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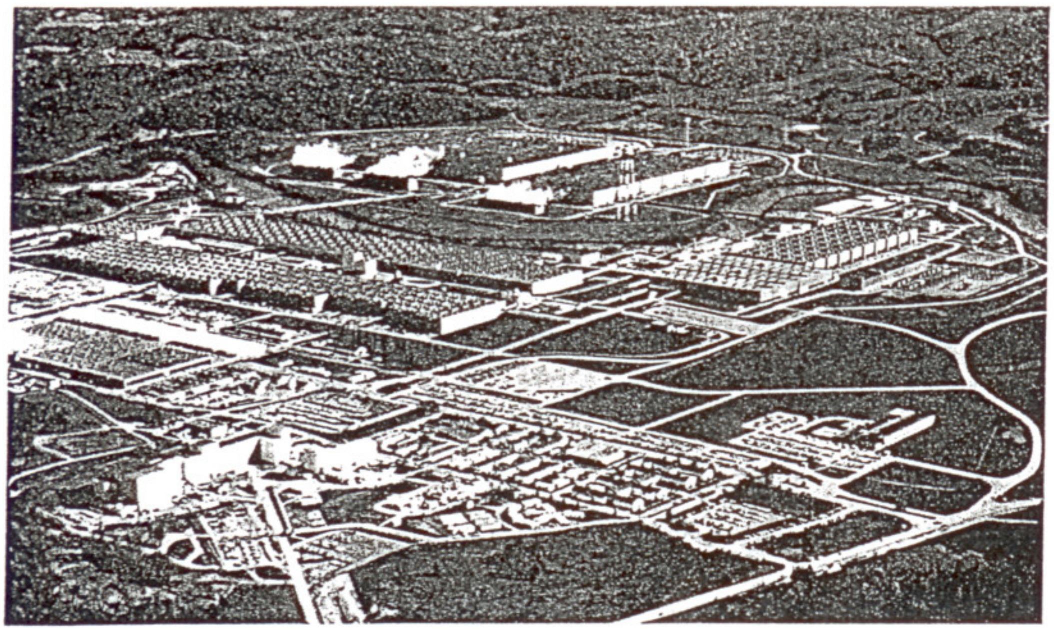
Nuclear weapon proliferation: Technical fundamentals



The K-25 gaseous diffusion uranium separation plant at Oak Ridge, TN.

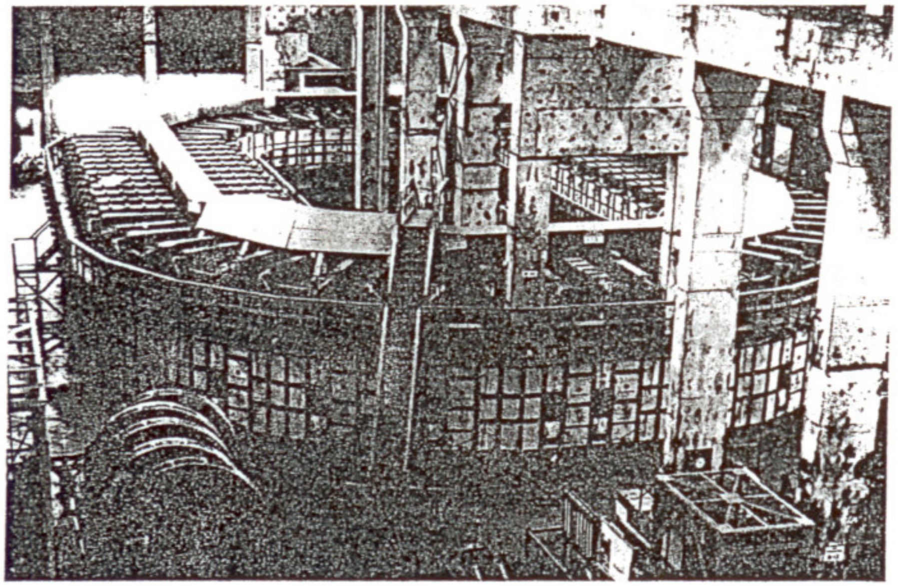
The attached article, in outline format, on the technical fundamentals of nuclear proliferation is designed to be a quick reference for nontechnical personnel to the basic technical aspects of nuclear weapon development. In the interest of conciseness, some statements are made that may have exceptions under certain specialized conditions, but the statements will hold in nearly all proliferation situations. Readers wishing more background are urged to attend the Department of Energy (DOE) Office of Export Control and International Safeguard's Nuclear Proliferation Workshop. Call (301) 365-0060 for further information. Also included is a brief outline of proliferation controls. More information is available in the 53-page DOE *Guide To Technology Security* issued May 1992. Call (202) 586-2112 for copies.

