

## **SECTION V**

### **NUCLEAR WEAPONS TECHNOLOGY**

## SECTION 5—NUCLEAR WEAPONS TECHNOLOGY

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### **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.

### *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.

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  $^{235}\text{U}$ , the production and extraction of plutonium, the production of tritium, and the separation of deuterium and  $^6\text{Li}$  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.<sup>1</sup>

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.<sup>2</sup> 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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<sup>1</sup> 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 <sup>235</sup>U and <sup>239</sup>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.

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<sup>2</sup> 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  $^{235}\text{U}$ ,  $^{233}\text{U}$ , 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  $^{235}\text{U}$ , the highly fissionable isotope, the rest of the material being largely the much less fissionable isotope  $^{238}\text{U}$  (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,<sup>3</sup> and gaseous diffusion, in which the gas uranium hexafluoride ( $\text{UF}_6$ ) is passed through a porous barrier material; the lighter molecules containing  $^{235}\text{U}$  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  $\text{UF}_6$  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  $\text{UF}_6$  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  $^{235}\text{U}$  content of around 3–5 percent in addition to making 80–93 percent  $^{235}\text{U}$  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  $^{235}\text{U}$  is called highly enriched (HEU). Uranium enriched above the natural  $^{235}\text{U}$  abundance but to less than 20 percent is called low-enriched (LEU).

Plutonium is produced in nuclear reactors by bombarding “fertile”  $^{238}\text{U}$  with neutrons on 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  $^{238}\text{U}$ .<sup>4</sup> A typical production reactor produces about 0.8 atoms of plutonium for each nucleus of  $^{235}\text{U}$  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 ( $^{131}\text{I}$ , 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,  $^6\text{Li}$  (actually the compound  $^7\text{Li}$  nucleus formed in the collision) frequently disintegrates into tritium and  $^4\text{He}$ . 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,  $^6\text{Li}$ , is separated from the principal isotope,  $^7\text{Li}$ , 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  $^7\text{Li}$  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.

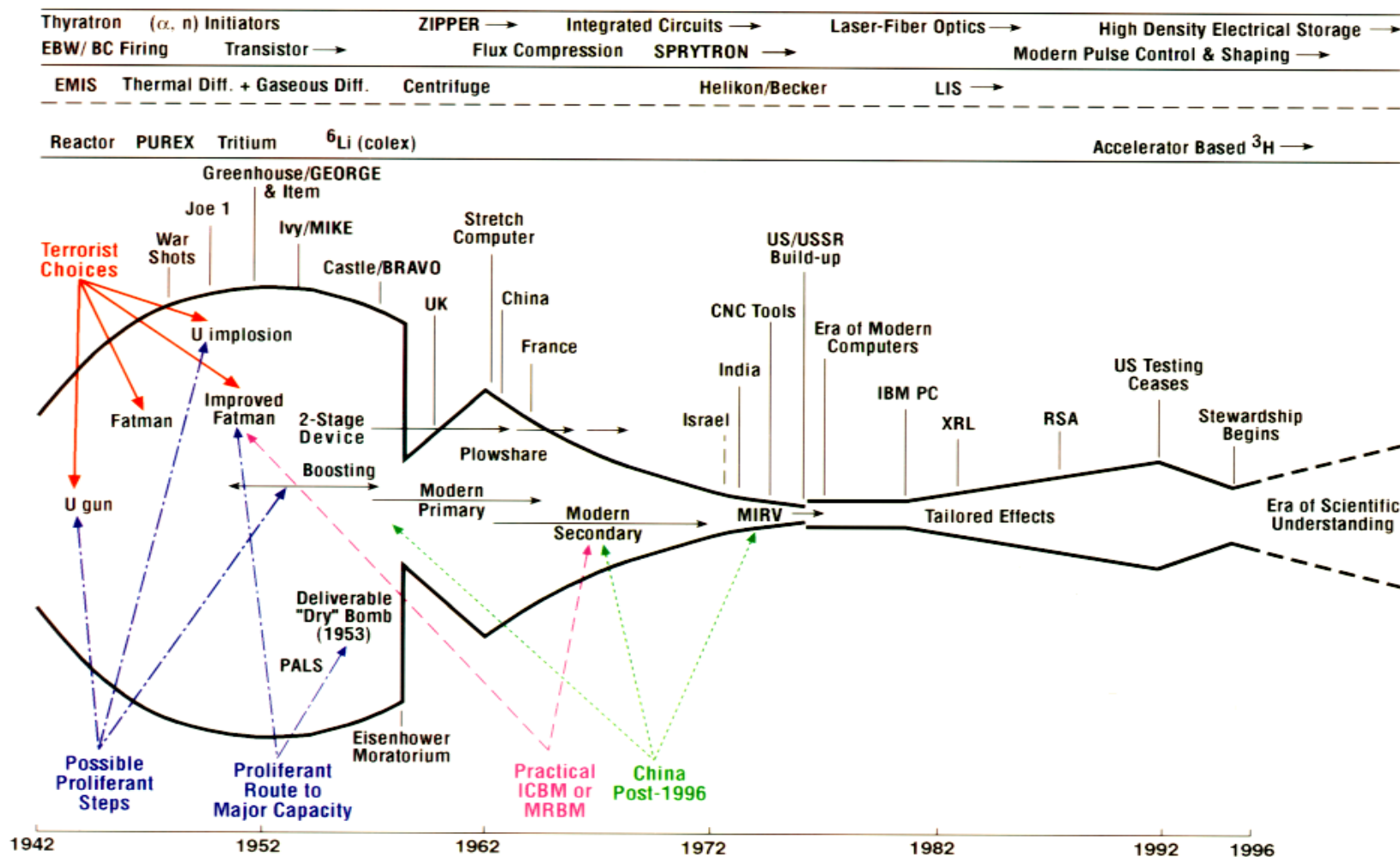
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<sup>3</sup> The first large-scale uranium enrichment facility, the Y-12 plant at Oak Ridge, Tennessee, used EMIS in devices called “calutrons.” The process was abandoned in the United States because of its high consumption of electricity, but was adopted by the Iraqis because of its relative simplicity and their ability to procure the magnet material without encountering technology transfer obstacles.

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<sup>4</sup> 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.

# Nuclear History



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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  $^{235}\text{U}$  and  $^{239}\text{Pu}$ , 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  $^{235}\text{U}$  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  $^{240}\text{Pu}$ , 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.<sup>5</sup> Implosion systems can be built using either  $^{239}\text{Pu}$  or  $^{235}\text{U}$ , 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  $^{235}\text{U}$ ; Iraq attempted to build an implosion bomb, also using  $^{235}\text{U}$ . In contrast, North Korea chose to use  $^{239}\text{Pu}$  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.

<sup>5</sup> 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.<sup>6</sup> 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 <sup>137</sup>Cs, <sup>60</sup>Co, <sup>131</sup>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 control-

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<sup>6</sup> 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.

lable 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<sub>2</sub>-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



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<br>Enrichment<br>Feed-<br>stocks<br>Production | Sec 5.2<br>Uranium<br>Enrichment<br>Processes | Sec 5.3<br>Nuclear<br>Fission<br>Reactors | Sec 5.4<br>Plutonium<br>Extraction<br>(Reprocessing) | Sec 5.5<br>Lithium<br>Production | Sec 5.6<br>Nuclear<br>Weapons<br>Design<br>and<br>Development | Sec 5.7<br>Safing,<br>Arming,<br>Fuzing,<br>and Firing | Sec 5.8<br>Radiological<br>Weapons | Sec 5.9<br>Manufacturing of<br>Nuclear<br>Components | Sec 5.10<br>Nuclear<br>Weapons<br>Development<br>Testing | Sec 5.11<br>Nuclear<br>Weapons<br>Custody,<br>Transport,<br>and<br>Control | Sec 5.12<br>Heavy<br>Water<br>Production | Sec 5.13<br>Tritium<br>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 ( $\text{UF}_6$ ) and uranium tetrachloride ( $\text{UCl}_4$ ) for subsequent use as feedstock in a uranium-enrichment process. Gaseous  $\text{UF}_6$  is used as the feed in the gas centrifuge and gaseous diffusion processes, and  $\text{UCl}_4$  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  $\text{UF}_6$  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  $\text{UF}_6$  or by fractional distillation of the  $\text{UF}_6$  after conversion.

In the *wet process*, yellowcake is dissolved in nitric acid ( $\text{HNO}_3$ ), 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 ( $\text{UO}_3$ ) via thermal denitration, and the trioxide is reduced to uranium dioxide ( $\text{UO}_2$ ) with hydrogen or cracked ammonia ( $\text{NH}_3$ ). 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  $\text{Na}_2\text{U}_2\text{O}_7$ ), the sodium must be removed from the material by partial digestion in sulfuric acid followed by ammonia precipitation of ammonium diuranate  $[(\text{NH}_4)_2\text{U}_2\text{O}_7]$ . The ammonium-containing uranium salt is decomposed to  $\text{UO}_3$  by heating, and this oxide is reduced to  $\text{UO}_2$  with hydrogen or cracked  $\text{NH}_3$ .

