean Salvage and Deep-Sea Implant			X
Propulsors and Propulsion Systems	12.1		X
Signature Control and Survivability	12.2		X
Subsurface and Deep Submergence Vehicles	12.3		X
Systems Integration			X
MEDICAL TECHNOLOGY			
Advanced Field Expedient Treatment			X
Artificial Skin			X
Blood Substitute			X
Human System Monitoring and Assessment			X
Immunizations and Neutralization			X
Performance Enhancement			X

	PART		
	I	II	III
	WST	WMD	DCT
NUCLEAR SYSTEMS TECHNOLOGY			
Enrichment Feedstocks Production		5.1	
Fissile Materials Enrichment		5.2	
Heavy Water Production		5.12	
Inertial Confinement Fusion			X
Lithium Production		5.5	X
Manufacturing of Nuclear Components		5.9	X
Nuclear Fission Reactors	13.1	5.3	
Nuclear Materials Processing	13.2	5.2,5.4, 5.13	X
Nuclear-Related Materials		5.1,5.5, 5.12	X
Nuclear Weapons	13.3	5.6, 5.7	X
Nuclear Weapons Custody, Transport, and Control		5.11	X
Nuclear Weapons Development Testing	13.3	5.10	X
Nuclear Weapons Design and Development		5.6	X
Plutonium Extraction (Reprocessing)	13.2	5.4	
Radiological Weapons		5.8	X
Safing, Arming, Fuzing, and Firing		5.7	X
Tritium Production	13.2	5.13	
Uranium Enrichment Processes	13.2	5.2	
POWER SYSTEMS TECHNOLOGY			
Biological Power			X
High-Density Conventional Systems	14.1		X
Magnetohydrodynamics			X
Mobile Electric Platform Power	14.2		X
Pulsed- and High-Power Systems	14.3		X
Superconductive Power Applications			X

	PART		
	I	II	III
	WST	WMD	DCT
SENSORS AND LASERS TECHNOLOGY			
Acoustic Sensors, Air and Terrestrial Platform	15.1		X
Acoustic Sensors, Marine, Active Sonar	15.2		X
Acoustic Sensors, Marine, Passive Sonar	15.3		X
Acoustic Sensors, Marine Platform	15.4		X
Electro-Optical Sensors	15.5		X
Gravity Meters and Gravity Gradiometers	15.6		
Lasers	15.7		X
Magnetometers and Magnetic Gradiometers	15.8		X
Radar	15.10		
SIGNATURE CONTROL TECHNOLOGY	16.1	1.3,1.4	X
Manufacturing and Validation			X
Readiness and Mission Support			X
Special Materials			X
System Concept Design and Integration			X
Test and System Validation			X
SPACE SYSTEMS TECHNOLOGY			
Astronics			X
Electronics and Computers	17.1		X
Launch Vehicles for Space Systems			X
Optronics	17.2		X
Power and Thermal Management	17.3		X
Propulsion for Space Systems	17.4		X
Qualification and Testing			X
Sensors for Space Systems	17.5		X
Signature Control and Survivability			X
Structures for Space			X
Systems Integration			X

	PART		
	I	II	III
	WST	WMD	DCT
WEAPONS EFFECTS AND COUNTER-MEASURES			
Blast and Shock Effects from Nuclear Detonations		6.2	X
High-Altitude Electromagnetic Pulse (HEMP) Effects		6.6	X
High-Power Microwave Weapons Effects			X
Induced Shock Waves From Penetrating Weapons	18.1		X
Laser Weapons			X
Nuclear Effects on Electromagnetic Signal Propagation		6.5	
Nuclear Thermal Radiation Effects		6.3	X

	PART		
	I	II	III
	WST	WMD	DCT
WEAPONS EFFECTS AND COUNTER-MEASURES (cont'd)			
Particle Beam Weapons			X
Pulsed-Power Nuclear Weapons Effects Simulation		6.8	X
Source Region Electromagnetic Pulse (SREMP) Effects		6.7	X
Transient Radiation Effects in Electronics (TREE) and System-Generated Electromagnetic Pulse Effects (SGEMP)		6.4	X
Underground Nuclear Weapons Testing		6.1	

APPENDIX B
EXPLANATION OF TABLE ELEMENTS

APPENDIX B
EXPLANATION OF TABLE ELEMENTS

Table B-1. Technology Parameters

Technology	Sufficient Technology Level	Export Control Reference	Critical Materials	Unique Test, Prlduction, and Inspection Equipment	Unique Software and Parameters
Technology is defined, giving specific information necessary for the development, production, or use of a product. This includes the hardware and software necessary to achieve that purpose.	The level of technology required for a proliferant to produce entry-level WMD, delivery systems, or other hardware or software useful in WMD development, integration or use.	International and National export control references that address the technology	Critical materials associated with this technology.	Critical/unique production, testing and inspection equipment. If these items were not available for some time, it would be expected that the capability would degrade.	Unique software needed to produce, operate or maintain this technology.

Table B-2. Reference Data

Technology	Technical Issues	Military Applications	Alternative Technologies
Technology is defined, giving specific information necessary for the development, production, or use of a product. This includes the hardware and software necessary to achieve that purpose.	Technical issues that drive/ significantly influence this technology.	Military uses of this technology.	Other technologies that could accomplish this step in WMD processes.

APPENDIX C
GLOSSARY OF ACRONYMS AND ABBREVIATIONS

APPENDIX C
GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ITEM	DESCRIPTION	SECTION
A	ampere	6.3
A/s	ampere/second	6.7
ACIPS	Advanced Collective Integrated Protection System	3.4
ACM	Attitude Control Module	1.1, 1.2, 1.3
ADTS	Asynchronous Digital Transmission Systems	2.2
AG	Australia Group	All
AGL	above ground level	1.1, 1.4
AGR	Advanced Gas Reactor	5.3
Am	Americium	6.7
AS-l5s	FSU Cruise Missile	1.3
ASTM	American Society for Testing Materials	5.12
ATCC	American Type Culture Collection	3.0, 3.1
ATACMS	Army Tactical Missile System	1.5
ATM	Asynchronous transfer mode	2.2, 2.5
AVLIS	Atomic Vapor Laser Isotope Separation System	5.2
B	Biological	3.0, 3.1, 3.2, 3.3, 3.4
B/T	Biological/Toxin	3.1, 3.3
BGO	Berium Germanate	5.10
BLOS	Beyond Line-of-Sight	2.1
BLSRs	Bi-directional Line-switched Rings	2.1, 2.2, 2.5
BLU 80/B	Bigeye Weapon	4.2
BRM	Biological response modifier	3.1, 3.4
BTU	British Thermal Units	1.1, 1.4
BW	Biological Weapon(s)	3.0, 3.1, 3.2, 3.3, 3.4
BWC	Biological Weapons Convention	3.0
BWR	Boiling Water Reactor	5.3
C2I	Command, Control, and Intelligence	2.1, 2.3, 2.4, 2.5, 2.6
C3	Command, Control, and Communications	6.0, 6.2, 6.4
C3I	Command, Control, Communications, and Intelligence	2.0, 3.3
C4I	Command, control, communications, computers, and intelligence	5.11
CAD	Computer-Aided Design	2.3
CAD/CAE	Computer-Aided Design/ Computer-Aided Engineering	1.1, 1.3
CAM	Chemical Agent Monitor, Computer-Aided Manufacturing	4.3
CANDU	Canadian Deuterium Uranium (Reactor)	5.12, 5.13
CAS	Chemical Abstract Service	4.1, 4.4
CBPS	Chemically and Biologically Protected Shelter	3.4
CC	Combinatorial Chemistry	3.0
CCD	Charge Coupled Device	5.10
CCL	Commerce Control List	All
CCM	Computer-Controlled Machines	5.9
CCS	Common Channeling Signaling	2.5
CEP	circular error probable	1.1, 1.2, 1.3
CFD	Computational Fluid Dynamics	1.3, 1.4, 5.2
CHEMEX	Chemical Exchange Process	5.2, 5.5, 5.12
CID	Charged Injection Device	5.10
CMIP	Common Management Information Protocol	2.5
CMM	Coordinate Measuring Machines	5.9
CNC	Computerized Numerically Controlled	5.0, 5.9
CNM	Customer Network Management	2.5
CO	Central Office	2.2

ITEM	DESCRIPTION	SECTION
COCOM	Coordinating Committee for Multilateral Strategic Export Controls	2.5
COLEX	Column Exchange	5.0, 5.5
CONUS	Continental United States	6.6
COTS	Commercial-off-the-shelf	2.0, 2.1, 2.2, 2.3, 2.4
CPE	Customer Premises Equipment	2.1, 2.5
CPU	Central processing unit	1.3
CSUs	Channel Service Units	2.1
CT	Computed Tomography	1.1, 1.2
CTBT	Comprehensive Test Ban Treaty	2.5, 5.10, 6.1
CVD	Chemical Vapor Deposition	1.4
CW	Chemical Weapon(s)	4.0, 4.1, 4.2, 4.3, 4.4
CWC	Chemical Weapons Convention	4.0, 4.1, 4.4
D	Deuterium	5.5, 5.6, 5.13
D.C.	Direct Current	4.1, 5.5, 5.7
dB	decibel	1.3
DCE	Distributed Computing Environment	2.3
DCN	Data Communication Networks	2.5
DCS	Digital Cross-Connect Systems	2.1, 2.2
DD/DT	Deuterium Deuterium/Deuterium Tritium	5.6
DEMP	Dispersed Electromagnetic Pulse	6.6
DES	Data Encryption Standard	1.1
DF	Difluor: methyl phosphonyl difluoride	4.1
DGZs	Designated Ground Zeros	2.1
DLC	Digital Loop Carrier	2.6
DMSO	Dimethyl sulfoxide	3.2
DNA	Desoxyribonucleic acid	3.0, 3.1, 3.3
DNHR	Dynamic Non-Hierarchical Routing	2.1
DoD	Department of Defense	2.3, 5.10, 5.11
DOE	Department of Energy	5.1, 5.2
DS	Digital Signals	2.2
DS-0	Digital Signal level 0	2.2
DS-I	Digital Signal level 1 = 544 mbytes	2.2

ITEM	DESCRIPTION	SECTION
DS-N	Digital Signal Hierarchy	2.2
DSUs	Data Service Units	2.1
DT	Deuterium Tritium	5.6
e.b.b	Equivalent blackbody	6.2, 6.3
EAA	Export Administration Act	Preface
EAR	Export Administration Regulations	1.4, 2.1, 2.2, 2.3, 2.5, 4.2, 4.4
EBR-II	Experimental Breeder Reactor II	5.4
ECCM	Electronic Counter-countermeasures	4.2, 5.7
ECM	Electronic Countermeasures	4.2, 5.7, 5.9
EDM	Electrical Discharge Machines	5.9
EHF	Extremely High Frequency	6.5
ELEX	Electroexchange	5.5
EM	Electromagnetic	5.0, 5.2, 6.6, 6.7
EMIS	Electromagnetic Isotope Separation	5.0, 5.1, 5.2
EMP	Electromagnetic Pulse	5.9, 6.0, 6.1, 6.4, 6.6, 6.7, 6.8
EO	Electro-Optical	5.7
EOD	Explosive Ordinance Disposal	5.11
EOS	Equation of State	5.10
ESA	Electronic Safe and Arm	4.2
FA	Functional Areas	2.0, 2.2, 2.3, 2.4, 2.5, 2.6
FAC	Fast-Acting Closure	6.1
FID	Flame Ionization Detector	4.3
FPD	Flame Photometric Detector	4.3
FRG	Federal Republic of Germany	5.6
FSU	Former Soviet Union	1.1, 1.2, 1.3, 1.4, 1.5, 4.0, 4.1, 5.0, 6.0
FTA	Foreign Technology Assessment	All
FWHM	full width at half maximun	6.7
FXR	Flash x-ray	6.8
G-7	Group of Seven Industrial Nations	1.4
G-8	G-7 Nations plus Russia	2.1

ITEM	DESCRIPTION	SECTION
G agents	Nerve Agents	4.0, 4.1
GA	Tabun (nerve agent)	4.0, 4.1
GB	Sarin (nerve agent)	4.0, 4.1, 4.2
GC	Gas Chromatography	4.3
GD	Soman (nerve agent)	4.0, 4.1
GDP	Gross Domestic Product	5.10
GDSS	Group Decision Support System	2.3
GHz	Gigahertz (10^{+9} hertz)	1.4, 5.2, 5.10, 6.6, 6.8
GMP	Good Manufacturing Practices	3.1
GPa	Gigapascals	6.3
GPS	Global Positioning System	1.1, 1.2, 1.3, 1.4, 2.3, 6.0
GS	Girdler Sulfide	5.12
g’s	Measure of Acceleration	1.1, 1.2, 1.5
GSAC	Gas Seal Auxiliary Closure	6.1
Gy	Gray (Gy) is a unit of absorbed dose of ionizing radiation equal to 1 joule per kilogram of absorber	2.6
HDO	Singly Deuterated Water	5.12
HE	High Explosives	1.5, 5.0, 5.6, 5.10
HEMP	High-Altitude Electromagnetic Pulse	6.0, 6.6, 6.7, 6.8
HEPA	High-Efficiency Particulate Air	3.1
HEU	Highly Enriched Uranium	5.0, 5.2, 5.3, 5.5, 5.10
HF	Hydrofluoric Acid	5.1, 5.4
HLOS	Horizontal Line-of-Sight	6.1
HNO3	Nitric Acid	5.1, 5.4
HOB	Height of Burst	4.2, 5.7, 6.0, 6.2, 6.3
HSD	High Strength-to-Density	5.0, 5.2
HTO	Singly Tritiated Water	5.13
HTT	Horizontal Tunnel Tests	6.1
HVAC	Heating, ventilation, and air conditioning	2.6
HWR	Heavy Water Reactor	5.3