In analyzing proliferant programs, it is apt to be misleading to expect these programs to mirror image the U.S. nuclear weapon program (at any stage) and drawing too much on the practices in the U.S. base will be misleading. This is particularly true with today's high level of environmental, safety, and health concerns in the DOE complex and the U.S. at large.

I. Fissile material is required for all nuclear weapons (roughly 10 to 40 kg per weapon, 0.5 to 2 liters in volume, depending on materials and design).

a. Uranium-235

- Usable in either gun-assembled or implosion weapons
- Occurs naturally at a concentration of 0.71% in uranium (most of which is uranium-238)
- Must be separated from natural uranium by enrichment methods (generally one wants 90% or higher enrichment for weapons use)
- Used in the Hiroshima uranium-235 gun-assembled bomb



A section of the electromagnetic isotope separation equipment used for enriching uranium during World War II in Oak Ridge, TN.

b. Plutonium-239

- Not found naturally, must be made in nuclear reactors by irradiating uranium-238 (the common form) with neutrons
- Used in the first nuclear detonation, the Trinity test, as well as the Nagasaki bomb (both implosion assembled)

c. Other fissile materials exist but are generally not of concern for weapons use because of their high cost to produce or obtain or because of undesirable physical properties. An exception may be uranium-233, which can be made from thorium in a nuclear reactor. India has large thorium deposits and has pursued a thorium-based breeder-reactor fuel cycle for civil nuclear power.

d. Proliferant nuclear weapon programs can be expected to have only limited amounts of fissile material in usable form in their first years.

II. Uranium enrichment (isotope separation)

- Enrichment is a costly difficult process requiring large or highly sophisticated plants for useful production rates. Most plants will use large amounts of electric power.
- Key components for most enrichment processes are under international export control.
- Most western power reactors require slightly enriched fuel (3%) and thus many countries operate enrichment plants producing low enriched uranium. All enrichment processes can be made to produce high enrichments. The amount of work needed to go from natural uranium at 0.71% to 3% is greater than that needed to go from 3% on to weapons grade (>90%). Thus obtaining power-reactor-grade fuel could shorten the time a proliferant needs to produce weapons-grade uranium.

Enrichment Methods:

a. Electromagnetic—the only method that is completely unclassified; very inefficient; used by the U.S. in World War II (Oak Ridge); used by Iraq with indigenous design—Iraq benefited from publications but did not copy earlier designs and got very poor performance; with time they probably would have improved it to slightly better than the original U.S. plants.

b. Gaseous Diffusion—used by the U.S. in World War II and afterwards (only operating U.S. systems); relatively inefficient; also used by France and Eurodiff consortium (France, Belgium, Italy, Spain—originally included Iran, France retains control over the technology). The U.S.S.R., the U.K., and China also built and used these plants.

c. Centrifuge—developed by Urenco consortium (U.K., Netherlands, Germany); by U.S.S.R., Japan, and others including the U.S.. Efficiency varies with the level of technology but can be high. Pakistan believed to have stolen Urenco drawings to build Kahuta plant. The best rotors are made from ultrahigh strength maraging steels or carbon fiber composites.

d. Chemical Exchange—France has pursued a solvent extraction system believed to be inefficient. The Japanese Asahi Company has developed an ion exchange process claimed to be efficient, but no full-scale plants have been built and work has been cut back.

e. Aerodynamic—less efficient than gaseous diffusion, developed by Germany (Becker nozzle process) and sold to Brazil. Brazil believed to have abandoned. South Africa indigenously developed a related process (Helikon) and built a pilot plant.