The remaining steps used to produce  $\text{UF}_6$  for both processes are similar in that the  $\text{UO}_2$  is converted to  $\text{UF}_4$  by hydrofluorination (using hydrogen fluoride gas—HF). The  $\text{UF}_4$  (impure in the dry process) is converted to  $\text{UF}_6$  using electrolytically generated fluorine gas ( $\text{F}_2$ ). In the dry process, the  $\text{UF}_6$  is purified in a two-stage distillation step. Direct fluorination of  $\text{UO}_3$  to  $\text{UF}_6$  has been used, but this procedure is more amenable to relatively small capacity plants.

### Highlights

- $\text{UF}_6$  and  $\text{UCl}_4$  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  $\text{UCl}_4$  for its feed material. Uranium tetrachloride is produced by the reaction of carbon tetrachloride ( $\text{CCl}_4$ ) with pure  $\text{UO}_2$  at 700 °F.

### RATIONALE

A country choosing to join the nuclear weapons community must acquire the necessary weapons (fissile) material ( $^{235}\text{U}$  or  $^{239}\text{Pu}$ ). A state selecting uranium for its weapons must obtain a supply of uranium ore and construct an enrichment plant because the  $^{235}\text{U}$  content in natural uranium is over two orders of magnitude lower than that found in weapons grade uranium (>90 percent  $^{235}\text{U}$ ). Nearly all uranium enrichment plants utilize  $\text{UF}_6$  as their feed. A country may select the EMIS process, which uses  $\text{UCl}_4$  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,  $\text{NH}_3$ ,  $\text{F}_2$ ,  $\text{CCl}_4$ , and precursor uranium compounds to prepare  $\text{UF}_6$  and  $\text{UCl}_4$ .

**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<br>Experience in using $\text{HNO}_3$                                                                                                                                                                | NTL 8F;<br>NRC J         | Yellowcake<br>Nitric acid ( $\text{HNO}_3$ )<br>tri-n-butyl phosphate (TBP)<br>Refined kerosene                              | Filters; centrifuges; pulse columns; concentration/thermal denitration systems; tanks resistant to $\text{HNO}_3$                                                                                                                                                                                              | Distribution coefficients for many elements<br>Aqueous solubility for many compounds |
| Purification of yellowcake (dry process: produces impure $\text{UO}_2$ )                      | Ability to handle $\text{H}_2$ at elevated temperature                                                                                                                                                                                             | NTL 8F;<br>NRC J         | Yellowcake (should not contain high concentrations of sodium or magnesium)<br>$\text{H}_2\text{SO}_4$<br>See citations below | Furnace; air filtration equipment; fluidized bed; temperature control; heat exchangers                                                                                                                                                                                                                         | None identified                                                                      |
| $\text{UO}_2$ preparation                                                                     | Ability to handle $\text{H}_2$ at elevated temperature                                                                                                                                                                                             | NTL 8F;<br>NRC J         | $\text{H}_2$<br>$\text{NH}_3$                                                                                                | Moving bed reactor; rotary kiln; air filtration equipment; fluidized bed; temperature control system                                                                                                                                                                                                           | None identified                                                                      |
| $\text{UF}_4$ preparation                                                                     | Ability to manage HF at elevated temperature<br>Ability to provide a dry environment                                                                                                                                                               | NTL 8F;<br>NRC J         | HF                                                                                                                           | Stirred fluidized bed reactors; rotary kiln; moving bed/screw reactor; air cleaning equipment (filters, scrubbers); fluoride-resistant equipment                                                                                                                                                               | None identified                                                                      |
| $\text{UF}_6$ preparation (used in gaseous diffusion and gas centrifuge enrichment processes) | Capability to control quantities of fluorine gas. Ability to operate a flame tower with $\text{F}_2$ . Experience in removing $\text{H}_2$ from electrolytic cells ( $\text{F}_2$ production). Experience in operating in an anhydrous environment | NTL 8F;<br>NRC J         | $\text{F}_2$<br>HF<br>$\text{KF} \cdot 2\text{HF}$                                                                           | Flame tower reactor; fluidized bed reactor; condensers (cold traps); electrolytic cells (for $\text{F}_2$ production); high-amperage, low-voltage supply (for $\text{F}_2$ production); air-cleaning equipment; $\text{F}_2$ -resistant equipment (Monel); fluoride-resistant equipment; $\text{UF}_6$ storage | Careful temperature control is required for fluorination                             |
| $\text{UCl}_4$ preparation (used in EMIS enrichment process)                                  | Water-free environment must be provided                                                                                                                                                                                                            | NTL 8F;<br>NRC H         | $\text{CCl}_4$                                                                                                               | 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 <sub>3</sub> solutions are relatively hazardous and require moderate care in handling                                                | None identified                                                 | Direct fluorination of UO <sub>3</sub>         |
| Purification of yellowcake (dry process produces impure UO <sub>2</sub> )                       | H <sub>2</sub> presents an explosive hazard                                                                                              | None identified                                                 | Direct fluorination of UO <sub>3</sub>         |
| UO <sub>2</sub> preparation                                                                     | H <sub>2</sub> presents an explosive hazard                                                                                              | None identified                                                 | Step may be bypassed using direct fluorination |
| UF <sub>4</sub> 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 <sub>6</sub> preparation (used in gaseous diffusion and gas centrifuge enrichment processes) | Producing F <sub>2</sub> is not an easy task. Flame towers can be difficult to operate. Moisture-sensitive material difficult to handle. | UF <sub>6</sub> product is feed to most U enrichment processes  | None identified                                |
| UCl <sub>4</sub> preparation (used in EMIS enrichment process)                                  | Moisture-sensitive material difficult to handle                                                                                          | UCl <sub>4</sub> 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.<sup>7</sup>

Fissile materials can produce energy by nuclear fission, either in nuclear reactors or in nuclear weapons. The principal fissile materials of interest are  $^{235}\text{U}$ ,  $^{233}\text{U}$ , and  $^{239}\text{Pu}$ . 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  $^{235}\text{U}$  atoms, and it can be assumed that all of the remaining atoms are  $^{238}\text{U}$  atoms.<sup>8</sup> Higher concentrations of  $^{235}\text{U}$  are required for many applications, and the use of uranium isotope separation processes to increase the assay of  $^{235}\text{U}$  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  $^{235}\text{U}$ , 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  $^{235}\text{U}$  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  $^{235}\text{U}$ .

When plutonium is produced in a nuclear reactor, inevitably some  $^{240}\text{Pu}$  (as well as heavier plutonium isotopes, including  $^{241}\text{Pu}$  and  $^{242}\text{Pu}$ ) is produced along with the more desirable  $^{239}\text{Pu}$ . 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  $^{240}\text{Pu}$ .

<sup>7</sup> 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.

<sup>8</sup> Natural uranium typically has a composition of 0.0055 atom %  $^{234}\text{U}$ , 0.7205 atom %  $^{235}\text{U}$ , and 99.274 atom %  $^{238}\text{U}$ . For most purposes, the tiny fraction of  $^{234}\text{U}$  can be neglected.

### 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.

A method for separating plutonium isotopes could be used to remove the heavier isotopes of plutonium (e.g.,  $^{240}\text{Pu}$ ) from reactor-grade plutonium, thus producing nearly pure  $^{239}\text{Pu}$ . 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  $^{240}\text{Pu}$ .

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;

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.,  $^{235}\text{U}^+$  and  $^{238}\text{U}^+$ ), will have different trajectories, with the heavier  $^{238}\text{U}^+$  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 ( $\text{UCl}_4$ ) is electrically heated to produce  $\text{UCl}_4$  vapor. The  $\text{UCl}_4$  molecules are bombarded with electrons, producing  $\text{U}^+$  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  $\text{UCl}_4$  feed is typically converted to the desired  $\text{U}^+$  ions, and less than half of the desired  $\text{U}^+$  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  $\alpha$  and  $\beta$  stages. The first ( $\alpha$ ) stage used natural or slightly enriched uranium as feed and enriched it to 12–20%  $^{235}\text{U}$ . The second ( $\beta$ ) stage used the product of the ( $\alpha$ ) 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 “race-tracks” 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  $^{235}\text{U}$  gas molecules will diffuse toward the hot surface, and the heavier  $^{238}\text{U}$  molecules will diffuse toward the cold surface. These two diffusive motions combined with the convection currents will cause the lighter  $^{235}\text{U}$  molecules to concentrate at the top of the film and the heavier  $^{238}\text{U}$  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  $\text{UF}_6$  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%  $^{235}\text{U}$ . 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  $\text{UF}_6$ .

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  $\text{UF}_6$ , the difference in velocities between molecules containing  $^{235}\text{U}$  and  $^{238}\text{U}$  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  $\text{UF}_6$  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  $\text{UF}_6$  and in-leakage of air. The chemical corrosiveness of  $\text{UF}_6$  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 co-workers 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  $\text{UF}_6$  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  $^{238}\text{UF}_6$  molecules to tend to move closer to the wall than the lighter  $^{235}\text{UF}_6$  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  $\text{UF}_6$ , all components that come in direct contact with  $\text{UF}_6$  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  $\text{UF}_6$  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  $\text{UF}_6$ .