ITEM	DESCRIPTION	SECTION
Hz	hertz	1.1, 1.2, 1.3, 1.4, 1.5, 5.0, 5.2, 5.7
IAEA	International Atomic Energy Agency	5.0, 5.4
IC	Intelligence Community	5.0
ICBM	Intercontinental Ballistic Missiles	Introduction, 1.0, 1.1, 1.2, 5.0, 6.2
IEEE	Institute of Electrical Engineers	2.5
IM&C	Information System Management and Control	2.1, 2.5
IMS	Ion Mobility Spectrometry	3.3, 4.3
IMUs	Inertial Measurement Units	1.2, 1.3, 1.4
IND	Improvised Nuclear Device	5.11
INFOSEC	Information Security	2.4
INMS	Integrated Network Management Systems	2.5
IP	Information Processing	2.3
IR	Infrared	1.3, 1.4, 4.3, 5.7, 6.3, 6.5
IS	Information System	2.0, 2.2, 2.3, 2.4, 2.5, 2.6
ISO	International Standards Organization	2.5, 5.10
ITU	International Telecommunications Union	2.1, 2.2, 2.5
IX	Information Exchange	2.2
IXCs	Inter-exchange Carrriers	2.1, 2.5
JSLIST	Joint Service Lightweight Suit Technology	4.4
JSTARs	Joint Surveillance Target Attack Radar System	1.4
K	Kelvin temperature	5.9, 5.10, 6.2, 6.3
kA	kiloamperes	6.7
kbar	kilobar	6.3
kbps	kilobits per second	2.2
keV	kilo (thousand) electron volt	5.9, 5.9, 5.10, 5.13, 6.1, 6.3, 6.8

ITEM	DESCRIPTION	SECTION
kHz	kilohertz	1.1, 6.5
kJ	kilojoule	6.3, 6.8
km	kilometer	1.1, 1.2, 1.3, 1.5, 3.2, 4.3, 5.10, 6.5, 6.6, 6.7
kPa	kilopascal (0.00987 atmospheres)	1.1, 1.2, 6.2
kT	kilotons	5.6, 6.0, 6.2, 6.3
ktap	one thousand dyne centimeters per second	6.3
kV	kilovolt	6.6, 6.7
kV/m	thousand volts per meter	6.6, 6.8
kV/ns	thousand volts per nanosecond	6.6
kW	kilowatts	1.4, 5.2, 5.9, 6.3
L	Lithium	5.0, 5.5
LANS	Local Area Networks	2.2
LBTS	Large Blast/Thermal Simulator	6.3
LECs	Local Exchange Carriers	2.1, 2.5
LEU	Low Enriched Uranium	5.0, 5.1, 5.3
LIDAR	Light detection and ranging	3.2, 3.3, 4.3
LIHE	Light-Initiated High Explosive	6.3
LIS	Laser Isotope Separation	5.0, 5.2
LMFBR	Liquid Metal Fast Breeder Reactor	5.3
LTBT	Limited Test Ban Treaty	5.10, 6.0, 6.3, 6.5, 6.6
LWIR	long-wave infrared	6.5
m/s	meters per second	6.1
MA	mega-ampere	6.8
mA	milliamperes	1.5
MAC	Modified Auxiliary Closure	6.1
MAN/WANS	Metropolitan Area and Wide-area Networks	2.2
Mbps	Megabytes per second	2.2
MC-1	Chemical Bomb	4.2
MCTL	Militarily Critical Technologies List	All
MeV	million electron volts	5.6, 5.9, 5.13, 6.1, 6.8

ITEM	DESCRIPTION	SECTION
MHD-EMP	Magnetohydrodynamic Electromagnetic Pulse	6.6
MHz	megahertz	2.1, 5.10, 6.1
MIB	Management Information Base	2.5
MIRV	Multiple Independently Targetable Reentry Vehicles	5.0
MIS	Management Information System	2.0
ML	Munitions List (Wassenaar Arrangement)	All
MLIS	Molecular Laser Isotope Separation	5.0, 5.2
MLRS	Multiple Launch Rocket System	1.0, 1.1, 1.2, 1.5, 4.0
mm	millimeter	1.4, 1.5, 4.1, 6.2
MMD	Mass Medium Diameter	3.2
MOD	Means of Delivery (of WMD)	Introduction
MOPP	Mission-Oriented Protective Posture	3.4
MOS	Metal-Oxide Semiconductor	6.4
MPa	megapascal	5.2, 5.12, 6.2
mph	mile per hour	6.2
ms	millisecond	6.1, 6.8
MS-MS	Mass Spectrometry–mass spectrometry	4.3
MT	metric ton	5.4, 6.0, 6.3
MTBF	Mean Time Between Failures	5.2
MTCR	Missile Technology Control Regime	All
MW	megawatt	5.2, 5.3, 6.3
NATO	North Atlantic Treaty Organization	4.4, 6.0, 6.2, 6.3, 6.6, 6.7
NC	numerically controlled	1.1, 1.3, 5.9
NCP	Network Control Points	2.5
NDUL	Nuclear Dual-Use List (NSG)	Introduction, 1.1, 5.2, 5.4, 5.5, 5.6, 5.7, 5.9, 5.10, 5.12, 5.13
NE	Network Element	2.5
nm	nanometer	6.2, 6.3
NNWS	Non-Nuclear Weapons States	Appendix E

ITEM	DESCRIPTION	SECTION
NOC	Network Operations Center	2.5
NPT	Nuclear Non-Proliferation Treaty	Appendix E
NRC	Nuclear Regulatory Commission	Introduction, 5.0
ns	nanosecond	5.10, 6.1, 6.2, 6.4, 6.6, 6.8
NSG	Nuclear Suppliers Group	Introduction, 5.0, 5.13
NTL	Nuclear Trigger List (Supplement of NSG)	Introduction, 5.3
NUDET	Nuclear Denotation	6.3
NWE	Nuclear Weapons Effects	6.0, 6.1, 6.2, 6.8
NWES	Nuclear Weapons Effects Simulation	6.8
NWSs	Nuclear Weapons States	5.0
OC	Optical Carrier	2.2
OLAP	On-Line Analytical Processing	2.3
OLTP	On-Line Transaction Processing	2.3
OOT	Object-Oriented Technologies	2.3
OPSEC	Operations Security	2.4, 5.11
OTS	off-the-shelf	5.10
Pa/s	pascals per second	6.3
PALs	Permissive Action Links	5.0, 5.7
PBV	Post-Boost Vehicle	1.2
PBX	Plastic-Bonded Explosives	5.9
PC	Personal Computer	1.3, 1.4, 2.3, 5.0
PD	Photo Detectors	5.10
PINs	Personal Identification Numbers	2.4
PM	Photo Multipler	5.10
psi	pounds per square inch	1.2, 5.2, 6.1, 6.2, 6.3
PSP	Plasma Separation Process	5.2
PTT	Postal, Telephone, and Telegraph	2.5
Pu	Plutonium	5.0, 5.6
PUREX	Plutonium Uranium Recovery by Extraction	5.4
PWR	Pressurized Water Reactor	5.3

ITEM	DESCRIPTION	SECTION
QL	CW Precursor	4.1
R&D	Research and Development	1.4
rad(si)	Radiation Absorbed Dose (in Silicon)	6.4, 6.7
rads	Radiation Absorbed Dose	6.4
RaLa	Radio Lanthanum	5.10
RBMK	(Russian) High-power Pressure-tube Reactor	5.3
rcs	radar cross section	1.3, 1.4
rf	radio frequency	6.5
RMS	root-mean-square	1.4, 5.9
rpm	Revolutions per minute	1.1, 1.2
RSCAAL	Remote Sensing Chemical Agent Alarm	4.3
RV	Reentry Vehicles	1.1, 1.2, 6.2, 6.3, 6.4, 6.5
SAFF	Safing, Arming, Fuzing, and Firing	5.0, 5.7
SAW	Surface acoustic wave	3.3, 4.3
SCPE	Simplified Collective Protection Equipment	3.4
SCUD	Short-Range Missile	1.0, 1.2
SDH	Synchronous Digital Hierarchy	2.1, 2.2
SDN	Software-Defined Network	2.1, 2.2
SELT	Sheet-Explosive Loading Technique	6.3
SEU	Single-Event Upset	6.4
SGEMP	System-Generated Electromagnetic Pulse	6.0, 6.4, 6.8
SHF	Super High Frequency	6.5
SI	Système Internationale d’Unités (the International System of Units)	2.6, 5.9
SLAM	Standoff Land Attack Missile	1.3
SMNP	Simple Management Network Protocol	2.5
SMR	Specialized Mobile Radio	2.1, 2.6
SMS	System Management System	2.5
SNM	Special Nuclear Material	5.0, 5.6, 6.0
SONET	Synchronous Optical Network	2.1, 2.2, 2.5

ITEM	DESCRIPTION	SECTION
SPES	Synchronous Payload Envelopes	2.2
SPLAT	Spray Lead at Target	6.3
SREMP	Source Region Electromagnetic Pulse	6.0, 6.1, 6.7, 6.8
SS	Signaling System	2.5
STS	Stockpile to Target Sequence	5.7
T	Tritium	5.5, 5.6, 5.13
TAPS	Tunnel and Pipe Seals	6.1
TBM	Theater Ballistic Missiles	1.1, 1.2
TBP	Tri-n-butyl-phosphate	5.1, 5.4
TDD	Target Detection Device	5.7
TEL	Transporter/Erector Launcher	1.1, 1.3
TERCOM	Terrain Contour Matching	1.3
TFC	Transverse Field Compensation	4.3
TMNs	Telecommunication Management Networks	2.2, 2.5
TMS	Thermomechanical Shock	6.8
TN	Thermonuclear	5.6, 5.13
TNT	Trinitrotoluene	5.0, 5.7, 5.10, 6.2
TREE	Transient Radiation Effects on Electronics	6.0, 6.4, 6.8
TSR	Thermostructural Shock	6.8
TSS	Telecommunications System Sector	2.5
TV	Television	3.1, 5.10
TVC	Thrust Vector Control	1.2
TW	Toxin weapon; throw weight	3.1, 6.8
TWG	Technology Working Group	Introduction, 5.0
U	Uranium	5.0, 5.1
UAV	Unmanned Aerial Vehicles	1.3, 1.5, 5.8
UGT	Underground Testing	6.0, 6.1
UGWET	Underground Weapons Evaluation and Testing	6.1
UHF	Ultra High Frequency	6.5
UK	United Kingdom	All
UN	United Nations	1.1, 4.1
USAMRIID	United States Army Medical Research Institute of Infectious Diseases	3.0
USML	United States Munitions List	All
USSR	Union of Soviet Socialist Republics	3.0
UV	Ultraviolet	3.1, 6.5
V/m	volts/meter	6.7
V-A	volt-ampere	5.2
V Agents	Nerve Agents	4.0, 4.1
VCNs	Voice Communications Network	2.5
VIS	Visible	6.5
VPNs	Virtual Private Networks	2.5
VSATs	Very-Small-Aperture Terminals	2.1
VX	Nerve Agent	4.0, 4.1, 4.2, 4.3
WA	Wassenaar Arrangement	All
WA Cat	Wassenaar Arrangement—Dual-use List Category	All
WA ML	Wassenaar Arrangement—Munitions List	All
WEB	Weapons Effects Test	2.3
WMD	Weapons of Mass Destruction	Introduction, 1.0, 1.3, 1.4, 1.5, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 3.0, 5.7
WSMR	White Sands Missile Range	6.2
WST	Weapons Systems Technologies	Introduction
WWI	World War I	4.0
WWMCCS	World-Wide Military Command and Control Systems	2.6

APPENDIX D
DEFINITIONS

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DEFINITIONS

Accuracy. (*Usually measured in terms of inaccuracy*) is maximum deviation, positive or negative, of an indicated value from an accepted standard of true value.

Active. Guidance by which a missile, warhead, or projectile emits radiation (usually radio frequency) and homes in on the signal reflected from a selected target.

Active cooling. Optical components use flowing fluids in the subsurface of the optical component to remove heat from the system.

Active flight control systems. Function to prevent undesirable "aircraft" and missile motions or structural loads by autonomously processing outputs from multiple sensors and then providing necessary preventive commands to effect automatic control.

Active pixel. A minimum (single) element of the solid-state array which has a photoelectric transfer function when exposed to light (electromagnetic) radiation.

Active tooling unit. A device for applying motive power, process energy, or sensing to the workpiece.

Adaptive control. A control system that adjusts the response from conditions detected during the operation. (Reference: ISO 2806-1980.)

Additives. Substances used in explosive formulations to improve their properties.

Aircraft. A fixed-wing, swivel-wing, rotary-wing (helicopter), tilt-rotor, or tilt-wing airborne vehicle. (See also "**Civil aircraft**.")

Alkylation. A reaction that introduces an alkyl group. For CWC purposes, a phosphorus-carbon bond is produced.

Alloyed aluminide coatings. Coatings of nickel or titanium aluminides modified with other metals such as chromium.

Aluminum alloys. Alloys having an ultimate tensile strength of 190 MPa or more measured at 293 K (20 °C).

Angular position deviation. The maximum difference between angular position and the actual, very accurately measured angular position after the workpiece mount of the table has been turned out of its initial position. (Reference: VDI/VDE 2617, Draft: "Rotary tables on coordinate measuring machines.")

Antibodies. See "**Anti-idiotypic antibodies**," "**Monoclonal antibodies**," and/or "**Polyclonal antibodies**."

Anti-idiotypic antibodies. Antibodies which bind to the specific antigen binding sites of other antibodies.

Application Specific Integrated Circuit (ASIC). Preprogrammed VLSI (Very Large Scale Integrated) or LSI (Large Scale Integrated) circuit used for a specific application.

Assemblies. A number of electronic components (i.e., circuit elements, discrete components, integrated circuits, etc.) connected together to perform a specific function, replaceable as an entity and normally capable of being disassembled.

Asynchronous transfer mode (ATM). A transfer mode in which the information is organized into cells; it is asynchronous in the sense that the recurrence of cells depends on the required or instantaneous bit rate. (CCITT Recommendation L. 113.)

Australia Group. An informal international forum, chaired by Australia, that seeks to discourage and impede the proliferation of chemical and biological weapons by harmonizing national export controls on chemical materials, biological organisms, and dual-use equipment that could be used in chemical and biological weapons production.

Automatic target tracking. A processing technique that automatically determines and provides as output an extrapolated value of the most probable position of the target in real time.

Bandwidth of one voice channel. In the case of data communication equipment designed to operate in one voice channel of 3,100 Hz, as defined in CCITT Recommendation G.151.

Bar. A unit of pressure that is equal to 10^6 dynes/cm^2, or 14.5 psi (i.e., approximately sea-level atmospheric pressure).