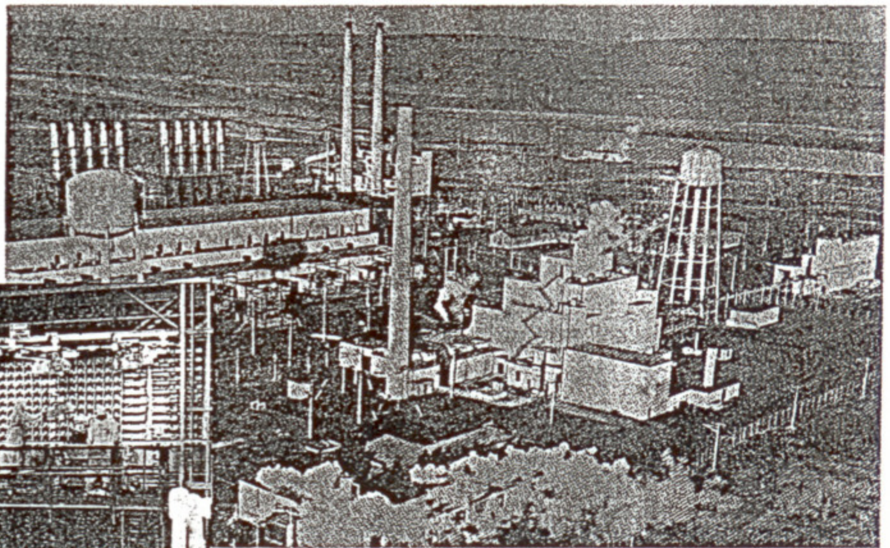
d. Laser and plasma—newer processes with potential for high efficiency; U.S. is pursuing atomic vapor laser isotope separation (AVLIS) but full-scale plants have not yet been built and many problems have been found; other countries are also pursuing these methods.

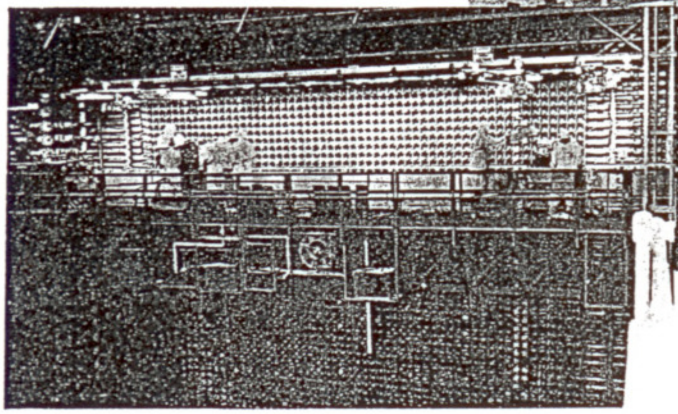
III. Plutonium production

- All reactors operating on the uranium fuel cycle produce plutonium.
- The first production reactors were built by the U.S. near Hanford, WA, during World War II for production of plutonium-239.
- For weapons use, the fuel rods should be discharged frequently to avoid excessive build-up of plutonium-240, which is undesirable in weapons. Thus reactors that can be easily refueled make better weapon plutonium producers.
- Most Western power reactors have large pressure vessels that must be opened to refuel and are designed to operate to high fuel burn-up without refueling; an exception is the Canadian CANDU heavy water moderated system which can be refueled on-line. Canada has, however, worked with the IAEA to develop good safeguards procedures and has been careful

where it makes sales of these reactors. Earlier a Canadian supplied reactor of this type (with U.S. supplied heavy water) was used to produce the plutonium for India's 1974 nuclear explosion.