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  $\text{UF}_6$  and  $\text{H}_2$  (or helium) is compressed and then directed along a curved wall at high velocity. The heavier  $^{238}\text{U}$ -bearing molecules move preferentially out to the wall relative to those containing  $^{235}\text{U}$ . 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  $10\text{ }\mu\text{m}$  (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  $\text{UF}_6$  and  $\text{H}_2$  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  $\text{UF}_6$  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  $^{235}\text{U}$  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  $^{235}\text{U}$  atoms and  $^{238}\text{U}$  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  $^{235}\text{U}$  atoms absorb the laser light. As the  $^{235}\text{U}$  atom absorbs the laser light, its electrons are excited to a higher energy state. With the absorption of sufficient energy, a  $^{235}\text{U}$  atom will eject an electron and become a positively charged ion. The  $^{235}\text{U}$  ions may then be deflected by an electrostatic field to a product collector. The  $^{238}\text{U}$  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  $^{235}\text{U}$  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,  $\text{UF}_6$  is irradiated by an infrared laser system operating near the  $16\text{ }\mu\text{m}$  wavelength, which selectively excites the  $^{235}\text{UF}_6$ , leaving the  $^{238}\text{UF}_6$  relatively unexcited. In the second step, photons from a

second laser system (infrared or ultraviolet) preferentially dissociate the excited  $^{235}\text{UF}_6$  to form  $^{235}\text{UF}_5$  and free fluorine atoms. The  $^{235}\text{UF}_5$  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  $\text{UF}_5$  product back to  $\text{UF}_6$  for further enrichment.  $\text{CO}_2$  lasers are suitable for exciting the  $^{235}\text{UF}_6$  during the first step. A XeCl excimer laser producing ultraviolet light may be suitable for the dissociation of  $^{235}\text{UF}_6$  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  $\text{UF}_6$  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  $^{235}\text{UF}_6$  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  $\text{UF}_6$  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 [ $\text{U}^{6+}$  as in uranyl chloride ( $\text{UO}_2\text{Cl}_2$ )] and the quadrivalent [ $\text{U}^{4+}$  as in uranium tetrachloride ( $\text{UCl}_4$ )]. The  $^{235}\text{U}$  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 ( $\text{U}^{3+}$ ) 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 ( $\text{U}^{3+}$  and  $\text{U}^{4+}$ ) of uranium ions in aqueous solution. Isotopic enrichment results from the tendency of  $^{238}\text{U}$  to concentrate in the  $\text{U}^{3+}$  compound while  $^{235}\text{U}$  concentrates in the  $\text{U}^{4+}$  compound. It is therefore possible to obtain enriched uranium by removing the  $\text{U}^{4+}$  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%  $^{235}\text{U}$  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                                                                                                                                            |
|-------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>ELECTROMAGNETIC ISOTOPE SEPARATION</b> |                                                                                                                                                                   |                             |                                                                         |                                                                                                            |                                                                                                                                                                           |
| 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 $\geq 50$ mA | NTL B5;<br>NDUL 3;<br>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;<br>NDUL 3;<br>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;<br>NDUL 3;<br>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;<br>NDUL 3;<br>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 $\geq 20,000$ V, output current $\geq 1$ A, voltage regulation $<0.01\%$ over 8-hour interval                     | NTL B5;<br>NDUL 3;<br>NRC H | None identified                                                         | None identified                                                                                            | None identified                                                                                                                                                           |
| DC magnet power supplies                  | Capable of continuously producing a voltage $\geq 100$ V, current $\geq 500$ A, and current or voltage regulation $<0.01\%$ over 8-hour interval.                 | NTL B5;<br>NDUL 3;<br>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 $\geq 38$ cm, pumping speed $\geq 15,000$ liters/sec, vacuum $< 10^{-4}$ Torr ( $1.33 \times 10^{-4}$ 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                                       |
| <b>THERMAL DIFFUSION</b>                |                                                                                                                                                                                                                                                     |                          |                                                                                         |                                                                                                                                   |                                                       |
| 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 <sub>6</sub> 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 <sub>6</sub> -resistant materials, fabricated for containment of UF <sub>6</sub> liquid at pressures of 7 MPa, and for interconnection of individual thermal diffusion columns at the top and bottom ends. | NTL B5                   | UF <sub>6</sub> corrosion-resistant materials                                           | None identified                                                                                                                   | None identified                                       |
| Liquid UF <sub>6</sub> Transfer Pumps   | Pumps capable of pressurizing liquid UF <sub>6</sub> to 7 MPa, leak tight and corrosion resistant to UF <sub>6</sub> .                                                                                                                              | NTL B5                   | Materials resistant to UF <sub>6</sub> corrosion.                                       | None identified                                                                                                                   | None identified                                       |
| Product and Tails Withdrawal Systems    | Expansion valves and heat exchangers for cooling liquid UF <sub>6</sub> to 65 °C and for removal into product and tails cylinders.                                                                                                                  | NTL B5                   | UF <sub>6</sub> corrosion-resistant materials                                           | UF <sub>6</sub> mass spectrometers/ion sources. UF <sub>6</sub> -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                                                                  |
| <b>GASEOUS DIFFUSION</b>    |                                                                                                                                                                                                                                                                    |                          |                                                                                                                                                                                                                                                        |                                                                                                                                                                                                               |                                                                                  |
| 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 <sub>6</sub>                                                                                       | NTL B5;<br>NRC C         | UF <sub>6</sub> -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 <sub>3</sub> . | 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;<br>NRC C         | Nickel-plated steel, aluminum, or nickel alloys containing ≥ 60% nickel; special UF <sub>6</sub> -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 <sup>3</sup> /min of UF <sub>6</sub> and with discharge pressure up to 100 psi designed to operate in UF <sub>6</sub> environment. Pressure ratio between 2:1 and 6:1 | NTL B5;<br>NRC C         | Nickel or high nickel alloy casing or plating on casing; rotor blades and impellers of same material or Al alloys.                                                                                                                                     | UF <sub>6</sub> 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 <sup>3</sup> /min. Adaptable to wide range of gas pressures and pressure disturbances, ease of maintenance, and UF <sub>6</sub> corrosion resistance.              | NTL B5;<br>NRC C         | Materials resistant to UF <sub>6</sub> 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 <sub>6</sub> -corrosion resistant materials, and intended for a leakage pressure change rate <10 N/m <sup>2</sup> (0.0015 psi) per hour under a pressure difference of 100 kN/m <sup>2</sup> (15 psi).                                    | NTL B5;<br>NRC C         | UF <sub>6</sub> 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 <sub>6</sub> to the gaseous diffusion cascades and capable of operating at pressures ≤ 300 kN/m <sup>2</sup> (45 psi). Cylinders and autoclaves ~ 3-m long and 1.8-m in diameter, and UF <sub>6</sub> corrosion resistant. | NTL B5;<br>NRC C         | UF <sub>6</sub> corrosion-resistant materials.    | UF <sub>6</sub> mass spectrometers/ion sources. Autoclaves. UF <sub>6</sub> -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;<br>NRC C         | Nickel, high-nickel alloys, aluminum, or copper   | UF <sub>6</sub> mass spectrometers/ion sources. UF <sub>6</sub> -compatible flow, mass, pressure, and temperature instrumentation.             | Compressor design codes and heat transfer design codes applicable to UF <sub>6</sub> |

(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 $\geq 5$ 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;<br>NRC C                           | Materials resistant to $UF_6$ including stainless steel, aluminum, aluminum alloys, nickel, or alloys containing $\geq 60\%$ 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;<br>NRC C                           | Aluminum, nickel, or alloys bearing $\geq 60\%$ 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;<br>NDUL 3;<br>NRC C;<br>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          |
|-----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|
| <b>GAS CENTRIFUGE</b>                         |                                                                                                                                                                                                                                      |                          |                                                                                                                                                                |                                                                                                                                              |                                         |
| 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;<br>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 $\leq 12$ mm, diameter 75 to 400 mm, made from high strength-to-density material, length-to-diameter ratio typically >2                                                                           | NTL B5;<br>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 $\leq 3$ 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;<br>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;<br>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;<br>NRC B         | HSD materials: maraging steel, high-strength aluminum alloys, filamentary materials suitable for use in composite structures.                                  | Equipment to manufacture 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)**

| <b>Technology</b>                                                      | <b>Sufficient Technology Level</b>                                                                                                                                                                                        | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                       | <b>Unique Test, Production, and Inspection Equipment</b>                                                                       | <b>Unique Software and Parameters</b>                                            |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Static Component: Magnetic Suspension Bearings (includes ring magnets) | Homogeneous ring-shaped annular magnet suspended within UF <sub>6</sub> -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 <sub>6</sub> 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 <sub>6</sub> -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 <sub>6</sub> to centrifuge cascades, desublimers that remove UF <sub>6</sub> from the cascades, product and tails stations for trapping UF <sub>6</sub> into containers.                     | NTL B5; NRC B                   | UF <sub>6</sub> -resistant materials used in piping                             | Mass spectrometers/ion sources. Autoclaves. UF <sub>6</sub> -compatible flow, mass, pressure, and temperature instrumentation. | Heat transfer codes applicable to UF <sub>6</sub> 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;<br>NRC B                           | UF <sub>6</sub> -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;<br>NRC B;<br>NDUL 3;<br>CCL Cat 3A | None identified                                     | None identified                                                                  | None identified                                |
| <b>AERODYNAMIC SEPARATION</b>                            |                                                                                                                                                                                                                                                      |                                            |                                                     |                                                                                  |                                                |
| 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;<br>NRC D                           | UF <sub>6</sub> -resistant materials                | Test facility to measure isotopic separation performance, pressure drops, etc.   | CFD software for nozzle design and performance |
| UF <sub>6</sub> /carrier gas separation systems          | Designed to reduce UF <sub>6</sub> 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 <sub>6</sub> cold traps.                      | NTL B5;<br>NRC D                           | UF <sub>6</sub> -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 <sub>6</sub> -resistant materials.                                                                           | NTL B5;<br>NRC D                           | UF <sub>6</sub> -resistant materials                | None identified                                                                  | None identified                                |