Basic scientific research. Experimental or theoretical work undertaken principally to acquire new knowledge of the fundamental principles of phenomena or observable facts, not primarily directed towards a specific practical aim or objective.

Bias (accelerometer). An accelerometer output when no acceleration is applied.

Biocatalysts. "Enzymes" or other biological compounds which bind to and accelerate the degradation of CW agents.

Biological Agent. A microorganism, or toxin derived from it, which causes disease in humans, animals or plants, or which causes the deterioration of material.

Biopolymers. Biological macromolecules as follows: "enzymes," "antibodies," "monoclonal," "polyclonal," or "anti-idiotypic," specially designed or specially processed "receptors."

Black body. A perfect emitter (radiator) of electromagnetic radiation having a characteristic temperature that is the sole determinant of its radiated energy spectrum.

Blast. The brief and rapid movement of air, vapor, or fluid away from a center of outward pressure.

Blister agent (vesicant). An agent that burns and blisters the skin, eyes, respiratory tract, and lungs.

Blood agent. An agent that prevents the normal transfer of oxygen from the blood to body tissues.

Brilliant munition. A many-on-many munition that operates autonomously to search for, detect, identify, acquire, and attack specific classes of targets. The sensor on each munition acquires and attacks one among the class of targets, so that in a battlefield situation two munitions may attack the same target leaving others inviolate.

Bulk. A comparatively large quantity of a substance or commodity that is manufactured, shipped, and stored as such, but which is characteristically broken down into smaller lots before application or further processing.

Burnout (electronics). A type of failure that implies the destruction of a component caused by a permanent change in one or more characteristics beyond an acceptable amount.

CAD (computer-aided design). The use of a computer and computer graphics in the design of parts, products, and others.

CAE (computer-aided engineering). Analysis of a design for basic error-checking, or to optimize manufacturability, performance, and economy (for example, by comparing various possible materials or designs).

Calorie. The amount of heat required to raise the temperature of 1 gram of water from 15 °C to 16 °C at 760 mm Hg pressure.

CAM (computer-aided manufacturing). The effective utilization of computer technology in the management, control, and operations of the manufacturing facility through either direct or indirect computer interface with the physical and human resources of the company.

C3I System. See "**Integrated C3I systems**."

Camming (axial displacement). Axial displacement in one revolution of the main spindle measured in a plane perpendicular to the spindle faceplate, at a point next to the circumference of the spindle faceplate. (Reference: ISO 230.1 1986, paragraph 5.63.)

Cathodic Arc Deposition. See "**Thermal evaporation-physical vapor deposition (TE-PVD)**."

CEP. Circular Error Probable or Circle of Equal Probability. A measure of accuracy at a specific range, expressed in terms of the radius of the circle, centered on the target, in which 50 percent of the payloads impact.

Chemical Abstract Service (CAS) registry number. A unique number which links the molecular structure of a chemical with its Chemical Abstracts index name and other data. Each number designates a single substance so far as its structure has been elucidated and can be defined in terms of atoms (composition), valence bonds (structure), and stereochemistry.

Chemical laser. A "laser" in which the excited species is produced by the output energy from a chemical reaction.

Chemical vapor deposition (CVD). An overlay coating or surface modification coating process wherein a metal, alloy, "composite," dielectric or ceramic is deposited upon a heated substrate. Gaseous reactants are decomposed or combined in the vicinity of a substrate resulting in the deposition of the desired elemental, alloy or compound material on the substrate. Energy for this decomposition or chemical reaction process may be provided by the heat of the substrate, a glow discharge plasma, or "laser" irradiation.

Chemical weapons (CW). (From the CWC)

"(a) Toxic chemicals and their precursors, except where intended for purposes not prohibited under this Convention, as long as the types and quantities are consistent with such purposes;

(b) Munitions and devices, specifically designed to cause death or other harm through the toxic properties of those toxic chemicals specified in subparagraph (a), which would be released as a result of the employment of such munitions and devices;

(c) Any equipment specifically designed for use directly in connection with the employment of munitions and devices specified in subparagraph (b)." (CWC, Article II)

Chemical Weapons Convention (CWC). A multilateral treaty that bans the development, production, acquisition, stockpiling, retention, and direct or indirect transfer and use of chemical weapons. It also prohibits the use or preparation for use of CW and the assistance, encouragement, or inducement of anyone else to engage in activities prohibited by the treaty. It further requires participating states to destroy existing chemical weapons and any CW production facilities.

Chip. Micromechanical/microelectronic devices on a single substrate.

Choking agent. An agent that attacks the eyes and respiratory tract from the nose to the lungs, primarily causing pulmonary edema ("dry drowning").

Circuit element. A single active or passive functional part of an electronic circuit, such as one diode, one transistor, one resistor, one capacitor, etc.

Circumvention (electronics). A system protection technique in which detection of the onset of nuclear radiation or EMP puts a critical portion of the system in a protected condition. A system-level technique using special hardware and software for recovering from a transient upset.

Civil aircraft. Those "aircraft" listed by designation in published airworthiness certification lists by the civil aviation authorities to fly commercial civil internal and external routes or for legitimate civil, private, or business use. (See also **"Aircraft."**)

CLOS. A "command-to-line-of-sight" guided-munition system in which an operator looks through a sight, searches, detects, and acquires a target, then aims and fires a missile. Guidance commands are automatically generated at the launcher by continually comparing the aimpoint to the current missile location. Corrective commands are transmitted to the missile through a wire link between the launcher and the missile, causing the missile to fly along the line of sight between the launcher and the target (for example, the TOW missile).

Cluster tool. A set of process chambers or modules linked by a wafer transport, in a controlled environment, and with a communication system that can control sequential processing in a semiconductor fab line.

Commingled. Filament-to-filament blending of thermoplastic fibers and reinforcement fibers in order to produce a fiber reinforcement/"matrix" mix in total fiber form.

Comminution. A process to reduce a material to particles by crushing or grinding.

Common channel signaling. A signaling method in which a single channel between exchanges conveys, by means of labeled messages, signaling information relating to a multiplicity of circuits or calls and other information such as that used for network management.

Communications. The process of representing, transferring, interpreting or processing information (data) among persons, places, or machines. Communications implies a sender, a receiver, and a transmission medium over which the information travels. The meaning assigned to the data must be recoverable without degradation. (See also Telecommunications)

Communications channel controller. The physical interface which controls the flow of synchronous or asynchronous digital information. It is an assembly that can be integrated into computer or telecommunications equipment to provide communications access.

Compensation (TREE). A general category of techniques employed to divert primary and secondary photocurrents or to nullify their effects as an aid to circuit hardening against ionizing radiation.

Composite. A "matrix" and an additional phase or additional phases consisting of particles, whiskers, fibers, or any combination thereof present for a specific purpose or purposes.

Composite theoretical performance (CTP). A measure of computational performance given in millions of theoretical operations per second (MTOPS), calculated using the aggregation of "computing elements (CE)."

Compound rotary table. A table allowing the workpiece to rotate and tilt about two nonparallel axes, which can be coordinated simultaneously for "contouring control."

Computer operating area. The immediate contiguous and accessible area around the electronic computer, where the normal operating, support, and service functions take place.

Computer using facility. The end-user's contiguous and accessible facilities housing the "computer operating area" and those end-user functions which are being supported by the stated application of the electronic computer and its related equipment; *and* not extending beyond 1,500 meters in any direction from the center of the "computer operating area."

Computing element (CE). The smallest computational unit that produces an arithmetic or logic result.

Contouring control. Two or more "numerically controlled" motions operating in accordance with instructions that specify the next required position and the required feed rates to that position. These feed rates are varied in relation to each other so that a desired contour is generated. (Reference: ISO/DIS 2806-1980.)

Control. The process of steering a missile, while stabilizing it against disturbances such as wind gusts or blast, by the operation of aerodynamic surfaces, air or jet vanes, gas jets, or attitude control of rocket motors. Control subsystems respond to guidance (q.v.) signals to correct the attitude and position of a missile, and to activate power sources, servomechanisms, and other components.

Conventional unguided projectiles. Those which do not incorporate directional warheads, including warheads employing multi-point initiation to achieve focused blast/fragmentation characteristics; submunitions or submunition capacity; fuel/air explosives; provisions for increasing the range or impact velocity; kinetic energy armor penetration capability; mid-flight guidance; terminal guidance.

Correlated munition. See **"Sentient"** munition.

Corrosion-resistant steel. Steel which is AISI (American Iron and Steel Institute) 300 series or equivalent national standard steels.

Co-spray. Simultaneously but separately injecting both ceramic and metal powders/particulates into a high-temperature plasma stream to form a metal matrix composite upon solidification on a substrate.

Critical Temperature. (Sometimes referred to as the transition temperature) of a specific "superconductive" material is the temperature at which the material loses all resistance to the flow of direct electrical current.

Cruise Missile. An unmanned self-propelled guided vehicle that sustains flight through aerodynamic lift for most of its flight path and whose primary mission is to place an ordnance or special payload on a target.

Cryptanalysis. The analysis of a cryptographic system or its inputs and outputs to derive confidential variables or sensitive data, including clear text. [ISO 7498-2-1988 (E), paragraph 3.3.18.]

Cryptography. The discipline which embodies principles, means, and methods for the transformation of data in order to hide its information content, prevent its undetected modification, or prevent its unauthorized use. "Cryptography" is limited to the transformation of information using one or more secret parameters (e.g., crypto variables) or associated key management.

Cryptomaterial. All material including documents, devices, equipment, and apparatus essential to the encryption, decryption, or authentication of telecommunications. When classified, it is designated CRYPTO and subject to special safeguards.

CWC Schedules. In the CWC, the three categories into which toxic chemicals and their precursors are divided based on the threat the chemicals/precursors pose to the purpose and objectives of the Treaty and the extent of their commercial use.

Cyanation. A reaction in which a cyanide group is added. For CWC purposes, a cyanide group is bonded to a phosphorus atom.

Data device. Equipment capable of transmitting or receiving sequences of digital information.

Designed or modified. Equipment, parts, components, or software that, as a result of "development or modification," have specified properties that make them fit for a particular application. The designed or modified equipment, parts, components, or software can be used for other applications. For example, a titanium-coated pump designed for a missile can be used with corrosive fluids other than propellants. (MTCR.)

Detonation (high-explosive). A violent chemical reaction with a chemical compound or mechanical mixture evolving heat and pressures.

Detonation, nuclear. A nuclear explosion resulting from fission or fusion reactions in nuclear materials, such as that from a nuclear weapon.

Developing Critical Technologies. Technologies which when fully developed and incorporated into a military system will produce increasingly superior performance or maintain a superior capability more affordably.

Digital computer. Equipment which can, in the form of one or more discrete variables, accept data, store data or instructions in fixed or alterable writable storage devices, process data by means of a stored sequence of instructions which is modifiable, and provide output of data.

Digitizing rate. The rate (in samples per second) at which the acquired signal can be converted to digital information.

Discrete component. A separately packaged circuit element with its own external connection.

Dose, absorbed. The amount of energy imparted by nuclear (or ionizing) radiation to unit mass of absorbing material. The unit is the rad. In current usage, the rad unit has been replaced by the SI unit, the gray (Gy) [1 Gy = 100 rads].

Doppler. The special radiation line broadening attributable to the motion of the source or of the target, and sensed by detection and tracking systems.

Drift. Environmental or thermal effects on response of a machine or device to gradually move away from the desired response.

Drift rate (gyro). The time rate of output deviation from the desired output. It consists of random and systematic components and is expressed as an equivalent input angular displacement per unit time with respect to inertial space.

Dynamic adaptive routing. Automatic rerouting of traffic based on sensing and analysis of current actual network conditions.

Dynamic signal analyzers. "Signal analyzers" which use digital sampling and transformation techniques to form a Fourier spectrum display of the given waveform including amplitude and phase information. (See also **"Signal analyzers."**)

Electron Beam PVD. See **"Thermal evaporation-physical vapor deposition (TE-PVD)."**

Electronically steerable phased array antenna. An antenna which forms a beam by means of phase coupling; i.e., the beam direction is controlled by the complex excitation coefficients of the radiating elements, and the direction of that beam can be varied in azimuth or in elevation, or both, by application, both in transmission and reception of an electrical signal.

End-effectors. "End-effectors" include grippers, "active tooling units" and any other tooling that is attached to the baseplate on the end of a "robot" manipulator arm.

Energetic materials. A collective term for military high explosives, propellants, and pyrotechnics, which is synonymous with the term "military explosives" (the preferred NATO/COCOM usage). Although the term has been adopted by some also to cover commercial explosives, it is used in the MCTL only to refer to military technology.

Ensembling. A process to improve clock performance by using multiple clocks and to improve reliability by redundancy, self-monitoring, or reduction of signal perturbations.

Enzymes. "Biocatalysts" for specific chemical or biochemical reactions.

Equivalent density. The mass of an optic per unit optical area projected onto the optical surface.

Expression vectors. Carriers (e.g., plasmid or virus) used to introduce genetic material into host cells.

Fast select. A facility applicable to virtual calls which allows data terminal equipment to expand the possibility to transmit data in call set-up and clearing "packets" beyond the basic capabilities of a virtual call.

Fault tolerance. The capability of a computer system, after any malfunction of any of its hardware or "software" components, to continue to operate without human intervention, at a given level of service that provides continuity of operation, data integrity and recovery of service within a given time.

Fibrous and filamentary materials. These materials include continuous monofilaments; continuous yarns and rovings; tapes, fabrics, random mats and braids; chopped fibers, staple fibers and coherent fiber blankets; whiskers, either monocrystalline or polycrystalline, of any length; aromatic polyamide pulp.

Film type integrated circuit. An array of "circuit elements" and metallic interconnections formed by deposition of a thick or thin film on an insulating "substrate."

Firmware. Implementation of software in hardware circuitry or read-only memory.

Fixed. The coding or compression (e.g., cryptographic or key variables) that cannot be modified by the user.

Fixed ammunition. Ammunition rounds in which the cartridge with propellant and the loaded shell or "bullet" are all in one unit. With semifixed rounds the cartridge case is not permanently fixed to the projectile, so that zone charges within cases can be adjusted to obtain desired ranges, but each round is inserted into a weapon as a unit.

Fixed-sequence manipulation mechanisms. Automated moving devices, operating according to mechanically fixed programmed motions. The program is mechanically limited by fixed stops, such as pins or cams. The sequence of motions and the selection of paths or angles are not variable or changeable by mechanical, electronic, or electrical means.