• Plutonium production reactors will generally be either **heavy water** (normal hydrogen replaced by deuterium) moderated or **graphite** moderated as these moderators allow using natural uranium (unenriched)





One of eight plutonium-producing reactors operating during the '40s in Hanford, WA. (bottom) Workmen loading uranium into the first production reactor at Hanford.

as fuel. Much of a reactor's core is filled with the moderator material which slows fission neutrons to thermal energies where fission cross-sections are higher.

• In proliferant countries, plutonium production reactors will tend to be either reactors built indigenously for that purpose or high-power (greater than 20 MW thermal) research reactors modified for production. A rule of thumb (not accurate for all situations) is that **0.8 g of plutonium can be produced per megawatt day** of reactor operation. The Israeli Dimona research reactor, sold by France, reportedly has been used for plutonium production. North Korea is suspected of having indigenously built a production reactor.

• Reactors capable of useful levels of plutonium production for a weapons program will need large cooling capacity (>50 MW) making them hard to conceal. (The U.S.S.R. built some production reactors underground near rivers making them hard to detect.)

• Reactor technology is unclassified for the most part.

IV. Plutonium recovery

• Plutonium, made in a reactor, is chemically separated from the removed fuel or targets. This is referred to as **reprocessing**. The removed fuel is dangerously radioactive and the chemical processing is done by remote manipulation behind thick shielding walls (>4 ft). Some reprocessing plants may be detected as they are constructed, but at Dimona the Israelis reportedly built a plant underground whose purpose went undetected for some time.

• Reprocessing technology is unclassified, although detailed construction drawings of modern plants are not released.

• **Plutonium can be recovered from nuclear weapons,** reworked and used either in new weapons or used to fuel power reactors. The U.S. policy against fueling power reactors with plutonium separates the military and civilian nuclear fuel cycles to prevent the possible diversion of plutonium from civil reactors to military application. The viewpoint is different in other countries and both in Europe and in Japan civil reactor fuel is or will be reprocessed and the plutonium separated and combined with uranium in mixed oxide (MOX) to be used as new civil reactor fuel. Japan plans to be handling 50-100 tons of plutonium in their civil fuel cycle early in the next century.

V. Weapon design

• Nuclear fission weapons operate by very quickly assembling a subcritical mass of fissile material into a supercritical mass and adding neutrons to initiate a chain reaction. Assembly may be done by a gun firing a mass of uranium-235 at a target of the same material or by using high explosives (implosion) to compress a subcritical mass of fissile material into a supercritical one. If the chain reaction starts before the fissile material is fully assembled, a low yield results. Because plutonium has a much higher spontaneous fission rate than uranium, it must be assembled faster to avoid a low yield. The implosion method is a faster system and must be used to assure reasonable yield if the fissile material is plutonium-239.

• In theory any amount of fissile material may be made to go supercritical if it is compressed enough. In practice one gets some compression in an implosion system and less fissile material is normally needed for implosion weapons relative to gun-assembled weapons. Thus most proliferants pursue implosion-assembled weapons even if their fissile material is uranium. (China's first device was made from uranium separated by gaseous diffusion and implosion assembled.)

• Some type of **neutron source (or generator)** will be used to give a burst of neutrons to start the nuclear chain reaction when fissile material assembly is nearly complete. The neutron source will also be tested in nonnuclear tests of either gun or implosion weapons. Thus even though a test will not generate nuclear yield, neutron detectors are apt to be used to measure the performance (timing and number of neutrons) of the neutron source.

• Nonnuclear testing (and nuclear testing if done) is apt to go on for years in order to develop smaller, lighter weapons that are safer to handle, easier to deliver, use less fissile material, are more rugged, etc.

• **Yields** (measured in TNT equivalent) from fission weapons are expected to be in the 5 kT to 20 kT range although yields greater than 100 kT are possible with advanced designs.

• Nuclear weapon programs have many **metallurgical and materials problems** that must be mastered.