(cont'd)

**Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)**

| <b>Technology</b>                                                                          | <b>Sufficient Technology Level</b>                                                                                                                                                                                                                                                | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                            | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                                                     | <b>Unique Software and Parameters</b>                                  |
|--------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| UF <sub>6</sub> -hydrogen (or helium) gas compressors, gas blowers, and rotary shaft seals | Axial, centrifugal, or positive displacement compressors or gas blowers, suction volume capacity of $\geq 2$ m <sup>3</sup> /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;<br>NRC D                | UF <sub>6</sub> -resistant materials                                                 | UF <sub>6</sub> -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 <sub>6</sub>                                                                                                                                                                                         | NTL B5;<br>NRC D                | UF <sub>6</sub> -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 <sub>6</sub> resistant materials                                                                                                                                                       | NTL B5;<br>NRC D                | UF <sub>6</sub> -resistant materials; bellows seals rather than packing glands       | None identified                                                                                                                                                                                              | None identified                                                        |
| Feed systems/product and tail withdrawal systems                                           | Feed autoclaves to pass UF <sub>6</sub> to the enrichment process; desublimers (cold traps) or solidification or liquefaction stations for removal of UF <sub>6</sub> from the process, product and tails stations for transferring UF <sub>6</sub> into containers               | NTL B5;<br>NRC D                | UF <sub>6</sub> -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;<br>NRC D                | UF <sub>6</sub> -resistant materials                                                 | None identified                                                                                                                                                                                              | None identified                                                        |
| Vacuum systems and pumps                                                                   | Vacuum systems having a suction capacity of $\geq 5$ m <sup>3</sup> /min with vacuum manifolds, headers, and pumps designed for service in corrosive atmosphere. Pumps may have fluorocarbon seals and special working fluids.                                                    | NTL B5;<br>NRC D                | UF <sub>6</sub> -resistant materials. Hydrocarbon or fluoro-carbon 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     |
|-------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|------------------------------------|
| <b>CHEMICAL EXCHANGE AND ION EXCHANGE</b>             |                                                                                                                                                                                                                                                     |                          |                                                                                                                                                                                                                                                         |                                                                                                               |                                    |
| 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 $\leq 30$ seconds. | NTL B5;<br>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 $\leq 30$ seconds and are corrosion resistant to concentrated HCl.                                         | NTL B5;<br>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, production, and operation of reduction cells that are corrosion resistant to concentrated HCl and prevent the reoxidation of $U^{3+}$ to $U^{4+}$ .                                                                           | NTL B5;<br>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;<br>NRC E         | Parts in contact with final feed solutions: suitable materials (glass, fluorocarbon polymers, poly-phenyl sulfate, poly-ether 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;<br>NRC E         | For portions of system processing high-purity $U^{3+}$ streams: suitable materials (glass, fluorocarbon polymers, poly-phenyl 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 capable of operating at a temperature of 100 °C to 200 °C and pressures >0.7 MPa (102 psi)   | NTL B5;<br>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;<br>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          |

(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                                |
|------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|-----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| <b>ATOMIC VAPOR LASER ISOTOPE SEPARATION (AVLIS)</b> |                                                                                                                                                                                                      |                                           |                                                                                         |                                                                                                                                              |                                                               |
| 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;<br>NDUL 3;<br>NRC F;<br>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;<br>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;<br>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;<br>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;<br>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                                                                       |
|-----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|---------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| <b>MOLECULAR LASER ISOTOPE SEPARATION (MLIS)</b>                |                                                                                                                                                                                                                                      |                                           |                                                                                                         |                                                                                                                                                                                                                                                                           |                                                                                                      |
| Laser Systems                                                   | Systems designed for separating uranium isotopes, usually consisting of CO <sub>2</sub> or excimer lasers and para-hydrogen Raman shifters. A spectrum frequency stabilizer is required for operation over extended periods of time. | NTL B5;<br>NDUL 3;<br>NRC F;<br>CCL Cat 6 | Lasing medium: CO <sub>2</sub> , N <sub>2</sub> , He, Ar, Kr, Xe, HCl, Cl <sub>2</sub> , F <sub>2</sub> | Pulsed CO <sub>2</sub> 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 <sub>6</sub> and carrier gas to ≤150 K and which are corrosion resistant to UF <sub>6</sub>                                                                                                | NTL B5;<br>NRC F                          | UF <sub>6</sub> corrosion-resistant materials<br>Ar, N <sub>2</sub>                                     | Test facility to measure diffuser pressure recovery                                                                                                                                                                                                                       | CFD software for compressible gas flow with shocks and significant viscous effects                   |
| UF <sub>5</sub> product collectors                              | Uranium pentafluoride (UF <sub>5</sub> ) solid product collectors consisting of filter, impact, or cyclone-type collectors, or combinations thereof.                                                                                 | NTL B5;<br>NRC F                          | UF <sub>5</sub> / UF <sub>6</sub> corrosion-resistant materials                                         | Test facility to measure pressure drop as a function of collector loading                                                                                                                                                                                                 | None identified                                                                                      |
| UF <sub>6</sub> /carrier gas compressors and rotary shaft seals | Compressors designed for long term operation in UF <sub>6</sub> environment. Seals with feed and exhaust connections; provide a reliable seal against outleakage or inleakage.                                                       | NTL B5;<br>NRC F                          | UF <sub>6</sub> corrosion-resistant materials                                                           | UF <sub>6</sub> /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 <sub>5</sub> (solid) to UF <sub>6</sub> (gas) for subsequent collection in product containers or for transfer for additional enrichment.                                                        | NTL B5;<br>NRC F                          | Fluorinating agent (e.g., ClF <sub>3</sub> ), corrosion-resistant materials                             | Equipment for storage and transfer of fluorinating agent and for collection and transfer of UF <sub>6</sub> . 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 <sub>6</sub> to the enrichment process; desublimers (cold traps) or solidification or liquefaction stations for removal of UF <sub>6</sub> from the process, product and tails stations for transferring UF <sub>6</sub> into containers | NTL B5;<br>NRC F         | UF <sub>6</sub> corrosion-resistant materials                                  | Mass spectrometers/ion sources. Autoclaves. UF <sub>6</sub> -compatible flow, mass, pressure, and temperature instrumentation. | None identified                                                                                                                             |
| UF <sub>6</sub> /carrier gas separation systems  | Systems designed to separate UF <sub>6</sub> from carrier gas (N <sub>2</sub> , Ar).                                                                                                                                                                                | NTL B5;<br>NRC F         | UF <sub>6</sub> corrosion-resistant materials                                  | Cryogenic heat exchangers or cryo-separators, cryogenic refrigeration units, or UF <sub>6</sub> cold traps.                    | None identified                                                                                                                             |
| <b>PLASMA SEPARATION PROCESS</b>                 |                                                                                                                                                                                                                                                                     |                          |                                                                                |                                                                                                                                |                                                                                                                                             |
| 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;<br>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;<br>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;<br>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;<br>NRC G         | Tantalum, yttria-coated graphite, graphite coated with other rare earth oxides | None identified                                                                                                                | None identified                                                                                                                             |