Fluoride fibers. Fibers manufactured from bulk fluoride compounds.

Frequency agility (frequency hopping). A form of "spread spectrum" in which the transmission frequency of a single communication channel is made to change by discrete steps.

Frequency agility (radar). See **"Radar frequency agility."**

Frequency switching time. The maximum time (i.e., delay) taken by a signal, when switched from one selected output frequency to another selected output frequency, to reach a frequency within 100 Hz of the final frequency *or* an output level within 1 dB of the final output level.

Frequency synthesizer. Any kind of frequency source or signal generator, regardless of the actual technique used, providing a multiplicity of simultaneous or alternative output frequencies, from one or more outputs, controlled by, derived from, or disciplined by a lesser number of standard (or master) frequencies.

Gas atomization. A process to reduce a molten stream of metal alloy to droplets of 500-micrometer diameter or less by a high-pressure gas stream.

Gateway. The function, realized by any combination of equipment and "software," to carry out the conversion of conventions or representing, processing, or communicating information used in one system into the corresponding but different conventions used in another system.

Generic software. A set of instructions for a "stored program controlled" switching system that is the same for all switches using that type of switching system.

Geneva Protocol of 1925. A multilateral agreement that prohibits the use of poisonous gases and bacteriological weapons in war. It was opened for signature in 1925 and was ratified by the United States in 1975.

Geographically dispersed. Sensors are considered "geographically dispersed" when each location is distant from any other more than 1,500 m in any direction. Mobile sensors are always considered "geographically dispersed."

Global interrupt latency time. The item taken by the computer system to recognize an interrupt due to the event, service the interrupt, and perform a context switch to an alternative memory-resident task waiting on the interrupt.

Gray. The gray (Gy) is a unit of absorbed dose of ionizing radiation; one Gy is an absorbed dose of ionizing radiation equal to one joule per kilogram of absorber. The gray replaces the rad. One rad = 0.01 Gy.

Guidance. The data collection and command process whereby a missile or space vehicle is directed to a specified destination. Guidance subsystems may be internal or external to a missile system; may be preset, active, passive or semi-active; and function independently over initial, midcourse, and terminal phases of a flight path.

Guidance munition. A "one-on-one" munition: a specific munition engages a specific target, which is advantageous during close combat situations. An operator is required in the loop to select the target and often assist in the guidance. The munitions may be either CLOS or "terminal homing" devices.

Guidance sets. A device that integrates the data collection and command process that directs a missile or space vehicle to its target.

High Energy Laser (HEL). A laser which has an average or CW power level of nominally tens of kilowatts of power and which operates for nominally a few seconds, providing energies of 10^4 Joules or larger. When the HEL is operated in a pulsed mode, the energy is averaged over 1 second or the duration of the laser train of pulses, whichever is longer.

"Hit-to-kill". A munition system incorporating integrated seeker, guidance and control, and fuze subsystems, the warhead of which is initiated upon target impact or in close proximity thereto.

Hot isostatic densification. A process of pressurizing a casting at temperatures exceeding 375 K (102 °C) in a closed cavity through various media (gas, liquid, solid particles, etc.) to create equal force in all directions to reduce or eliminate internal voids in the casting.

Hybrid computer. Equipment which can accept and process data in both analog and digital representations *and* provide output of data.

Hybrid integrated circuit. Any combination of integrated circuit(s), or integrated circuit with "circuit elements" or "discrete components" connected to perform specific function(s), and having all of the following characteristics: containing at least one unencapsulated device; connected using typical IC production methods; replaceable as an entity; *and* not normally capable of being disassembled.

Image enhancement. The processing of externally derived information-bearing images by algorithms such as time compression, filtering, extraction, selection, correlation, convolution, or transformations between domains (e.g., fast Fourier transform or Walsh transform). This does not include algorithms using only linear or rotational transformation of a single image, such as translation, feature extraction, registration, or false coloration.

Impulse, specific. The thrust developed in burning unit weight of a propellant, corrected for standard operating and discharge pressures. Specific impulse may be measured, or they may be estimated theoretically from the thermochemical properties of propellant formulations and their decomposition products.

Impulse, total. The integral of the thrust of a rocket motor over the burning time. Other factors being equal the same total impulse can result from a small thrust over a long burn time as from a high thrust over a short burn time.

In the public domain. Means technology or software which has been made available without restrictions upon its further dissemination. (Copyright restrictions do not remove technology or software from being in the public domain.)

In-bulk. See **"Bulk."**

Inertial environmental test conditions.

(1) Input random vibration with an overall "g" level of 7.7 g rms in the first half hour and a total test duration of 1-1/2 hour per axis in each of the three perpendicular axes, when the random vibration meets the following:
  (a) A constant power spectral density (PSD) value of 0.04 g^2/Hz over a frequency interval of 15 to 1,000 Hz; and
  (b) The PSD attenuates with frequency from 0.04 g^2/Hz to 0.001 g^2/Hz over a frequency interval from 1,000 to 2,000 Hz;

(2) A roll and yaw rate of equal to or more than + 2.62 radian/s (150 deg/s); or

(3) According to national standards equivalent to (1) or (2) above.

Information security. All the means and functions ensuring the accessibility, confidentiality or integrity of information or communications, excluding the means and functions intended to safeguard against malfunctions. This includes "cryptography," "cryptanalysis," protection against compromising emanations, and computer security.

Information system. People, technologies, and machines used to capture or generate, collect, record, store, retrieve, process, display and transfer or communicate information to multiple users at appropriate levels of an organization to accomplish a specified set of functions.

Information systems. The entire infrastructure, organization, personnel, and components that collect, process, store, disseminate, and act on information.

Information warfare. Actions taken to achieve information superiority by affecting adversary information, information-based processes, information systems, and computer-based networks while defending one's own information, information-based processes, information systems, and computer-based networks.

Instantaneous bandwidth. The bandwidth over which output power remains constant within 3 dB without adjustment of other operating parameters.

Instrumented range. The specified unambiguous display range of a radar.

Integrated C3I systems. Fabricated combinations of platforms; sensors and weapons; "software" and data-processing equipment; related communications subsystems; and user-system interfaces specifically designed for the control of U.S. armed forces and weapons systems. Command, control, communications, and intelligence systems are integrated combinations of military *command information processing, communications network,* and *intelligence gathering subsystems* (including surveillance, warning, and identification subsystems) that make up the U.S. C^2I systems. These combined technologies support U.S. authorities at all echelons with the "integrated C^2I systems" that provide the timely and adequate data "required" to plan, direct, and control U.S. military forces and operations in the accomplishment of their missions.

Integrated services digital network (ISDN). A unified end-to-end digital network, in which data originating from all types of communication (e.g., voice, text, data, still and moving pictures) are transmitted from one port (terminal) in the exchange (switch) over one access line to and from the subscriber.

Interconnected radar sensors. Two or more radar sensors are interconnected when they mutually exchange data in real time.

Interpolation. The means in NC by which curved sections are approximated by a series of straight lines or parabolic segments.

Intrinsic magnetic gradiometer. A single magnetic field gradient sensing element and associated electronics, the output of which is a measure of magnetic field gradient. (See also **"Magnetic Gradiometers."**)

Ion implantation. A surface modification coating process in which the element to be alloyed is ionized, accelerated through a potential gradient, and implanted into the surface region of the substrate. This includes processes in which ion implantation is performed simultaneously with electron beam physical vapor deposition or sputter deposition.

Ion plating. A special modification of a general TE-PVD process in which a plasma or an ion source is used to ionize the species to be deposited, and a negative bias is applied to the substrate to facilitate the extraction of the species to be deposited from the plasma. The introduction of reactive species, evaporation of solids within the process chamber, and the use of monitors to provide in-process measurement of optical characteristics and thicknesses of coatings are ordinary modifications of the process.

Isostatic presses. Equipment capable of pressurizing a closed cavity through various media (gas, liquid, solid particles, etc.) to create equal pressure in all directions within the cavity.

K-factor. A standard method for expressing the surface hardness and finish of a machined gear tooth.

Laser. An assembly of components which produce both spatially and temporally coherent light that is amplified by stimulated emission or radiation.

Latch-Up Free. A device or an integrated circuit which does not have an intentional or non-intentional four-layer p-n-p-n structure. For example, integrated circuits properly fabricated on silicon on insulator (SOI) substrates would be latch-up free.

Linearity. (Usually measured in terms of non-linearity) is the maximum deviation of the actual characteristics (average of upscale and downscale readings), positive or negative, from a straight line so positioned as to equalize and minimize the maximum deviations.

Line of sight. Guidance by which the missile, warhead, or projectile is commanded to follow a trajectory that will cause it to intercept a target in a direction defined by a target tracker. The method requires two-way communication with the missile, warhead, or projectile either by means of an IR, RF, wire, or fiber-optic link.

Local area network. A data communication system which allows an arbitrary number of independent "data devices" to communicate directly with each other *and* is confined to a geographic area of moderate size (e.g., office building, plant, campus, warehouse).

Mach number. The ratio of the speed of an object to the speed of sound in the surrounding medium.

Magnetic gradiometers. Instruments designed to detect the spatial variation of magnetic fields from sources external to the instrument. They consist of multiple "magnetometers" and associated electronics, the output of which is a measure of magnetic field gradient. (See also **"Intrinsic magnetic gradiometer."**)

Magnetometers. Instruments designed to detect magnetic fields from sources external to the instrument. They consist of a single magnetic field sensing element and associated electronics, the output of which is a measure of the magnetic field.

Main storage. The primary storage for data or instructions for rapid access by a central processing unit. It consists of the internal storage of a "digital computer" and any hierarchical extension thereto, such as cache storage or non-sequentially accessed extended storage.

Maraging steels. A special class of high-strength, low-carbon, nickel-alloy steels, wherein the high strength (greater than 1,030 MPa) is derived from age hardening or precipitation of intermetallic compounds in the grain structure and does not involve carbon. These steels typically contain no less than 10 percent nickel; no more than 0.03 percent carbon; and Co, Mo, Ti, and Al, as alloying elements.

Mass fraction. The ratio of the weight of the propellant to the weight of the loaded rocket. The larger the ratio the longer the range of the rocket.

Matrix. A substantially continuous phase that fills the space between particles, whiskers, or fibers.

Maximum bit transfer rate. Of a disk drive or solid-state storage device: the number of data bits per second transferred between the drive or the device and its controller.

Measurement uncertainty. The characteristic parameter that specifies in what range around the output value the correct value of the measurable variable lies with a confidence level of 95 percent. It includes the uncorrected systematic deviations, the uncorrected backlash, and the random deviations. (Ref.: VDI/VDE 2617.)

Mechanical alloying. An alloying process resulting from the bonding, fracturing and rebonding of elemental and master alloy powders by mechanical impact. Non-metallic particles may be incorporated in the alloy by the addition of the appropriate powders.

Mechanically controlled variable sequence manipulation mechanisms. Automated moving devices, operating according to mechanically fixed programmed motions. The program is mechanically limited by fixed, but adjustable, stops such as pins or cams. The sequence of motions and the selection of paths or angles are variable within the fixed program pattern. Variations or modifications of the program pattern (e.g., changes of pins or exchanges of cams) in one or more motion axes are accomplished only through mechanical operations.

Media access unit. Equipment which contains one or more communication interfaces ("network access controller," "communications channel controller," modem, or computer bus) to connect terminal equipment to a network.

Median Lethal Dosage (vapor/aerosol, LCt_{50}). The amount of agent (vapor, aerosol) expected to kill 50 percent of exposed, unprotected people.

Median Lethal Dose (liquid, LD_{50}). The single dose of a substance that causes death of 50 percent of a population from exposure to the substance by any route other than inhalation.

Melt extraction. A process to "solidify rapidly" and extract a ribbon-like alloy product by the insertion of a short segment of a rotating chilled block into a bath of a molten alloy.

Melt spinning. A process to "solidify rapidly" a molten metal stream impinging upon a rotating chilled block, forming a flake, ribbon or rod-like product.

Microcomputer microcircuit. A "monolithic integrated circuit" or "multichip integrated circuit" containing an arithmetic logic unit capable of executing general-purpose instructions from an internal storage on data contained in the internal storage. (The internal storage may be augmented by an external storage.)

Microprogram. A sequence of elementary instructions, maintained in a special storage, the execution of which is initiated by the introduction of its reference instruction into an instruction register.

Militarily critical technologies. Technologies, the technical performance parameters of which are at or above the minimum level necessary to ensure continuing superior performance of U.S. military systems.

Military high explosives. Solid, liquid, or gaseous substances or mixtures of substances which are required to detonate in their application as primary, booster, or main charge in warhead, demolition, and other military applications.

Military propellants. Solid, liquid, or gaseous substances or mixtures of substances used for propelling projectiles and missiles or to generate gases for powering auxiliary devices for embargoed military equipment and which, when ignited, burn or deflagrate to produce quantities of gas capable of performing work; but in their application these quantities are required not to undergo a deflagration- to-detonation transition.

Military pyrotechnics. Mixtures of solid or liquid fuels and oxidizers which, when ignited, undergo an energetic chemical reaction at a controlled rate intended to produce specific time delays, or quantities of heat, noise, smoke, visible light, or infrared radiation. Pyrophorics are a subclass of pyrotechnics which contain no oxidizers but ignite spontaneously on contact with air.

Minimum smoke. A descriptive term used for propellants that produce the least amount of smoke under specified conditions. The term is difficult to quantify, but AGARD identifies these as class AA propellants.

Mirrors. Reflective optical elements.

Monoclonal antibodies. Proteins which bind to one antigenic site and are produced by a single clone of cells.

Monolithic integrated circuit. A combination of passive or active "circuit elements" or both which are formed by means of diffusion processes, implantation processes or deposition processes in or on a single semiconducting piece of material, a so-called "chip;" can be considered as indivisibly associated *and* perform the function(s) of a circuit.

Most immediate storage. The portion of the "main storage" most directly accessible by the central processing unit:

a. For single level "main storage," the inertial storage; or

b. For hierarchical "main storage," the cache storage; the instruction stack; or the data block.

Motion control board. An electronic assembly of a number of connected electronic components (i.e., "circuit element," "discrete components," integrated circuits, etc.), specially designed to provide a computer system with the capability to coordinate simultaneously the motion of axes of machine tools for "contouring control."