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**Table 5.2-1. Uranium Enrichment Processes Technology Parameters (cont'd)**

| <b>Technology</b>         | <b>Sufficient Technology Level</b>                                                                                                                            | <b>Export Control Reference</b> | <b>Critical Materials</b>        | <b>Unique Test, Production, and Inspection Equipment</b>                                   | <b>Unique Software and Parameters</b> |
|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|----------------------------------|--------------------------------------------------------------------------------------------|---------------------------------------|
| 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;<br>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;<br>CCL Cat 3A          | Liquid He, liquid N <sub>2</sub> | Liquid He and N <sub>2</sub> 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              |
|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| <b>ELECTROMAGNETIC ISOTOPE SEPARATION (EMIS)</b> |                                                                                                                                                                                                                           | Production of HEU for use in nuclear weapons, naval propulsion, research reactors                                                    | Other uranium enrichment technologies |
| Ion source                                       | Obtaining high U <sup>+</sup> 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                                  |
| <b>THERMAL DIFFUSION</b>                         |                                                                                                                                                                                                                           | Production of uranium enriched up to 1.2% <sup>235</sup> 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 <sub>6</sub> 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 <sub>6</sub> 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                                                   |
| <b>GASEOUS DIFFUSION</b>             |                                                                                                                                                                     | 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 <sub>6</sub> 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 <sub>6</sub> 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                       |
| <b>GAS CENTRIFUGE</b>                                                  |                                                                                                                                                                                                                    | 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                       |
| <b>AERODYNAMIC SEPARATION</b>                                                              |                                                                                                                        | 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 <sub>6</sub> carrier-gas separation equipment                                           | Large building ventilation system, H <sub>2</sub> 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 <sub>6</sub> -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                                                 |
|-------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| <b>CHEMICAL AND ION EXCHANGE</b>                      |                                                                                                                                                                                    | 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                                                          |
| <b>ATOMIC VAPOR LASER ISOTOPE SEPARATION (AVLIS)</b>  |                                                                                                                                                                                    | 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<br>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                       |
| <b>MOLECULAR LASER ISOTOPE SEPARATION (MLIS)</b>                |                                                                                                                                                                                  | 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 <sub>5</sub> product collectors                              | High UF <sub>5</sub> collection efficiency, criticality concerns with HEU collection, corrosion resistance                                                                       | None identified                                                                                                   | None identified                       |
| UF <sub>6</sub> /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 <sub>5</sub> 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 <sub>5</sub> /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              |
|------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| <b>PLASMA SEPARATION PROCESS SYSTEMS</b> |                                                                                   | 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, <sup>235</sup> 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  $^{240}\text{Pu}$  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  $^{240}\text{Pu}$  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 ( $^{238}\text{U}$  for Pu,  $^6\text{Li}$  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  $^{238}\text{U}$  in which plutonium can be bred. Cooling requirements and shielding requirements are relatively

### 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.

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.

- (2) **Power reactors.** These are used to generate electric power. Few use fuel enriched to greater than 5–7%  $^{235}\text{U}$ . 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<sub>2</sub>-, or helium-cooled. The longer a given sample of fuel is irradiated, the greater the build-up of <sup>240</sup>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 <sup>240</sup>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 <sup>238</sup>U blanket. Plutonium produced in the fuel generally has a higher fraction of <sup>240</sup>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 <sup>240</sup>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 <sup>238</sup>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 <sup>238</sup>U with neutrons to produce the isotope <sup>239</sup>U, which beta decays (half-life 23 minutes), emitting an electron to become the (almost equally) radioactive <sup>239</sup>Np (neptunium). The neptunium isotope again beta decays (half-life 56 hours) to <sup>239</sup>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 <sup>235</sup>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, <sup>3</sup>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, <sup>238</sup>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, <sup>240</sup>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<sub>2</sub>) 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 <sup>240</sup>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.<sup>9</sup> 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 <sup>235</sup>U atoms are required to make a fission device.<sup>10</sup>

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.

<sup>9</sup> Lack of an adequate supply of electricity is one obstacle to a successful enrichment program; inability to acquire uranium or specialized technologies can be another.

<sup>10</sup> 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**

| <b>Technology</b>                                                                                                 | <b>Sufficient Technology Level</b>                                                                                                                                                                                                              | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                                                                                                                                                                                                                                                                                                                                                             | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                                                                                                                 | <b>Unique Software and Parameters</b> |
|-------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| 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;<br>NRC A                | <i>Fuel:</i> stainless steel clad UO <sub>2</sub> /PuO <sub>2</sub> fuel pellets.<br><i>Coolant:</i> 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;<br>NRC A                | <i>Fuel:</i> 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); <i>Moderator:</i> ordinary (light) water, heavy water (deuterium oxide); <i>Coolant:</i> 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;<br>NRC A                | <i>Fuel:</i> usually Low Enriched Uranium (LEU); <i>Moderator:</i> graphite.<br><i>Coolant:</i> Helium (HTGR), carbon dioxide (AGR)                                                                                                                                                                                                                                                                                   | Specially designed production equipment to fabricate special fuel assemblies. High pressure CO <sub>2</sub> or He gas handling equipment.                                                                                                                                | None Identified                       |

(cont'd)

**Table 5.3-1. Nuclear Fission Reactors Technology Parameters (cont'd)**

| <b>Technology</b>   | <b>Sufficient Technology Level</b>                                                                                                               | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                                                                                                                                                                                         | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                                                                  | <b>Unique Software and Parameters</b> |
|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| Production Reactors | Target and fuel reprocessing facilities to extract plutonium or tritium. High purity graphite. Heavy water production. Uranium metal production. | NTL                             | <i>Fuel:</i> natural or slightly enriched uranium for plutonium production, HEU and <sup>6</sup> Li - enriched target for tritium production.<br><i>Moderator:</i> heavy water, can be graphite.<br><i>Coolant:</i> 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                             | <i>Fuel:</i> HEU or LEU;<br><i>Moderator:</i> graphite, hydrides, organic materials (hydrocarbons), light water, heavy water.<br><i>Coolant:</i> 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)<br>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):<br>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  $^{238}\text{U}$  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,  $^{233}\text{U}$ , 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 ( $\text{HNO}_3$ ). 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  $\text{HNO}_3$ . 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  $\text{PuF}_3$  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  $\text{HNO}_3$  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 ( $\text{HNO}_3$ ) 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  $^{235}\text{U}$  as of  $^{239}\text{Pu}$  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  $^{235}\text{U}$  in natural uranium (0.7 percent) is much lower than the concentration normally used in fission weapons (>90 percent), and the enrichment of  $^{235}\text{U}$  is difficult because of the very slight differences in the physical and chemical properties of the uranium isotopes.

Alternatively,  $^{239}\text{Pu}$  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  $^{238}\text{U}$  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**

| <b>Technology</b>                               | <b>Sufficient Technology Level</b>                                                                                                                                                                                  | <b>Export Control Reference</b>             | <b>Critical Materials</b>                                                                                                                                | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                                                                         | <b>Unique Software and Parameters</b>                                                   |
|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| 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;<br>NDUL 1;<br>NDUL 8;<br>CCL Cat 2B | High-density concrete                                                                                                                                    | Radiation monitoring (applies to all processes)<br>Fuel storage pool<br>Cranes<br>Hot cells<br>Remote manipulators<br>High-density radiation shielding windows<br>Radiation-hardened TV cameras<br>Air filtration<br>Evaporators | Shielding software<br>Criticality software<br>Radiation generation/depletion software   |
| Fuel storage and movement                       | Sufficient storage pool capacity and depth.<br>Ability to move radioactive material.                                                                                                                                | NTL B3;<br>NRC A                            | None identified                                                                                                                                          | Remotely operated cranes<br>Specially designed shipping casks<br>Criticality control                                                                                                                                             | None identified                                                                         |
| Fuel disassembly (breaching)                    | Capability to separate cladding from fissile material mechanically or chemically.                                                                                                                                   | NTL B3;<br>NRC A                            | None identified                                                                                                                                          | Cut-off wheel<br>Shear dissolver (for Al cladding)<br>Laser                                                                                                                                                                      | None identified                                                                         |
| Fuel dissolution                                | Ability to handle highly corrosive liquids containing radioactivity.<br>Adequate knowledge of uranium, plutonium, and fission product chemistry.                                                                    | NTL B3;<br>NRC A                            | Nitric acid (HNO <sub>3</sub> )<br>Hydrogen fluoride (HF)<br>HNO <sub>3</sub> 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.<br>Understand distribution of uranium, plutonium, and fission products between two immiscible liquids.                                                              | NTL B3;<br>NRC A                            | None identified                                                                                                                                          | Mixer/settlers<br>Pulse columns<br>Centrifugal contactors                                                                                                                                                                        | Distribution coefficients for many elements.<br>Aqueous solubility for many substances. |

(cont'd)

**Table 5.4-1. Plutonium Extraction (Reprocessing) Technology Parameters (cont'd)**

| <b>Technology</b>                  | <b>Sufficient Technology Level</b>                                                                                                                            | <b>Export Control Reference</b>            | <b>Critical Materials</b>                                                                                                                                        | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                      | <b>Unique Software and Parameters</b>                                                 |
|------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| U and Pu product purification      | Cognizant of liquid-liquid extraction systems<br>Familiar with ion exchange resin systems                                                                     | NTL B3;<br>NTL 3;<br>NRC A                 | Tri-n-butyl phosphate (TBP)<br>Refined kerosene<br>Ion exchange resins                                                                                           | Mixer/settlers<br>Pulse columns<br>Centrifugal contactors<br>Chemical holding or storage vessels                                                                              | Distribution coefficients for many elements<br>Aqueous solubility for many substances |
| Metal preparation (Pu exclusively) | Ability to handle plutonium in glove boxes                                                                                                                    | NTL B3;<br>NDUL 2;<br>CCL Cat 1C;<br>NRC A | HF Reducing agents (high-purity Ca or Mg)<br>CaF <sub>2</sub> or MgF <sub>2</sub> (used as liner for reduction bomb)<br>Iodine (serves as catalyst in reduction) | Drying Furnace; Fluoride resistant (Monel)<br>Furnace capable of reaching 600 °F<br>Sealed reaction tube<br>Temperature control/measurement<br>High temperature furnace (arc) | None identified                                                                       |
| Waste treatment/recycle            | Ability to recycle valuable components (TBP, HNO <sub>3</sub> )<br>Ability to process streams containing high levels of radioactivity and hazardous materials | NTL B3;<br>NRC A                           | Resistant to HNO <sub>3</sub> (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.<br>Sufficient storage capacity for fuel.<br>Cranes of sufficient capacity to handle shipping casks.    | None identified                                            | Use reactor storage pool if close proximity to reprocessing facility.<br>Possible storage (dry) in specially designed casks.                      |
| Fuel disassembly (breaching)                    | Capability to remove as much extraneous material from fuel element as possible.<br>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.<br>Aqueous solution from separation process contains extremely hazardous radioactive materials.                     | None identified                                            | Use one of the nonaqueous processes.<br>Replace solvent extraction with ion exchange process.<br>Use a precipitation process (bismuth phosphate). |
| U and Pu product purification                   | Ability to obtain a pure product.<br>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).<br>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.<br>Minimal recycling (expensive but may be used for limited production).                |

## SECTION 5.5—LITHIUM PRODUCTION

### OVERVIEW

This subsection discusses chemical methods for separation of  ${}^6\text{Li}$  from natural lithium, which is predominantly composed of the isotope  ${}^7\text{Li}$ .  ${}^6\text{Li}$  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  ${}^6\text{Li}$  is combined with deuterium to form the compound  ${}^6\text{Li D}$  (lithium-6 deuteride). Neutrons from a fission “primary” device bombard the  ${}^6\text{Li}$  in the compound, liberating tritium, which quickly fuses with the nearby deuterium. The  $\alpha$  particles, being electrically charged and at high temperatures, contribute directly to forming the nuclear fireball. The neutrons can bombard additional  ${}^6\text{Li}$  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.

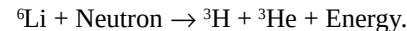
Lithium enriched in the isotope  ${}^6\text{Li}$  remains a controlled material because of its utility in the production of compact and highly efficient thermonuclear secondaries. Two-stage nuclear weapons incorporating a lithium-deuteride-fueled component can deliver greater nuclear yield from a smaller 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,  ${}^6\text{Li}$  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  ${}^7\text{Li}$ , consisting of three protons and four neutrons; less common, comprising 7.4 percent of normal lithium, is  ${}^6\text{Li}$ , which has three protons and three neutrons in its

### Highlights

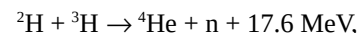
- Lithium-6, combined with deuterium, is a key ingredient of modern thermonuclear weapons.
- Lithium-6 can be separated from the more common  ${}^7\text{Li}$  isotope by purely chemical means using the fact that  ${}^6\text{Li}$  will migrate to a mercury amalgam and  ${}^7\text{Li}$  to a lithium hydroxide solution when the amalgam and hydroxide solutions are intimately mixed.
- The presence of a  ${}^6\text{Li}$  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  ${}^6\text{Li}$  in 1963 because it had acquired an adequate stockpile of the material for the foreseeable future.

nucleus. In a relatively crude sense,  ${}^6\text{Li}$  can be thought of as consisting of an alpha particle ( ${}^4\text{He}$ ) and a deuteron ( ${}^2\text{H}$ ) bound together. When bombarded by neutrons,  ${}^6\text{Li}$  disintegrates into a triton ( ${}^3\text{H}$ ) and an alpha:

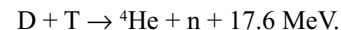


This is the key to its importance in nuclear weapons physics.

The nuclear fusion reaction which ignites most readily is



or, phrased in other terms, deuterium plus tritium produces  ${}^4\text{He}$  plus a neutron plus 17.6 MeV of free energy:



Lithium-7 also contributes to the production of tritium in a thermonuclear secondary, albeit at a lower rate than  ${}^6\text{Li}$ . The fusion reactions derived from tritium produced from  ${}^7\text{Li}$  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.

### ***RATIONALE***

Lithium-6 is most often separated from natural lithium by the *COLEX* (Column exchange) electrochemical process, which exploits the fact that  ${}^6\text{Li}$  has a greater affinity for mercury than does  ${}^7\text{Li}$ . 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  ${}^6\text{Li}$  concentrates in the amalgam, and the more common  ${}^7\text{Li}$  migrates to the hydroxide. A counter flow of amalgam and hydroxide passes through a cascade of stages until the desired enrichment in  ${}^6\text{Li}$  is reached. The  ${}^6\text{Li}$  product can be separated from the amalgam, and the “tails” fraction of  ${}^7\text{Li}$  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  ${}^6\text{Li}$  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  ${}^6\text{Li}$  in the quantities needed for the manufacture of large nuclear stockpiles. Russia exploded a device making use of  ${}^6\text{Li}$  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  ${}^6\text{Li}$  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;<br>NRC 110.8     | Mercury<br>Lithium salts<br>Nickel<br>Carbon steel | Electrolysis cells<br>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;<br>NRC 110.8     | Mercury<br>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;<br>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;<br>NRC 110.8     | Mercury<br>Nitric acid                             | Mercury cleaning system                                                                                                                             | None identified                                                                                   |

**Table 5.5-2. Lithium Production Reference Data**

| <b>Technology</b>        | <b>Technical Issues</b>                                                                                               | <b>Military Applications</b>                                                                                                        | <b>Alternative Technologies</b>                                                                                                                                                               |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrolysis             | Ability to control large d.c. currents at low voltages                                                                | Fusion weapons                                                                                                                      | None                                                                                                                                                                                          |
| Enrichment               | Adequate supply of high purity lithium salts and mercury.<br>Knowledge of lithium hydroxide/mercury/aqueous chemistry | <sup>6</sup> LiD (lithium-6 deuteride) used as fusion weapon fuel.<br><sup>6</sup> Li used as target material in tritium production | Electroexchange (ELEX) process using a series of stirred tray contactors.<br>Liquid-liquid extraction systems using macrocyclic 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

### *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.

whatever. Several ways to produce neutrons at the appropriate moment have been developed.

#### *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  $^{210}\text{Po}$  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  $^9\text{Be}$  or some other light element by alpha particles. This requires a strong source of alpha particles, something of the order of 10 curies of  $^{210}\text{Po}$  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  $^{210}\text{Po}$  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  $^{235}\text{U}$  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<sup>11</sup> 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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<sup>11</sup> 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  $^{239}\text{Pu}$  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  $^{238}\text{U}$ , 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                                                                                                                                                                 |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>WEAPONS</b>                                                        |                                                                                                                                                                                                                                         |                          |                                                                                                                                                                               |                                                                                                                                                                                                                                            |                                                                                                                                                                                                |
| 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 micro-sec into load <40 ohms. | NDUL 6;<br>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;<br>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;<br>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    |
| <b>INITIATORS</b>                                                                      |                                                                                                                                |                          |                                                                                                                                                                                                                            |                                                                                                                                                                                                                                    |                                                                                                                                                                |
| Alpha-induced neutron emission (crushable initiators such as the one used at Trinity). | Identification of performance characteristics of alpha-n initiators.                                                           | NDUL 8;<br>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)**

| <b>Technology</b>                                                                                                                          | <b>Sufficient Technology Level</b>                                                      | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                            | <b>Unique Test, Production, and Inspection Equipment</b>                                 | <b>Unique Software and Parameters</b>                                                                           |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
| 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;<br>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;<br>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                                                                    |
|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| <b>WEAPONS</b>                                                         |                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                   |                                                                                             |
| 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. |

(cont'd)

**Table 5.6-2. Nuclear Weapons Design and Development Reference Data (cont'd)**

| Technology                                                                             | Technical Issues                                                                                                                                                                                                                                         | Military Applications                                                                                                                                                                                                         | Alternative Technologies                                                                                   |
|----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| <b>INITIATORS</b>                                                                      |                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                               |                                                                                                            |
| 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                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|---------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Safing</b> | <p>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.</p> <p><i>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 (&gt;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.<sup>12</sup> 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.</i></p> |
| <b>Arming</b> | <p>Placing the nuclear warhead in a ready operational state, such that it can be initiated under specified firing conditions.</p> <p><i>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.</i></p>                                                                                                                                                                                                                                                         |
| <b>Fuzing</b> | <p>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.</p> <p><i>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.</i></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |

<sup>12</sup> 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.