Multichip integrated circuit. Two or more "monolithic integrated circuits" bonded to a common "substrate."

Multi-data-stream processing. The "Microprogram" or equipment architecture technique which permits simultaneous processing of two or more data sequences under the control of one or more instruction sequences by means such as:

Single Instruction Multiple Data (SIMD) architectures such as vector or array processors;

Multiple Single Instruction Multiple Data (MSIMD) architectures;

Multiple Instruction Multiple Data architectures, including those which are tightly coupled, closely coupled or loosely coupled; or

Structured arrays of processing elements, including systolic arrays.

Multilevel security. A class of system containing information with different sensitivities that simultaneously permits access by users with different security clearances and needs-to-know, but prevents users from obtaining access to information for which they lack authorization.

Multiple transverse mode. Any laser, the average divergence of which is larger than that allowed for a "single transverse mode" laser will be considered to be multimode.

Multispectral imaging sensors. Sensors capable of simultaneous or serial acquisition of imaging data from two or more discrete spectral bands. Sensors having more than 20 discrete spectral bands are sometimes referred to as hyperspectral imaging sensors.

Nerve agent. Extremely toxic compounds that produce convulsions and rapid death by inactivating an enzyme (acetylcholinesterase) essential for the normal transmission of nerve impulses.

Network access controller. A physical interface to a distributed switching network. It uses a common medium which operates throughout at the same "digital transfer rate" using arbitration (e.g., token or carrier sense) for transmission. Independently from any other, it selects data packets or data groups (e.g., IEEE 802) addressed to it. It is an assembly that can be integrated into computer or telecommunications equipment to provide communications access.

Neural computer. A computational device designed or modified to mimic the behavior of a neuron or a collection of neurons; i.e., a computational device which is distinguished by its hardware capability to modulate the weights and numbers of the interconnections of a multiplicity of computational components based on previous data.

Neural networks. Computational devices designed to emulate in a simplistic manner the computational processes of the brain by utilizing a variety of simple computational devices (artificial neurons) arranged in large networks that can be trained.

Noble metal modified aluminide. Nickel or titanium aluminide modified with noble metals such as platinum or rhodium.

Noise level. An electrical signal given in terms of power spectral density. Th relation between "noise level" expressed in peak-to-peak is given by $S^2_{pp} = 8N_o(f_2 - f_1)$, where S_{pp} is the peak to peak value of the signal (e.g., nanoteslas), N_o is the power spectral density [e.g., (nanotesla)2/Hz] and $(f_2 - f_1)$ defines the bandwidth of interest.

Non-servo-controlled variable sequence manipulation mechanisms. Automated moving devices operating according to mechanically fixed programmed motions. The program is variable but the sequence proceeds only by the binary signal from mechanically fixed electrical binary devices or adjustable stops.

Nuclear reactor. Includes the items within or attached directly to the reactor vessel, the equipment which controls the level of power in the core, and the components which normally contain or come into direct contact with or control the primary coolant of the reactor core.

Numerical control. The automatic control of a process performed by a device that makes use of numeric data usually introduced as the operation is in progress. (Reference: ISO 2382.)

Object code (or object language). The machine-readable code. (See also **"Source code."**)

Obscurant. A substance or radiation absorber that blocks the radiation emitted from a target, thereby preventing the continuous tracking or detection of the target.

Observable. The parameters (such as distance, speed, or shape) of a vehicle that can be seen optically, electronically, magnetically, acoustically, or thermally.

One-point safe. A nuclear weapon is one-point safe if there is a probability of less than one part in a million of a nuclear energy release greater than or equal to 4 pounds TNT equivalent when the high explosives are detonated at the single point most likely to produce nuclear yield.

Operate autonomously. Refers to the ability of a vehicle to move between two or more known locations without the need for human intervention.

Operate-through. The ability of an electronic system to function without major degradation during transient nuclear events.

Optical amplification. In optical communications, an amplification technique that introduces a gain of optical signals that have been generated by a separate optical source without conversion to electrical signals (i.e., using semiconductor optical amplifiers, optical fiber luminescent amplifiers).

Optical computer. A computer designed or modified to use light to represent data and with computational logic elements based on directly coupled optical devices.

Optical fiber preforms. Bars, ingots, or rods of glass, plastic, or other materials which have been specially processed for use in fabricating optical fibers. The characteristics of the preform determine the basic parameters of the resultant drawn optical fibers.

Optical integrated circuit. A "monolithic integrated circuit" or a "hybrid integrated circuit" containing one or more parts designed to function as a photosensor or photoemitter or to perform (an) optical or (an) electro-optical function(s).

Optical switching. The routing of or switching of signals in optical form without conversion to electrical signals.

Overall current density. The total number of ampere-turns in the coil (i.e., the sum of the number of turns multiplied by the maximum current carried by each turn) divided by the total cross section of the coil (comprising the superconducting filaments, the metallic matrix in which the superconducting filaments are embedded, the encapsulating material, any cooling channels, etc.).

Pack cementation. Any surface modification coating or overlay coating process wherein a substrate is immersed in a powder mixture (a pack) that consists of:

(1) The metallic powders that are to be deposited (usually aluminum, chromium, silicon, or combinations thereof);

(2) An activator (normally a halide salt); *and*

(3) An inert powder, most frequently alumina.

The substrate and powder mixture are contained within a retort which is heated to between 1,030 K (757 °C) to 1,375 K (l,102 °C) for sufficient time to deposit the coating.

Passive. Missile or warhead guidance by which the device homes in on the natural radiation (RF, IR, or visible) from the target. The device is autonomous, incorporating a seeker that requires no external illumination of the target

Peak power. Energy per pulse in joules divided by the pulse duration in seconds.

Plasma spraying. Any overlay coating process wherein a gun (spray torch), which produces and controls a plasma, accepts powder or wire coating materials, melts them, and propels them towards a substrate, whereon an integrally bonded coating is formed.

Polyclonal antibodies. A mixture of proteins which bind to the specific antigen and are produced by more than one clone of cells.

Positioning accuracy. Of "numerically controlled" machine tools is to be determined and presented in accordance with ISO/DIS 230/2, paragraph 2.13, in conjunction with the requirements below:

1. Test conditions (paragraph 3):
    a. For 12 hours before and during measurements, the machine tools and accuracy measuring equipment will be kept at the same ambient temperature. During the premeasurement time the slides of the machine will be continuously cycled in the same manner that the accuracy measurements will be taken;
    b. The machine shall be equipped with any mechanical, electronic, or software compensation to be exported with the machine;
    c. Accuracy of measuring equipment for the measurements shall be at least four times more accurate than the expected machine tool accuracy;
    d. Power supply for slide drives shall be as follows:
        (1) Line voltage variation shall not be greater than ±10 percent of nominal rated voltage;
        (2) Frequency variation shall not be greater than ±2 Hz of the normal frequency;
        (3) Lineouts or interrupted service is not permitted.

2. Test program (paragraph 4):
    a. Feed rate (velocity of slides) during measurement shall be the rapid traverse rate. In case of machine tools which generate optical quality surfaces, the feed rate shall be equal to or less than 50 mm per minute;
    b. Measurements shall be made in an incremental manner from one limit of the axis travel to the other without returning to the starting position for each move to the target position;
    c. Axes not being measured shall be retained at mid travel during test of an axis.
3. Presentation of test results (paragraph 2): the results of the measurements must include:
    a. "Positioning accuracy" (A); and
    b. The mean reversal error (B).

Power management. Changing the transmitted power of the altimeter signal so that received power at the "aircraft" altitude is always at the minimum necessary to determine the altitude.

Precision-guided munition. A munition equipped with a sensor that interacts with its aerodynamic control surfaces that falls into one of the following categories: "guided," "smart," or "brilliant."

Precursors. Specialty chemicals used in the manufacture of military explosives.

Primary smoke. The solid particulates from the combustion of a fuel, pyrotechnic, or propellant. Metal and elemental fuels and other additives in energetic materials or by themselves contribute significantly to primary smoke. (See **"Secondary smoke."**)

Principal element. An element is a "principal element" when its replacement value is more than 34 percent of the total value of the system of which it is an element. Element value is the price paid for the element by the manufacturer of the system, or by the system integrator. Total value is the normal international selling price to unrelated parties at the point of manufacture or consolidation of shipment.

Producibility. The elements of a design by which a product or a commodity, while meeting all of its performance objectives within the design constraints, may be produced in the shortest total time, at the lowest cost, with the most readily available materials using the most advantageous processes and assembly methods. (U.S. Army, AMC definition.)

Production. All production stages, such as product engineering, manufacture, integration, assembly (mounting), inspection, testing, and quality assurance.

Progressivity. The rate of increase of the burning rate or of the surface area of burning propellant. (See **"Propellant grain."**)

Proof test. The on-line or off-line production screen testing that dynamically applies a prescribed tensile stress over a 0.5 to 3 m length of fiber at a running rate of 2 to 5 m/s while passing between capstans approximately 15 cm in diameter. The ambient temperature is a nominal 293 K and relative humidity 40 percent.

Propellant grain. A single piece of propellant, the dimensions of which may vary from a few millimeters to several meters and are known as the configuration for single grains or the granulation for charges consisting of more than one grain. Configurations are changed to vary the exposed surface of grains and thus vary the burning surface. A grain that maintains a constant burning surface has a neutral configuration; a grain with a surface area or burning rate that increases has a progressive configuration; a grain with a burning surface that decreases has a degressive configuration.

Public domain. See **"In the public domain."**

Pulse compression. The coding and processing of a radar signal pulse of long time duration to one of short time duration, while maintaining the benefits of high pulse energy.

Pulse duration. Duration of a "laser" pulse measured at Full-Width Half-Intensity (FWHI) levels.

Pyrophorics. See **"Military Pyrotechnics."**

Q-switched laser. A "laser" in which the energy is stored in the population inversion or in the optical resonator and subsequently emitted in a pulse.

Radar frequency agility. Any technique which changes, in a pseudo-random sequence, the carrier frequency of a pulsed-radar transmitter between pulses or between groups of pulses by an amount equal to or larger than the pulse bandwidth.

Radar spread spectrum. Any modulation technique for spreading energy origination from a signal with a relatively narrow frequency band over a much wider band of frequencies, by using random or pseudo-random coding.

Real-Time. (a) In solving a problem, a speed sufficient to give an answer within the actual time the problem must be solved; (b) Pertaining to the actual time during which a physical process occurs; and (c) Pertaining to the performance of a computation during the actual time that the related physical process occurs so that results of the computation can be used in guiding the physical process.

Real-time bandwidth. For "dynamic signal analyzers," the widest frequency range the analyzer can output to display or mass storage without causing any discontinuity in the analysis of the input data. For analyzers with more than one channel, the channel configuration yielding the widest "real-time bandwidth" shall be used to make the calculation.

Real-time processing. The processing of data by a computer system providing a required level of service, as a function of available resources, within a guaranteed response time, regardless of the load of the system, when stimulated by an external event.

Real-time spectrum analyzers. See **"Dynamic signal analyzers."**

Receptors. Biological macromolecular structures capable of binding ligands, the binding of which affects physiological functions.

Reduced smoke. A descriptor for propellants that have been tailored to produce less smoke than standard formulations of aluminum and ammonium perchlorate (see **"Smoky"**). They may be classified by AGARD as either class AC or BC.

Repeatability. Closeness of agreement of repeated position movements to the same indicated location and under the same conditions.

Required. As applied to "technology," refers to only that portion of "technology" which is peculiarly responsible for achieving or exceeding the embargoed performance levels, characteristics, or functions. Such "required" "technology" may be shared by different products.

Resistive heating PVD. See **"Thermal evaporation-physical vapor deposition (TE-PVD)."**

Resolution. The least increment of a measuring device; on digital instruments, the least significant bit. (Reference: ANSI B-89.1.12.)

Riot control agents. Substances which in low concentrations produce temporarily irritating or disabling physical effects that disappear within minutes of removal from exposure. There is minimal risk of permanent injury, and medical treatment is rarely required.

Robot. A manipulation mechanism, which may be of the continuous path or of the point-to-point variety, may use sensors, and has all the following characteristics:

a. Is multifunctional;
b. Is capable of positioning or orienting material, parts, tools, or special devices through variable movements in three-dimensional space;
c. Incorporates three or more closed- or open-loop servo-devices which may include stepping motors; *and*
d. Has "user-accessible programmability" by means of the teach/playback method or by means of an electronic computer which may be a programmable logic controller, i.e., without mechanical intervention.

N.B. The above definition does not include the following devices:

1. Manipulation mechanisms which are only manually/teleoperator controllable.
2. Fixed sequence manipulation mechanisms which are automated moving devices, operating according to mechanically fixed programmed motions. The program is mechanically limited by fixed stops, such as pins or cams. The sequence of motions and the selection of paths or angles are not variable or changeable by mechanical, electronic, or electrical means.
3. Mechanically controlled variable sequence manipulation mechanisms which are automated moving devices, operating according to mechanically fixed programmed motions. The program is mechanically limited by fixed but adjustable stops, such as pins or cams. The sequence of motions and the selection of paths or angles are variable within the fixed program pattern. Variations or modifications of the program pattern (e.g., changes of pins or exchanges of cams) in one or more motion axes are accomplished only through mechanical operations.
4. Non-servo-controlled variable sequence manipulation mechanisms which are automated moving devices, operating according to mechanically fixed programmed motions. The program is variable but the sequence proceeds only by the binary signal from mechanically fixed electrical binary devices or adjustable stops.
5. Stacker cranes defined as Cartesian coordinate manipulator systems manufactured as an integral part of a vertical array of storage bins and designed to access the contents of those bins for storage or retrieval.

Rocket motor. A non-airbreathing reaction propulsion device consisting of a thrust or combustion change in which formulations of solid fuels, oxidizers, and additives are burned and expanded through an exhaust nozzle.

Rotary atomization. A process to reduce a stream or pool of molten metal droplets to a diameter of 500 micrometers or less by centrifugal force.

Run out (out-of-true running). Radial displacement in one revolution of the main spindle measured in a plane perpendicular to the spindle axis at a point on the external or internal revolving surface to be tested. (Reference: ISO 230/1-1986, paragraph 5.61).

Scale factor (gyro or accelerometer). The ratio of change in output to a change in the input intended to be measured. Scale factor is generally evaluated as the slope of the straight line that can be fitted by the method of least squares to input-output data obtained by varying the input cyclically over the input range.

S**canning spectrum analyzer.** See "**Signal analyzer.**"

Secondary smoke. Smoke that results from the interaction of propellant or pyrotechnics and water to form droplets that condense on submicron atmospheric particles. Low temperatures, high humidity, and acid vapors, such as the HCI combustion products of ammonium perchlorate, all contribute to secondary smoke formation.

Secret parameter. A constant or key kept from the knowledge of others or shared only within a group.

Seeker. A device that orients a munition's sensor to survey, acquire, lock-on, and track a target.

Semi-active. Missile or warhead guidance by which the target is illuminated by an auxiliary emitter (e.g., a laser or radar beam) and the missile or warhead homes in on the signal (reflection) from the target.

Sensor fuzed munition. A "shoot-to-kill," "smart" munition of relatively low complexity and cost, which is most effective "close-in" against targets with a narrowly defined location and for which there are small delivery errors.

Sentient (or correlated). A descriptor for a "brilliant" munition that is aware of itself and its surroundings; for example, a brilliant munition that responds to its environment, or communicates with others among the same payload or salvo to share out the targets and maximize interception.

Settling time. The time required for the output to come within 1/2 bit of the final value when switching between any two levels of the converter.

Shared aperture optical elements. Optics that reflect a portion of the impinging radiation similarly to conventional beam splitters and composed of buried lenses or buried "gratings."

Shoot-to-kill system. A sensor-fuzed munition that does not incorporate expensive seeker and guidance and control subsystems. The warhead is initiated tens of meters from the target while the munition is aimed at the target.

Signal analyzer. Apparatus capable of measuring and displaying basic properties of the signal-frequency components of multi-frequency signals.

Signal analyzers (dynamic). See "Dynamic signal analyzers."

Signal processing. The processing of externally derived information-bearing signals by algorithms such as time compression, filtering, extraction, selection, correlation, convolutions or transformations between domains (e.g., fast Fourier transform or Walsh transform).

Signature. Any or all of the properties of a gun or a rocket motor that may be used for the detection, identification, or interception of the device or its launch site. Plume signature characteristics include smoke, radiation emissions, visibility, radar absorption, self absorption, etc.

Single-transverse mode. Any laser with an average beam divergence measured on any two orthogonal axes equal to or less than 3.45 times the wavelength, divided by the aperture diameter along that axis for the angle containing 84 percent of the beam energy will be considered a single transverse mode laser.

Slurry deposition. A surface modification coating or overlay coating process wherein a metallic or ceramic powder with an organic binder is suspended in a liquid and is applied to a substrate by either spraying, dipping, or painting followed by air or oven drying and heat treatment to obtain the desired coating.

Smart materials. Materials that have the capability to respond to an external stimulus by changing, in a controlled manner according to prescribed functional relationships or control algorithms, their energy dissipation properties and geometric configuration, or by changing their stiffness.

Smart munition. A "many-on-many" munition with a minimal target selection capability that does not require an operator in the loop. There are two prime categories: terminally guided ("hit-to-kill") and sensor-fuzed ("shoot-to-kill").

Smoky. A particular term used to describe rocket and missile propellants with high aluminum and ammonium perchlorate contents. An AGARD class CC composition.

Software. Programs, data bases, and associated documentation available on human- and/or machine-readable media such as paper, magnetic tapes, disks, or embedded firmware that operate computers.

Software Documentation. Information in human-readable form, including computer source code listings and printouts, which documents the design or details of the computer software, explains the capabilities of the software, or provides operating instructions for using the software to obtain the desired results from a computer.

Software Support. Resources such as people, facilities, documentation, information, and instrumentation to operate, maintain, or produce software products.

Solidify rapidly. Solidification of molten material at cooling rates exceeding 1,000 K/sec.

Solids loading. The percentage of particulate matter in the total weight/volume of a propellant composition or grain. The solids loading attainable for a given fuel-oxidizer particulate composition depends on the binder and additives used to form a grain. Missile propellants are commonly rated in terms of a weight percentage; gun propellants, in terms of a volume percentage.

Source code (or source language). Source code, a subset of computer software documentation, is a set of symbolic computer instructions that is written in a high-level/human-readable language that cannot be directly executed by the computer without first being translated into object code.

Spacecraft. Active and passive satellites and space probes.

Space qualified. Products designed, manufactured and tested to meet the special electrical, mechanical, or environmental requirements for use in the launch and deployment of satellites or high-altitude flight systems operating at altitudes of l00 km or higher.

Spatial light modulators. Optical devices that dynamically modulate the spatial distribution of the amplitude or phase of an incident light waveform across an aperture in either a transmissive or reflective mode of operation under the control of an electronic or optical signal. "Spatial light modulators" are also known as non-linear adaptive optics.

Specific impulse (I_s). The total impulse per unit weight of propellant.

Specific modulus. Young's modulus in pascals, equivalent to N/m^2 (lb force/sq in.) divided by specific weight in N/m^3 (lb force/cu in.) measured at temperature of (296 ± 2 K; (23 ± 2) °C) and a relative humidity of (50 ± 5) percent.

Specific tensile strength. Ultimate tensile strength in pascals, equivalent to N/m^2 (lb force/sq in.) divided by specific weight in N/m^3 (lb force/cu in.) measured at a temperature of (296 ± 2) K and a relative humidity of (50 ± 5) percent.

Spectral efficiency. A figure of merit parameterized to characterize the efficiency of transmission system which uses complex modulation schemes such as QAM (quadrature amplitude modulation), Trellis coding, QPSK (Q-phased shift key), etc. It is defined as follows:

$$\text{Spectral efficiency} = \frac{\text{“Digital transfer rate” (bits/second)}}{\text{6 dB spectrum bandwidth (Hz)}}$$

Spherical Error Probable or Sphere of Equal Probability (SEP). A measure of accuracy at a specific range, expressed in terms of the radius of a sphere, centered on the target, in which 50 percent of the payloads impact.

Splat quenching. A process to “solidify rapidly” a molten metal stream impinging upon a chilled block, forming a flake-like product.

Spread spectrum. The technique whereby energy in a relatively narrow-band communication channel is spread over a much wider energy spectrum.

Spread spectrum (radar). See **“Radar spread spectrum.”**

Sputter deposition. An overlay coating process based on a momentum transfer phenomenon, wherein positive ions are accelerated by an electric field towards the surface of a target (coating material). The kinetic energy of the impacting ions is sufficient to cause target surface atoms to be released and deposited on an appropriately positioned substrate.

Sputtering. An overlay coating process wherein positively charged ions are accelerated by an electric field towards the surface of a target (coating material). The kinetic energy of the impacting ions is sufficient to cause target surface atoms to be released and deposited on the substrate.

N.B. Triode, magnetron, or radio frequency sputtering to increase adhesion of coating and rate of deposition are ordinary modifications of the process.

Stability. Standard deviation (1 sigma) of the variation of a particular parameter from its calibrated value measured under stable temperature conditions. This can be expressed as a function of time.

Stabilizers. Substances used in explosive formulations to improve their shelf life.

Stacker cranes. Cartesian coordinate manipulator systems manufactured as an integral part of a vertical array of storage bins and designed to access the contents of those bins for storage or retrieval.

Stored program control. A control using instructions stored in an electronic storage which a processor can execute to direct the performance of predetermined functions.

Strong mechanical bond. In solid rocket motors, the requirement to have a bond between the rocket propellant and the motor casing that is equal to or greater than the tensile strength of the propellant.

Substrate. A sheet of base material with or without an interconnection pattern and on which or within which “discrete components” or integrated circuits or both can be located.

Substrate blanks. Monolithic compounds with dimensions suitable for the production of optical elements such as mirrors or optical windows.

Sufficient Technology. The level of technology required for a proliferant to produce entry level WMD, delivery systems, or other hardware or software useful in WMD development integration or use.

Superalloys. Nickel-, Cobalt-, or Iron-Base alloys having strengths superior to any alloys in the AISI 300 series at temperatures of 922 K (649 °C) under severe environmental and operating conditions.

Superconductive. Materials (i.e., metals, alloys, or compounds) which can lose all electrical resistance (i.e., which can attain infinite electrical conductivity) and carry very large electrical currents without Joule heating.

Super high power laser (SHPL). A “laser” capable of delivering (the total or any portion of) the output energy exceeding 1 kJ within 50 ms or having an average or CW power exceeding 20 kW.

Superplastic forming. A deformation process using heat for metals that are normally characterized by low values of elongation (less than 20 percent) at the breaking point as determined at room temperature by conventional tensile strength testing, in order to achieve elongations during processing which are at least two times those values.

Swept frequency network analyzers. Involves the automatic measurement of equivalent circuit parameters over a range of frequencies, involving swept frequency measurement techniques but not continuous-wave point-to-point measurements.

Switch fabric. That hardware and associated “software” which provides the physical or virtual connection path for in-transit message traffic being switched.

Synchronous digital hierarchy (SDH). A digital hierarchy providing a means to manage, multiplex, and access various forms of digital traffic using a synchronous transmission format on different types of media. The format is based on the Synchronous Transport Module (STM) which is defined by CCITT Recommendation G.703, G.708, G.709, and others yet to be published. The first level rate of “SDH” is 155.52 Mbit/s.

Synchronous optical network (SONET). A network providing a means to manage, multiplex and access various forms of digital traffic using a synchronous transmission format on fiber optics. The format is the North America version of “SDH” and also uses the Synchronous Transport Module (STM). However, it uses the Synchronous Transport Signal (STS) as the basic transport module with a first level rate of 51.81 Mbit/s. The SONET standards are being integrated into those of “SDH.”

Systems tracks. Processed, correlated (fusion of radar target data to flight plan position), and updated aircraft flight position report available to the Air Traffic Control center controllers.

Systolic array computer. A computer where the flow and modification of the data are dynamically controllable at the logic gate level by the user.

Tear gases. Gases which produce temporarily irritating or disabling effects which disappear within minutes of removal from exposure.

Technical assistance. May take forms such as instruction, skills, training, working knowledge, consulting services.

N.B. "Technical assistance" may involve transfer of "technical data."

Technical data. May take forms such as blueprints, plans, diagrams, models, formulae, tables, engineering designs and specifications, manuals, and instructions written or recorded on other media or devices such as disk, tape, and read-only memories.

Technologies for weapons of mass destruction. Technologies required for development, integration, or employment of biological, chemical, or nuclear weapons and their means of delivery.

Technology. Specific information and know-how necessary for the development, production, or use of a product. This includes the hardware and software necessary to achieve that purpose.

Telecommunications. Any process that enables one or more users to pass to one or more other users information of any nature delivered in any usable form by wire, radio, visual, or other electrical, electromagnetic, or optical means. The word is derived from the Greek *tele*, "far off," and the Latin *communicare,* "to share." (See also **"Communications."**)

Terrain Contour Matching (TERCOM). A guidance and navigation system which measures the topography below a flight vehicle with radar or other electromagnetic energy and compares the results to onboard maps, in order to determine location.

Terminal interface equipment. Equipment at which information enters or leaves the telecommunication system, e.g., telephone, data device, computer, and facsimile device.

Thermal evaporation-physical vapor deposition (TE-PVD). An overlay coating process conducted in a vacuum with a pressure less than 0.1 Pa wherein a source of thermal energy is used to vaporize the coating material. This process results in the condensation, or deposition, of the evaporated species onto appropriately positioned substrates.

The addition of gases to the vacuum chamber during the coating process to synthesize compound coatings is an ordinary modification of the process.

The use of ion or electron beams, or plasma, to activate or assist the coating's deposition is also a common modification in this technique. The use of monitors to provide in-process measurement of optical characteristics and thickness of coatings can be a feature of these processes.

Specific TE-PVD processes are as follows:

(1) Electron Beam PVD uses an electron beam to heat and evaporate the material which forms the coating;

(2) Resistive Heating PVD employs electrically resistive heating sources capable of producing a controlled and uniform flux of evaporated coating species;

(3) "Laser" Evaporation uses either pulsed- or continuous-wave "laser" beams to heat the material which forms the coating; and

(4) Cathodic Arc Deposition employs a consumable cathode of the material which forms the coating and has an arc discharge established on the surface by a momentary contact of a ground trigger. Controlled motion of arcing erodes the cathode surface, creating a highly ionized plasma. The anode can be either a cone attached to the periphery of the cathode through an insulator or the chamber. Substrate biasing is used for non-line-of-sight deposition.

Three-dimensional vector rate. The number of vectors generated per second which have 10 pixel poly line vectors, clip tested, randomly oriented, with either integer or floating point X-Y-Z coordinate values (whichever produces the maximum rate).

Thrust. The force that propels a body or the rate of change of momentum of a burning propellant.

Tilting spindle. A tool-holding spindle which alters, during the machining process, the angular position of its center line with respect to any other axis.

Time constant. The time taken from the application of a line stimulus for the current increment to reach a value of 1-1/e times the final value (i.e., 63 percent of the final value).

Total digital transfer rate. The number of bits, including line coding, overhead, and so forth per unit time passing between corresponding equipment in a digital transmission system. (See also **"Digital transfer rate."**)

Total impulse (I_t). The thrust force F (which can vary with time) integrated over the burning time, t.

Toxic chemical. Any chemical which through its chemical action on life processes can cause death, temporary incapacitation, or permanent harm to humans or animals in military feasible quantities.

Transfer laser. A "laser" to produce a continuous output at all wavelengths over a range of several "laser" transitions. A line-selectable "laser" produces discrete wavelengths within one "laser" transition and is not considered "tunable."

Tunable. The ability of a "laser" to produce a continuous output at all wavelengths over a range of several "laser" transitions. A line-selectable "laser" produces discrete wavelengths within one "laser" transition and is not considered "tunable."

Turnkey plant. Consists of all the hardware, software, technical data, and technical assistance necessary for the installation of a complete operating facility for the production of the commodity, a chemical substance, at defined production rates and to specified product qualities. Hardware consists of all the equipment, components, control valves, instruments, reaction vessels, feed lines, and exposition proof barriers necessary for the conduct of the unit operations of the overall production process, whether the items are assembled or disassembled for transportation. The plant may be designed for installation at a prepared site that includes locally constructed and installed explosion-proof barricades.

Two-dimensional vector rate. The number of vectors generated per second which have 10-pixel polyline vectors, clip tested, randomly oriented, with either integral or floating point X-Y coordinate values (whichever produces the maximum rate).