**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

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 |
|-----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|------------------------------|---------------------------------------------------|--------------------------------|
| <b>SAFING DEVICES</b>                                                                                                                         |                                                                                                                      |                                                 |                              |                                                   |                                |
| Mechanical devices designed to provide for positive interruption and connection of explosive or pyrotechnic devices                           | Any capability is a concern.                                                                                         | WA ML 3;<br>USML III;<br>MTCR 2;<br>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;<br>USML III;<br>USML 121.16            | None identified              | None identified                                   | None identified                |
| Devices designed to detect one or more of the following phenomena:<br>- air flow<br>- linear or angular acceleration<br>- barometric pressure | Simple barometric sensor<br>Low-cost accelerometer                                                                   | WA ML 3;<br>USML III                            | None identified              | None identified                                   | None identified                |
| <b>ARMING DEVICES</b>                                                                                                                         |                                                                                                                      |                                                 |                              |                                                   |                                |
| Precision mechanical devices designed to use any of the following:<br>- air flow<br>- linear or angular acceleration<br>- barometric pressure | Externally powered (spring or electrical) switches enabled by one or more of the stimuli listed in Technology Column | WA ML 4;<br>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                                                       |
|------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>FUZING</b>                                                                                        |                                                                                                                      |                                               |                                                                                                                                                                                                     |                                                       |                                                                                      |
| 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 characterized 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)**

| <b>Technology</b>                                                                                                                                    | <b>Sufficient Technology Level</b>                                                         | <b>Export Control Reference</b> | <b>Critical Materials</b>               | <b>Unique Test, Production, and Inspection Equipment</b>                                                             | <b>Unique Software and Parameters</b> |
|------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|---------------------------------|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| Compact, high-performance stripline or microstrip microwave components, including--<br>- low-noise balanced mixers<br>- high ratio circulators       | Conventional stripline design techniques                                                   | None Identified                 | Low-loss dielectric substrate materials | Swept frequency analyzers<br>Engineering models                                                                      | None identified                       |
| <b>FIRING SETS</b>                                                                                                                                   |                                                                                            |                                 |                                         |                                                                                                                      |                                       |
| Capacitive discharge units                                                                                                                           | Conventional high-voltage (>300 V) capacitors, with capacitance greater than 25 nanofarads | NDUL 6;<br>CCL Cat 3A           | None identified                         | None identified                                                                                                      | None identified                       |
| Cold cathode tubes and switches                                                                                                                      | Anode delay: <10 micro-seconds;<br>Peak voltage: 2,500 V;<br>Peak current: >100 Å          | NDUL 6;<br>CCL Cat 3A           | None identified                         | None identified                                                                                                      | None identified                       |
| Pyrotechnic logic and delay devices                                                                                                                  | Any capability is a concern.                                                               | NDUL 6;<br>CCL Cat 3A           | None identified                         | None identified                                                                                                      | None identified                       |
| Detonators and initiator couplers and connectors, including:<br>- exploding bridge wires<br>- exploding foil<br>- hot wire<br>- semiconductor bridge | Conventional weapons squibs.                                                               | NDUL 6;<br>CCL Cat 3A           | None identified                         | Specially designed explosive component test facilities or load simulators which do not require the use of explosives | None identified                       |
| <b>OPERATIONAL SECURITY</b>                                                                                                                          |                                                                                            |                                 |                                         |                                                                                                                      |                                       |
| 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                                                                                                                             |
|-----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>SAFING DEVICES</b>                                                                                                                         |                                                                                                         |                                                                                                                              |                                                                                                                                                      |
| 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:<br>- air flow<br>- linear or angular acceleration<br>- 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                                                                                            |
| <b>ARMING DEVICES</b>                                                                                                                         |                                                                                                         |                                                                                                                              |                                                                                                                                                      |
| Precision mechanical devices designed to use any of the following:<br>- air flow<br>- linear or angular acceleration<br>- 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). |
| <b>FUZING</b>                                                                                                                                 |                                                                                                         |                                                                                                                              |                                                                                                                                                      |
| 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: <ul style="list-style-type: none"> <li>- low-noise balanced mixers</li> <li>- high ratio circulators</li> </ul>                    | 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                                                                           |
| <b>FIRING SETS</b>                                                                                                                                                                                                    |                                                                                                                                                                |                                                                                                                            |                                                                                                    |
| 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: <ul style="list-style-type: none"> <li>- exploding bridge wires</li> <li>- exploding foil</li> <li>- hot wire</li> <li>- semiconductor bridge</li> </ul> | Reliability and precision of initiation vs. safety                                                                                                             | Technology common to some aimable ordnance warhead concepts                                                                | Detonating devices derived from commercial civil explosives                                        |
| <b>OPERATIONAL SECURITY</b>                                                                                                                                                                                           |                                                                                                                                                                |                                                                                                                            |                                                                                                    |
| 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.,  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ ). 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 ( $^4\text{He}$  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).<sup>13</sup> If, however, correctly sized particles containing alpha-emitting isotopes

<sup>13</sup> The rate at which a heavy charged particle loses energy is proportional to the square of its charge.

### 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.

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  $^{60}\text{Co}$  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

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**

| <b>Technology</b>                                             | <b>Sufficient Technology Level</b>                                                                                                                                                               | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                                                                                                                               | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                                                                                                  | <b>Unique Software and Parameters</b>                                                                                                           |
|---------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
| 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  $\pm 1$  nm (corresponding to an optical surface finish prepared by diamond turning with ion beam polishing) to  $\pm 10$   $\mu$ m (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                                       |
|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|---------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|----------------------------------------------------------------------|
| <b>MANUFACTURING EQUIPMENT</b>                                                                            |                                                                                                                                                                                                                     |                                     |                                                                                                                           |                                                   |                                                                      |
| 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;<br>NDUL 1;<br>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;<br>NDUL 1;<br>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;<br>NDUL 1;<br>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;<br>NDUL 1;<br>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;<br>NDUL 1;<br>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)**

| <b>Technology</b>                                                          | <b>Sufficient Technology Level</b>                                                                                                                                                                                  | <b>Export Control Reference</b>                | <b>Critical Materials</b>                                                                              | <b>Unique Test, Production, and Inspection Equipment</b> | <b>Unique Software and Parameters</b>                                |
|----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------------------|
| 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;<br>MTCR 3;<br>WA Cat 2B;<br>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;<br>WA Cat 1B;<br>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;<br>CCL Cat 2B                          | Specially designed power supplies with power output of $\geq 5$ 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;<br>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;<br>NDUL 1;<br>CCL Cat 2B            | None identified                                                                                        | Control units                                            | None identified                                                      |

(cont'd)

**Table 5.9-1. Manufacturing of Nuclear Components Technology Parameters (cont'd)**

| <b>Technology</b>                                                                 | <b>Sufficient Technology Level</b>                                                                                                                                                                                                                                | <b>Export Control Reference</b>                 | <b>Critical Materials</b> | <b>Unique Test, Production, and Inspection Equipment</b>                  | <b>Unique Software and Parameters</b>                                                              |
|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|---------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| 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 $\geq 15$ g RMS, between 20 Hz and 2,000 Hz, imparting forces of $\geq 30$ kN (5,625 lb) | NDUL 1;<br>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;<br>MTCR 15;<br>CCL Cat 9B;<br>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 $\geq 30$ kN (5,625 lb) would be a concern.                                                                                                             | NDUL 1;<br>MTCR 15;<br>CCL Cat 9B;<br>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;<br>CCL Cat 2B                           | None identified           | Mandrels, clamps, and shrink fit machines.                                | None identified                                                                                    |
| Rotor-straightening equipment                                                     | Any capability is a concern.                                                                                                                                                                                                                                      | NDUL 3;<br>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;<br>CCL Cat 2B                           | None identified           | Mandrels and dies                                                         | None identified                                                                                    |
| Centrifugal multiplane balancing machines for flexible rotors                     | Any capability is a concern.                                                                                                                                                                                                                                      | NDUL 3;<br>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;<br>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 $\geq 300$ keV, but $< 25$ MeV; and with a figure of merit (K) of $\geq 0.25$ , where $K = 1.7 \times 10^3 V^{2.65} Q$ ; or an accelerator peak electron energy $\geq 15$ MeV and a peak power $> 40$ MW. | NDUL 5;<br>CCL Cat 3A               | None identified                                                                                                                                         | None identified                                                                                                                                          | None identified                                                                 |
| Remote manipulators                                                             | Such equipment is useful, but not necessary for nuclear programs.                                                                                                                                                                                                             | NDUL 8;<br>CCL Cat 2B;<br>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.            |
| <b>METROLOGY</b>                                                                |                                                                                                                                                                                                                                                                               |                                     |                                                                                                                                                         |                                                                                                                                                          |                                                                                 |
| Numerically controlled dimensional inspection machines                          | Accurate computer controlled coordinate measuring machines (CMM) would be a concern.                                                                                                                                                                                          | WA Cat 2B;<br>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 $\leq 0.5 \mu\text{m}$ within a measuring range of 0.2 mm                                                                                                                                                                                  | WA Cat 2B;<br>NDUL 1                | Measurement probes, sensors, etc.                                                                                                                       | None identified                                                                                                                                          | None identified                                                                 |
| Linear measuring machines using linear voltage differential transformer systems | Having both: linearity $\leq 0.5\%$ within a measuring range up to 5 mm; and drift $\leq 0.2\%$ per day at a standard ambient room temperature $\pm 1$ K.                                                                                                                     | WA Cat 2B;<br>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, <i>and</i> the capability to maintain, for at least 8 hours, over a temperature range of $\pm 1$ K around a standard temperature and pressure, both: a resolution $\leq 0.4 \mu\text{m}$ over full scale <i>and</i> a measurement uncertainty $\leq (0.2 \text{ L}/2,000 \mu\text{m})$ | WA Cat 2B;<br>NDUL 1                | Measurement probes, sensors, and lasers                                                                                                                                                   | None identified                                                                                        | None identified                                               |
| Angular displacement measuring devices                                                        | Having an angular position deviation $\leq 0.001$ deg                                                                                                                                                                                                                                                        | WA Cat 2B;<br>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 $5.0 \mu\text{m}$ per 5 mm and an angular position deviation equal to or less than 0.05 deg                                                                                                                        | NDUL 1;<br>CCL Cat 2B               | Measurement probes, sensors, etc.                                                                                                                                                         | None identified                                                                                        | None identified                                               |
| <b>ROBOTICS</b>                                                                               |                                                                                                                                                                                                                                                                                                              |                                     |                                                                                                                                                                                           |                                                                                                        |                                                               |
| 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;<br>NDUL 1;<br>CCL Cat 2B | Sensors, end-effectors, ruggedized hydraulic lines (e.g., self-sealing lines), hydraulic fluids with flash points $> 839$ K ( $565^\circ\text{C}$ ) 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;<br>NDUL 1;<br>CCL Cat 2B | Sensors, end-effectors, electronics capable of operating in radiation levels of $5 \times 10^4$ grays [ $5 \times 10^6$ 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                                                                                      |
|----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| <b>MANUFACTURING</b>                                                                                     |                                                                                                                                                                                                        |                                                                                                                                                                                                                                                              |                                                                                                               |
| 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 centrifuge 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 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 balancing machines could be used.                                                                                       |
| Centrifugal multiplane balancing machines for hollow cylindrical 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. However, 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 electrical, 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                                                                                                                                                                                   |
| <b>METROLOGY</b>                                                                                             |                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                            |                                                                                                                                                                                                  |
| 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 alignment 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. |