Uranium enriched in the isotopes 235 or 233. Uranium containing the isotopes 235, 233, or both in the amount such that the abundance ratio of the sum of these isotopes to the isotope 238 is more than the ratio of the isotope 235 to the isotope 238 occurring in nature (isotopic ratio: 0.72 percent).

Use. Operation, installation (including on-site installation), maintenance (checking), repair, overhaul, and refurbishing.

User-accessible programmability. The facility allowing a user to insert, modify, or replace "programs" by means other than (1) a physical change in wiring or interconnections *or* (2) the setting of function controls including entry of parameters.

Vaccines. Materials that when injected into immune-competent responsive persons and animals will enable the human and animal recipient to become resistant to infection.

Vacuum atomization. A process to reduce a molten stream of metal to droplets of a diameter of 500 micrometers or less by the rapid evolution of a dissolved gas upon exposure to a vacuum.

Variable geometry airfoils. Trailing edge flaps or tabs or leading edge slats or pivoted nose droop, the position of which can be controlled in flight.

Vector rate. See **"Two-dimensional vector rate"** and/or **"Three-dimensional vector rate."**

Vehicle management system (VMS). A vehicle control system characterized by a high degree of physical and functional integration of manual and automatic flight controls, propulsion controls, and airframe utility subsystem controls.

Vesicant. Toxic chemicals that have a blistering effect on the skin.

Weapons of mass destruction technologies. Technologies used in weapons of mass destruction and their means of delivery.

Weapons Systems Technologies (WST). Technologies critical to the development and production of superior weapons.

Yield. In chemical reactions, the quantity of pure product divided by the starting material.

APPENDIX E
INTERNATIONAL REGIMES

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There are a number of international treaties, agreements, regimes, and informal arrangements that seek to constrain the spread of nuclear, biological, and chemical weapons and missiles as well as conventional weapons. Some address material/agents and equipment in general terms while others are more specific. Some have led to explicit export control arrangements limiting the transfer of technologies, materials and equipment while others contain broad prohibitions of activities. All have varying degrees of participation and adherence. The agreements, in many cases, establish an international norm of behavior that can be used to highlight aberrant actions.

NUCLEAR NON-PROLIFERATION TREATY (NPT)

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force in 1970 and is adhered to by over 170 nations. A fundamental objective of the NPT is to prevent the further spread of nuclear weapons. To this end, the nuclear weapons states (five had tested and manufactured nuclear weapons by the time the treaty was negotiated and available for signature) agreed not to transfer nuclear weapons or other nuclear explosive devices, and not to assist, encourage, or induce non-nuclear weapons states (NNWS) to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices. Each NNWS pledged not to receive nuclear weapons or other nuclear explosive devices, not to manufacture or otherwise acquire them, and not to seek or receive assistance in their manufacture. The treaty also obliged each NNWS party to the NPT to accept international safeguards through agreements negotiated with the International Atomic Energy Agency (IAEA). The intent of these safeguards is to prevent by deterring, via IAEA inspections, the diversion of nuclear material for nuclear explosive purposes. Nuclear material and specified equipment would be exported to NNWS only under IAEA safeguards.

An offshoot of the NPT, the Zangger Committee, which first met in 1971, maintains a list of nuclear exports that require IAEA safeguards as a condition of supply. The Committee is made up of 30 NPT members who export nuclear material and equipment. The **Nuclear Suppliers Group (NSG)** reinforces the work of the Zangger Committee through an expanded set of controls and by potentially including non-NPT states that are nuclear suppliers. In April 1992, the NSG approved a comprehensive arrangement to prohibit exports of some 65 dual-use items of equipment and materials to unsafeguarded nuclear activities and nuclear explosive programs. It also agreed to a common policy not to engage in significant, new nuclear cooperation with any NNWS that has not committed itself to full-scope safeguards on all present and future nuclear activities.

The NSG conditions for transfer apply to all NNWS whether or not they are NSG members. Nuclear transfers require acceptance of IAEA safeguards; dual-use transfers are prohibited for use in unsafeguarded nuclear fuel-cycle activities and nuclear explosives activities.

Legal authority in the United States for controlling the export of specialized nuclear items is the Atomic Energy Act and the NPT. The licensing agencies are the Nuclear Regulatory Commission and the Department of Energy. The Code of Federal Regulations (CFR) #110 and #810 address federal regulations regarding nuclear equipment and material and assistance to foreign atomic energy activities. On an international basis, CFR #110 controls items on the International Atomic Energy List.

GENEVA PROTOCOL OF 1925 (GP)

At the Geneva Conference for the Supervision of the International Traffic in Arms of 1925, the United States took the initiative of seeking to prohibit the export of gases for use in war. At French suggestion, it was decided to draw up a protocol on non-use of poisonous gases. Poland recommended that bacteriological weapons be covered in the prohibition. The Geneva Protocol was signed on June 17, 1925, and restated the prohibition previously laid down by the Versailles and Washington treaties and added a ban on bacteriological warfare.

The Protocol contained a one-paragraph prohibition against the use of chemical (and bacteriological) weapons. However, agents could be legally developed, produced, stockpiled, and transferred. Several countries, as conditions of their ratification or accession, reserved the right to respond in kind to aggressors using these weapons.

BIOLOGICAL WEAPONS CONVENTION (BWC)

The 1972 Convention on the Prohibition of the Development, Production, and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction (BWC) entered into force in 1975 and has been signed and ratified by over 135 parties. The BWC prohibits the development, production, and stockpiling of toxins or of microbial or other biological agents of types and in quantities that have no justification for prophylactic, protective, or other peaceful purposes; also prohibited are development, production, and stockpiling of weapons, equipment, or means of delivery designed to use such agents or toxins for hostile purposes or in armed conflict. It does not provide a mechanism for controlling export of these items.

During the two decades since the BWC entered into force, there have been increasing concerns about biological weapons proliferation and the ability of the Convention to deter it. Efforts at periodic review conferences have centered on strengthening the implementation and effectiveness of the Convention. The treaty as written has no verification measures. Although confidence-building measures have been approved, there is still concern whether verification could be effective. There is no existing BWC committee comparable to the Zangger Committee in the NPT. The Convention does not prohibit exchange of equipment, materials, or scientific and technical information for peaceful purposes.

The Second Review Conference, held in 1986 in an effort to reduce the occurrence of ambiguities, doubts, and suspicions and to improve international cooperation in peaceful biological activities, adopted voluntary measures to strengthen confidence in treaty compliance and to help deter violations.

Because of continuing concerns about proliferation, possible noncompliance of some parties, and the rapid and significant advances in biotechnology, the Third Review Conference, held in 1991, reaffirmed and extended the voluntary confidence-building measures. As a result of a mandate of the Third Review Conference, an Ad Hoc Group of Government Experts convened to identify, examine, and evaluate potential measures for verifying the provisions of the BWC from a scientific and technical viewpoint.

The Ad Hoc Group (also known as “Verification Experts”) assessed 21 potential off-site and on-site measures using six mandated evaluation criteria. They also considered some combination of measures. The group’s final report concluded that because of the dual-use nature of nearly all biological-weapons-related facilities, equipment, and materials, and the huge overlap between prohibited and permitted purposes, no single approach could fulfill the mandated criteria for a stand-alone verification measure. Nevertheless, the group found that some measures, either singly or in combination, have the potential to strengthen the BWC by helping to differentiate between prohibited and permitted activities and thus to reduce ambiguities about compliance.

CHEMICAL WEAPONS CONVENTION (CWC)

The Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction [referred to as the Chemical Weapons Convention (CWC)] was opened for signature in January 1993. Over 160 countries have signed the Treaty. It entered into force on April 29, 1997.

The CWC bans the production, acquisition, stockpiling, and use of chemical weapons. It charges each party not to develop, produce, otherwise acquire, stockpile, or retain chemical weapons; transfer, directly or indirectly, chemical agents to anyone; use chemical weapons; engage in any military preparations to use chemical weapons; and assist, encourage, or induce, in any way, anyone to engage in any activity prohibited to a party to the Convention. Each Party undertakes in accordance with the provisions of the Convention to destroy the chemical weapons it possesses or that are located in any place under its jurisdiction or control, destroy all chemical weapons it abandoned on the territory of another Party, and destroy any chemical weapons production facilities it owns or possesses or that are located in any place under its jurisdiction or control. Finally, each Party undertakes not to use riot control agents as a method of warfare.

The CWC provides for routine and challenge inspections to assist in the verification of compliance with the Convention. Routine inspections of declared facilities are mandated by the Convention. In accordance with CWC provisions, challenge inspections may be conducted at a facility where a Party suspects illegal activities.

The CWC does not include a specific list of controlled chemicals or equipment. It does contain an Annex on Chemicals in which are listed three “Schedules” of toxic chemicals and their precursors based on the threat they pose to the purpose and objectives of the CWC and the extent of their commercial use. The Verification Annex describes restrictions on transfers of scheduled chemicals in detail. Transfers of some chemicals to countries who have not ratified the Convention will be prohibited by the CWC.

AUSTRALIA GROUP (AG)

In 1984, several countries, reacting to the use of chemical weapons in the Iran-Iraq War, began informal consultations, the goal of which was to discourage and impede proliferation by harmonizing national export controls on chemical weapon (CW) materials. This informal, international forum was chaired by Australia and became known as the Australia Group.

At their December 1992 meeting the AG members, recognizing the need to take steps to address the increasing problem of the spread of biological weapons, agreed on measures to control the export of biological agents and dual-use equipment which could be used in the production of biological weapons. They also agreed on a framework paper for effective licensing arrangements for export controls, thereby further strengthening measures to address the problem of chemical and biological weapon (CBW) proliferation and use.

Today, the AG controls extend to 54 dual-use chemical precursors for CW, microorganisms and toxins that could be used in BW, and dual-use equipment and technology that could be used in chemical or biological weapons production. Controls agreed to during meetings of the AG are applied on a national basis, although all participants are agreed that controls will be more effective if similar measures are introduced by all potential exporters of relevant chemicals and equipment and by countries of possible transshipment. In the United States, the Commerce Control List (CCL) is the vehicle that implements AG agreements.

There are currently 30 members of the AG. It has no charter or constitution and operates on consensus. The AG’s actions are viewed as complementary measures in support of the 1925 Geneva Protocol, the 1972 Biological and Toxins Weapons Convention, and the 1993 Chemical Weapons Convention. In tandem with export controls, the AG has periodically used warning mechanisms to sensitize the public to CBW proliferation. The AG has issued an informal "warning list" of dual-use CW precursors and bulk chemicals and of CW-related equipment. Members develop and share the warning lists with their chemical industry and ask it to report on any suspicious transactions. The AG has also used an approach to warn industry, the scientific community, and other relevant groups of the risks of inadvertently aiding BW proliferation.

Meetings of the AG focus on sharing information about national export controls, considering proposals for "harmonization"—the adoption of common export controls by all members—and considering other measures to address CBW proliferation and use.

MISSILE TECHNOLOGY CONTROL REGIME (MTCR)

The Missile Technology Control Regime currently provides the central institutional arrangement as well as the base international norm for dealing with missile proliferation. The aim of the MTCR is to restrict the proliferation of missiles, unmanned air vehicles, and related technology for those systems capable of carrying a 500-kilogram payload at least 300 kilometers as well as systems intended for the delivery of weapons of mass destruction .

The MTCR is neither an international agreement nor a treaty but a voluntary arrangement among countries which share a common interest in limiting the spread of missiles and missile technology. The MTCR considers "missiles" to include ballistic missiles, space launch vehicles (SLV), and sounding rockets. Unmanned air vehicles (UAVs) include cruise missiles, drones, and remotely piloted vehicles (RPVs). The MTCR's members cooperate by applying on a national level common export control guidelines to an agreed list of items (the Equipment and Technology Annex).

When the MTCR was instituted in 1987 by the United States and six other concerned countries, it was intended to limit the risks of nuclear proliferation by controlling technology transfers relevant to nuclear weapon delivery other than by manned aircraft (i.e., by restricting the proliferation of missiles and related technology). In 1993, MTCR member states tightened export controls further, agreeing to also control transfers of rocket systems or UAVs (including cruise missiles) capable of a 300-km range regardless of range or payload. Also, if the seller has any reason to believe these systems would be used to deliver WMD, there is a "strong presumption to deny" the transfer regardless of the inherent range and/or payload of the system. There are now 29 MTCR members; other countries have agreed to abide by the basic tenets of the MTCR.

The annex of controlled equipment and technology is divided into "Category I" and "Category II" items. It includes equipment and technology, both military and dual-use, that are relevant to missile development, production, and operation. Category I consists of complete missile systems (including ballistic missile systems, space launch vehicles, and sounding rockets); unmanned air-vehicle systems such as cruise missiles, and target and reconnaissance drones; specially designed production facilities for these systems; and certain complete subsystems such as rocket engines or stages, reentry vehicles, guidance sets, thrust-vector controls, and warhead safing, arming, fuzing, and firing mechanisms. According to the MTCR Guidelines, export of Category I items is subject to a presumption of denial.

Category II covers a wide range of parts, components, subsystems, propellants, structural materials, test and production equipment, and flight instruments usable for the Category I systems and subsystems. These items are less sensitive components and technologies, most of which have dual-use applications. Category II also covers those systems that have a range of 300 km (but cannot carry a 500-kg payload to that range) and some associated subsystems. Category II items may be exported by MTCR members on a case-by-case basis, provided that the importing state furnishes sufficient end-use guarantees for the item.

The MTCR Guidelines specifically state that the Regime is "not designed to impede national space programs or international cooperation in such programs as long as such programs could not contribute to delivery systems for weapons of mass destruction." The United States maintains a strict interpretation of this statement. Despite some differences of opinion with regard to commercial space applications, all members agree that the technology used in an SLV is virtually identical to that used in a ballistic missile.

WASSENAAR ARRANGEMENT (WA)

In December 1995, 28 governments agreed to establish a new international regime to increase transparency and responsibility for the global market in conventional arms and dual-use goods and technologies. The official name of the regime is "The Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies," Wassenaar being the town outside The Hague where five rounds of negotiations took place over a 2-year period. The arrangement will respond to the new security threats of the post Cold War by providing greater openness through information sharing about arms and technology transfers worldwide.