**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 alignment 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 alignment 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 alignment 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.                                                                                                                                           |
| <b>ROBOTICS</b>                                                                           |                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                             |
| 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.<sup>14</sup> 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.<sup>15</sup> Many states of concern for nuclear proliferation<sup>16</sup> 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<sup>17</sup> 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

### 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 CTBT, a prohibited test of an explosively assembled device from one which is allowed.

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

<sup>14</sup> For example, laser and particle beam fusion.

<sup>15</sup> 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.

<sup>16</sup> India, Iraq, and Pakistan are not CTBT signatories; all five nuclear weapons states are.

<sup>17</sup> In a *hydrodynamic* test, inert material (e.g., <sup>238</sup>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.<sup>18</sup> 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.

<sup>18</sup> 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.

## **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

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,<sup>19</sup> 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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<sup>19</sup> 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                                                                                            |
|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|--------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| <b>HYDRODYNAMIC TESTING</b>                       |                                                                                                                                                                     |                          |                                            |                                                                                                                                  |                                                                                                                           |
| 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)**

| <b>Technology</b>                      | <b>Sufficient Technology Level</b>                                                                                                                                                               | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                                                                                                           | <b>Unique Test, Production, and Inspection Equipment</b>                                                      | <b>Unique Software and Parameters</b>                                                                                                            |
|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| 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;<br>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.<br><br>Special equipment to halt the propagation of physical bomb debris. | NDUL 5;<br>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;<br>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;<br>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)**

| <b>Technology</b>                                                                                                               | <b>Sufficient Technology Level</b>                            | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                            | <b>Unique Test, Production, and Inspection Equipment</b>                                                                                   | <b>Unique Software and Parameters</b>                                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| 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;<br>CCL Cat 2B           | None identified                                                                      | None identified                                                                                                                            | None identified                                                                                                                                     |
| <b>HYDRONUCLEAR TESTING (up to few ton yield range)</b>                                                                         |                                                               |                                 |                                                                                      |                                                                                                                                            |                                                                                                                                                     |
| 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.  |

(cont'd)

**Table 5.10-1. Nuclear Weapons Development Testing Technology Parameters (cont'd)**

| <b>Technology</b>                              | <b>Sufficient Technology Level</b>                                                                               | <b>Export Control Reference</b> | <b>Critical Materials</b> | <b>Unique Test, Production, and Inspection Equipment</b>                                                  | <b>Unique Software and Parameters</b>                                                                                             |
|------------------------------------------------|------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| 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 <sup>2</sup>                                       | 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                                                                                                                     |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>NUCLEAR YIELD TESTING (Underground)</b>                  |                                                                                                                                          |                          |                                                                                                                                                 |                                                                                                                                                                           |                                                                                                                                                    |
| 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 bore-shaft 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 <sup>2</sup>                                                                             | NDUL 7; CCL Cat 6A       | None identified                                                                                                                                 | None identified                                                                                                                                                           | None identified                                                                                                                                    |
| Microchannel plates                                         | Rise time order of 1 ns or faster; area > 20 cm <sup>2</sup>                                                                             | 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)**

| <b>Technology</b>                                  | <b>Sufficient Technology Level</b>                                                                                                                                                                                                        | <b>Export Control Reference</b> | <b>Critical Materials</b> | <b>Unique Test, Production, and Inspection Equipment</b>                            | <b>Unique Software and Parameters</b>                                                                                                          |
|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| 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 understanding 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)**

| <b>Technology</b>             | <b>Sufficient Technology Level</b>                                                                                                                          | <b>Export Control Reference</b> | <b>Critical Materials</b>                               | <b>Unique Test, Production, and Inspection Equipment</b>                  | <b>Unique Software and Parameters</b>                                                                                                            |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Streak cameras                | Cameras capable of 50 ns or better time resolution.                                                                                                         | NDUL 5;<br>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;<br>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 predictions 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;<br>CCL Cat 3A           | None identified                                         | None; available commercial OTS                                            | None, but ability to forecast 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)**

| <b>Technology</b>            | <b>Sufficient Technology Level</b>                                                                                                                         | <b>Export Control Reference</b>      | <b>Critical Materials</b> | <b>Unique Test, Production, and Inspection Equipment</b> | <b>Unique Software and Parameters</b>                                                                                     |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|---------------------------|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| 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;<br>CCL Cat 3A;<br>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                                                                                                                                                                                                                                       |
|---------------------------------------------------|---------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>HYDRODYNAMIC TESTING</b>                       |                                                                                                               |                                                                                                       |                                                                                                                                                                                                                                                                |
| Pin domes                                         | Electrical connections, readouts.<br>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                                                                                                                                                       |

(cont'd)



**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.                                                                 |
| <b>HYDRONUCLEAR TESTING (up to few ton yield range)</b>                                                                          |                                                                                                                                                                        |                                                                                                                                             |                                                                                                                                 |
| 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 impedance 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                                                                                                                                                                                   |
|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>NUCLEAR YIELD TESTING (Underground)</b>                  |                                                                                                                                                                        |                                                                                                                                                                                                                                                            |                                                                                                                                                                                                            |
| 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                                                                                                                                                                                             |

(cont'd)

**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 recording 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.

### 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.

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

### 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**

| <b>Technology</b>                                                                                                                                                                                                                           | <b>Sufficient Technology Level</b>                                                                                                        | <b>Export Control Reference</b> | <b>Critical Materials</b>   | <b>Unique Test, Production, and Inspection Equipment</b> | <b>Unique Software and Parameters</b> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|-----------------------------|----------------------------------------------------------|---------------------------------------|
| 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, sub-systems or equipment developed or modified for security communications networks or C <sup>4</sup> I systems that perform integrated C <sup>4</sup> I 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 access 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 <sup>4</sup> I systems that perform integrated C <sup>4</sup> I 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 <sup>4</sup> I 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  $1.50 \text{ gm/cm}^3$ ). 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 ( $101.4^\circ\text{C}$ ) and normal water ( $100^\circ\text{C}$ ) or the difference in boiling points between deuterium ( $-249.7^\circ\text{C}$ ) and hydrogen ( $-252.5^\circ\text{C}$ ). 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  $^{235}\text{U}$  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<sub>2</sub>O. 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.<sup>20</sup>

#### ***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 <sup>6</sup>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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<sup>20</sup> *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 <sub>2</sub> S 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 <sub>2</sub> S 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)**

| <b>Technology</b>                                                                                                             | <b>Sufficient Technology Level</b>                                                                                                            | <b>Export Control Reference</b> | <b>Critical Materials</b>                                                                                   | <b>Unique Test, Production, and Inspection Equipment</b> | <b>Unique Software and Parameters</b> |
|-------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|---------------------------------------|
| 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;<br>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;<br>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;<br>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;<br>CCL Cat 1B           | Stainless steel lining                                                                                      | None identified                                          | None identified                       |

**Table 5.12-2. Heavy Water Production Reference Data**

| <b>Technology</b>                                                                                                              | <b>Technical Issues</b> | <b>Military Applications</b>                                            | <b>Alternative Technologies</b>                        |
|--------------------------------------------------------------------------------------------------------------------------------|-------------------------|-------------------------------------------------------------------------|--------------------------------------------------------|
| 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 ( $^3\text{H}$ ) 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  $^3\text{He}$  (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  $\text{T}_2\text{O}$ ) 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  $^3\text{He}$  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  $^6\text{Li}$  [ $^6\text{Li}(\text{n}, \text{a})^3\text{H}$ ] 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  $5.6 \times 10^7$  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  $^3\text{He}$ .

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;<br>NRC L         | <sup>6</sup> 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;<br>NRC A         | <sup>6</sup> 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); <sup>6</sup> 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 |