The Wassenaar Arrangement is an international framework that will need to be elaborated and defined more fully. It will focus on the threats to international and regional peace and security. A central part of the regime is the commitment by its members to prevent the acquisition of armaments and sensitive dual-use items for military end-users to states whose behavior today is, or becomes, a cause for serious concern, such as Iran, Iraq, Libya, and North Korea.

The regime will also undertake to prevent destabilizing accumulations of conventional arms worldwide. The Iraq war taught that indiscriminate exports of conventional weapons and sensitive dual-use technologies can pose serious threats to U.S. interests, to foreign policy goals, and to international security. This regime will seek to apply the lessons of Iraq to prevent similar destabilizing buildups. It will also fill an important gap in the global non-proliferation regimes by covering conventional arms and associated dual-use technologies. The WA, by requiring its members to adhere to current non-proliferation regimes, will encourage non-members to also adhere to these regimes.

The WA seeks to prevent destabilizing buildups of weapons by establishing a formal process of transparency and consultation. Participants have agreed to control through their national policies those items and technologies contained in a list of Dual-Use Goods and Technologies and in a separate Munitions List.

OTHER NUCLEAR-RELATED AGREEMENTS

There are a number of other agreements that restrict nuclear weapons in some way. Many of them ban nuclear weapons from a location or geographic area (i.e., nuclear-weapon-free zones). The following lists the treaty/agreement, the year it entered into force, the number of signatories, and a brief description of its provisions.

Antarctic Treaty: 1961; 37 countries; internationalized and demilitarized the Antarctic Continent and provided for its cooperative exploration and future use. The treaty prohibits "any measures of a military nature, such as the establishment of military bases and fortifications, the carrying out of military maneuvers, as well as the testing of any type of military weapons."

Limited Test Ban Treaty (LTBT): 1963; 117 countries; prohibits nuclear weapons tests "or any other nuclear explosion" in the atmosphere, in outer space, and under water.

Outer Space Treaty: 1967; 98 countries; parties undertake not to place in orbit around the Earth, install on the moon or any other celestial body, or otherwise station in outer space nuclear or other weapons of mass destruction .

Latin American Nuclear-Free Zone Treaty (Treaty of Tlatelolco): 1968; 29 countries (24 in force); obligates Latin American parties not to acquire or possess nuclear weapons, nor permit the storage or deployment of nuclear weapons on their territories by other countries.

Seabed Treaty: 1972; 94 countries; prohibits emplacing nuclear weapons or weapons of mass destruction on the sea bed and the ocean floor beyond the 12-mile coastal zone.

Threshold Test Ban Treaty (TTBT): 1974; United States, USSR; prohibits underground nuclear tests having a yield exceeding 150 kilotons.

South Pacific Nuclear Free-Zone Treaty (Treaty of Rarotonga): 1985; 15 countries; prohibits testing, deployment, or acquisition of nuclear weapons in the South Pacific.

Intermediate Range Nuclear Forces (INF) treaty: 1987; United States, USSR; eliminated ground-launched ballistic and cruise missiles with a range between 500 and 5,500 kilometers. All of these missiles, their launchers, and associated support structures and support equipment were destroyed.

START I: 1994; United States, USSR; reduces arsenals by about 30 percent. The original signatory, the USSR, has since dissolved and the states of Russia, Belarus, Kazakhstan, and Ukraine have endorsed the treaty by signing the START I Protocol.

African Nuclear Weapons Free-Zone (Treaty of Pelindaba): 1996; 53 signatories, three ratifications; prohibits building, testing, burying, or stockpiling nuclear materials.

Comprehensive Test Ban Treaty (CTBT): 1996; 148 signatories, 7 ratifications (as of 1 October 1997): bans any nuclear weapon test explosion or any other nuclear explosion.

SELECTED REGIME PARTICIPANTS

	NSG	GP	BWC	CWC**	AG	MTCR	WA
Argentina	●	●	●	●	●	●	●
Australia	●	●	●	●	●	●	●
Austria	●	●	●	●	●	●	●
Belgium	●	●	●	●	●	●	●
Brazil	●	●	●	●		●	
Bulgaria	●	●	●	●			●
Canada	●	●	●	●	●	●	●
China*	N	●	●	●			
Czech Republic	●	●	●	●	●		●
Denmark	●	●	●	●	●	●	●
Egypt	N	●	S				
Finland	●	●	●	●	●	●	●
France	●	●	●	●	●	●	●
Germany	●	●	●	●	●	●	●
Greece	●	●	●	●	●	●	●
Hungary	●	●	●	●	●	●	●
Iceland	N	●	●	●	●	●	
India		●	●	●			
Iran	N	●	●	●			
Iraq	N	●	●				
Ireland	●	●	●	●	●	●	●
Israel*		●		S			
Italy	●	●	●	●	●	●	●
Japan	●	●	●	●	●	●	●
Korea, North	N	●	●				
Korea, South	●	●	●	●	●		●
Libya	N	●	●				
Luxembourg	●	●	●	●	●	●	●
Netherlands	●	●	●	●	●	●	●
New Zealand	●	●	●	●	●	●	●
Norway	●	●	●	●	●	●	●
Pakistan		●	●	●			
Poland	●	●	●	●	●		●
Portugal	●	●	●	●	●	●	●
Romania*	●	●	●	●	●		●
Russian Fed.	●	●	●	●		●	●
Slovak Republic	●	●	●	●	●		●
South Africa	●	●	●	●		●	
Spain	●	●	●	●	●	●	●
Sweden	●	●	●	●	●	●	●
Switzerland	●	●	●	●	●	●	●
Syria	N	●	S				
Turkey	N	●	●	●		●	●
Ukraine	●		●	S			●
United Kingdom	●	●	●	●	●	●	●
United States	●	●	●	●	●	●	●

Regime	Total number of participants (as of date)
Nuclear Suppliers Group (**NSG**)	34 (N = NPT: 185) (1/97)
Geneva Protocol (**GP**)	145 (7/96)
Biological Weapons Convention (**BWC**)	140 (S = signed: 158) (5/97)
Chemical Weapons Convention (**CWC**)**	106 (S = signed: 168) (11/97)
Australia Group (**AG**)	30 (10/96)
Missile Technology Control Regime (**MTCR**)	29 (11/97)
Wassenaar Arrangement (**WA**)	33 (12/96)

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* China, Israel, and Romania have pledged to abide by the basic tenets of the Missile Technology Control Regime.

** For the latest list of CWC signatories/parties, see http://www.opcw.nl/

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APPENDIX F-1
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APPENDIX F-2
CONTROL LIST REFERENCES

APPENDIX F-2
CONTROL LIST REFERENCES

CL-ITEM	DESCRIPTION	SECTION REFERENCE
AG LIST	Australia Group List	3.1, 3.2, 4.1, 4.2, 4.3
CCL Cat 0B	Nuclear Materials—Test, Inspection, and Production Equipment	5.2
CCL Cat 1A	Materials, Chemicals, Microorganisms, and Toxins—Systems, Equipment, and Components	3.3, 3.4, 5.8, 5.12
CCL Cat 1B	Materials, Chemicals, Microorganisms, and Toxins—Test, Inspection, and Production Equipment	1.1, 1.3, 5.9, 5.12
CCL Cat 1C	Materials, Chemicals, Microorganisms, and Toxins—Materials	1.1, 1.2, 1.3, 3.1, 3.2, 4.2, 5.4
CCL Cat 1E	Materials, Chemicals, Microorganisms, and Toxins—Technology	4.1
CCL Cat 2A	Materials Processing—Systems, Equipment, and Components	5.2
CCL Cat 2B	Materials Processing—Test, Inspection, and Production Equipment	1.1, 3.1, 3.2, 4.2, 4.3, 5.2, 5.4, 5.8, 5.9, 5.10
CCL Cat 2D	Materials Processing—Software	1.3
CCL Cat 2E	Materials Processing—Technology	1.4
CCL Cat 3A	Electronics Design, Development, and Production—Systems, Equipment, and Production	1.5, 3.3, 4.3, 5.2, 5.6, 5.7, 5.9, 5.10
CCL Cat 5.A-P1	Telecommunications—Systems, Equipment, and Components	1.1, 1.2, 2.1, 2.2, 2.5, 5.7, 5.10
CCL Cat 5.E-P1	Telecommunications—Technology	2.1, 2.2
CCL Cat 5A-P2	Information Security—Systems, Equipment, and Components	1.1, 1.2, 2.4, 2.5
CCL Cat 6A	Sensors and Sensors—Systems, Equipment, and Components	4.3, 5.2, 5.10
CCL Cat 7A	Navigation and Avionics—Systems, Equipment, and Components	1.1, 1.3, 1.4, 1.5, 5.7

CL-ITEM	DESCRIPTION	SECTION REFERENCE
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CCL Cat 9A	Propulsion Systems, Space Vehicles, and Related Equipment—Systems, Equipment, and Components	1.1, 1.2, 1.3
CCL Cat 9B	Propulsion Systems, Space Vehicles, and Related Equipment—Test, Inspection, and Production Equipment	1.1, 1.2, 1.3, 1.4, 5.9
CCL Cat 9D	Propulsion Systems, Space Vehicles, and Related Equipment—Software	1.4
CCL Cat 9E	Propulsion Systems, Space Vehicles, and Related Equipment—Technology	1.4
CCL EAR 99	Items subject to the EAR that are not elsewhere specified in any CCL Category are designated by EAR 99	1.1, 1.2, 1.3, 1.4, 1.5, 2.1, 2.2, 2.3, 2.5, 3.1, 3.2, 3.3, 3.4, 4.2, 4.3, 4.4, 5.2, 5.7, 5.10, 5.11, 5.13
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MTCR 2	Complete Subsystems	1.1, 1.2, 1.3, 1.4, 5.7
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MTCR 4	Propellants and Constituent Chemicals	1.1, 1.2
MTCR 5	Production Technology, or Production Equipment	1.1, 1.2
MTCR 7	Structural Composites Production Equipment	1.3
MTCR 8	Structural Materials	1.1, 1.2
MTCR 9	Instrumentation, Navigation, and Direction-Finding Equipment	1.1, 1.2, 1.3, 1.4
MTCR 10	Flight Control Systems and Technology	1.1, 1.3
MTCR 11	Avionics Equipment	1.1, 1.3, 1.4, 1.5, 5.7

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MTCR 17	Materials, Devices, and Specially Designed Software for Reduced Observables	1.3, 1.4
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NDUL 3	Uranium Isotope Separation Equipment and Components	5.2, 5.9
NDUL 4	Heavy-Water Production Plant Related Equipment	5.12
NDUL 5	Implosion Systems Development Equipment	5.9, 5.10
NDUL 6	Explosives and Related Equipment	5.6, 5.7
NDUL 7	Nuclear Testing Equipment and Components	5.10
NDUL 8	Other Dual-Use Nuclear Items (Lithium)	5.4, 5.5, 5.6, 5.7, 5.8, 5.9, 5.13
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NRC-B	NRC Appendix B—Illustrative List of Gas Centrifuge Enrichment Plant Components	5.2
NRC-C	NRC Appendix C—Illustrative List of Gaseous Diffusion Enrichment Plant Assemblies and Components	5.2
NRC-D	NRC Appendix D—Illustrative List of Aerodynamic Enrichment Plant Assemblies and Components	5.2
NRC-E	NRC Appendix E—Illustrative List of Chemical Exchange or Ion Exchange Enrichment Plant Assemblies and Components	5.2
NRC-F	NRC Appendix F—Illustrative List of Laser-Based Enrichment Plant Assemblies and Components	5.2
NRC-G	NRC Appendix G—Illustrative List of Plasma Separation Enrichment Plant Assemblies and Components	5.2
NRC-H	NRC Appendix H—Illustrative List of Electromagnetic Enrichment Plant Assemblies and Components	5.1, 5.2
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USML V	Explosives, Propellants, Incendiary Agents, and their Constituents	4.2
USML VII	Tanks and Military Vehicles	2.6
USML VIII	Aircraft and Associated Equipment	1.2, 1.4
USML X	Protective Personnel Equipment	1.1, 1.2, 4.4
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USML XII	Fire Control, Range Finder, Optical, and Guidance Control Equipment	1.4, 4.2
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WA Cat 1A	Advanced Materials—Systems, Equipment, and Components	3.3, 4.2, 4.3
WA Cat 1B	Advanced Materials—Test, Inspection, and Production Equipment	1.1, 1.3, 5.9
WA Cat 1C	Advanced Materials—Materials	1.1, 1.3, 3.3, 4.2
WA Cat 1E	Advanced Materials—Technology	4.4
WA Cat 2B	Materials Processing—Test, Inspection, and Production Equipment	1.1, 5.9
WA Cat 2D	Materials Processing—Software	1.3
WA Cat 2E	Materials Processing—Technology	1.4
WA Cat 3A	Electronics—Systems, Equipment, and Components	1.5, 4.3, 5.7, 5.10
WA Cat 5.A-P1	Telecommunications—Systems, Equipment, and Components	2.1, 2.2, 2.5, 5.7, 5.10
WA Cat 5.E-P1	Telecommunications—Technology	2.1, 2.2, 5.7
WA Cat 5A-P2	Information Security—Systems, Equipment, and Components	1.1, 1.2, 2.4, 2.5
WA Cat 6A	Sensors and Lasers—Systems, Equipment, and Components	4.3, 5.10
WA Cat 7A	Navigation and Avionics—Systems, Equipment, and Components	1.1, 1.3, 1.4, 1.5
WA Cat 7E	Navigation and Avionics—Technologies	1.4
WA Cat 9A	Propulsion—Systems, Equipment, and Components	1.1, 1.2, 1.3, 1.4
WA Cat 9B	Propulsion—Test, Inspection, and Production Equipment	1.1, 1.3, 1.4, 5.9
WA Cat 9D	Propulsion—Software	1.4
WA Cat 9E	Propulsion—Technology	1.4
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WA ML 5	Fire Control	1.4, 4.2
WA ML 7	Toxicological Agents	3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4
WA ML 8	Military Explosives and Fuels	1.1, 1.2, 4.2
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WA ML 11	Electronic Equipment	1.1, 1.2, 1.3, 1.5, 2.4, 4.2
WA ML 13	Armoured or Protective Equipment	2.6
WA ML 15	Imaging or Countermeasure Equipment	4.2
WA ML 16	Forgings, Castings and Other Unfinished Products	4.2
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