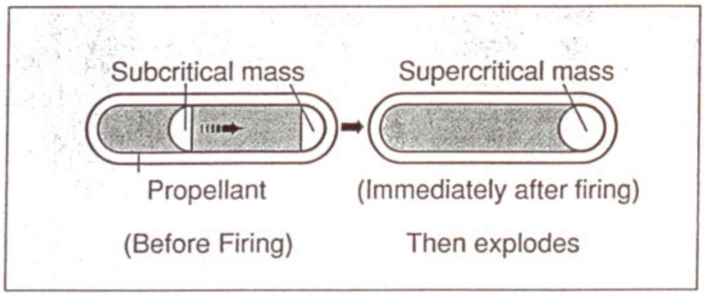


Diagram of a gun-assembled nuclear device.

• It is generally agreed by weapon designers that a proliferant country could now design either implosion or gun type weapons and be **confident of their working *without* nuclear testing.** Indeed, the first nuclear weapon used in warfare, the uranium gun-assembled Hiroshima bomb, had never been tested.

a. Gun nuclear weapon design

—Gun weapon design is relatively simple, uses many of the same techniques as military gun design, and its nonnuclear testing is easy to conceal.

—A gun type weapon might be built by a terrorist group that had stolen or otherwise acquired fissile material.

b. Implosion nuclear weapon design

—In an implosion system the fissile material must be smoothly, uniformly, and rapidly compressed to obtain reliable and high yield. This requires careful design of the **high explosive system** and the coupling between it and the fissile material. Also the outer surface of the high explosive must be initiated over its entirety almost simultaneously. While simple in concept, it requires high quality, high energy explosive with good homogeneity, machined to close tolerances as well as insightful design. An implosion weapon design program will use both computer modeling and high explosive testing with mock material substituted for the fissile material **(hydrodynamic tests).**

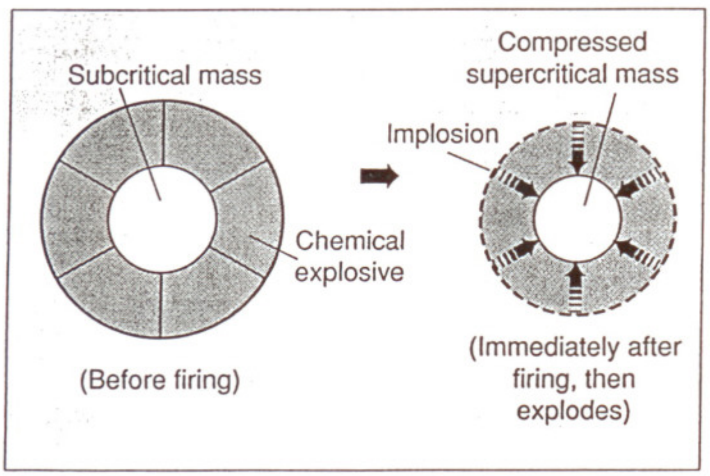


Diagram of an implosion-assembly nuclear device.

—The **diagnostics**, and many of the techniques used in implosion testing are similar to those used in antiarmor munitions development—**flash x-ray, high speed rotating mirror cameras, fast pulsed image intensifier cameras, electric pin sensors, precision electronic timing systems, etc.** (A limited amount of this equipment might also be used in **gun type nuclear weapon development.**)

—The **high explosives** used are usually military types—HMX, RDX, and plastic bonded composites (PBX).

—For many years the major requirement for high explosives and detonators (initiators) in a new weapons program is apt to be in the hydrodynamic testing program rather than in weapons being put into stockpile. The hydrodynamic testing is somewhat difficult to conceal although it is possible to do underground.

—There is a **trade-off** between the amount of **computer modeling** and the **number of high explosive tests** required and both can be reduced through cleverness or the acquisition of design information for proven weapons. **High-end personal computers** now have sufficient computing power to handle much of the modeling needed for implosion system design and it is impossible to control their availability.

—The result of hydrodynamic tests and computer modeling can be a design that the designers have **confidence will work *without* full-scale nuclear testing** although the size of the yield probably cannot be accurately predicted.

VI. Nuclear Weapon Safety

• There are many **ways of insuring that a nuclear weapon cannot accidentally detonate** or be easily detonated by sabotage. One of the most obvious is to not install part or all of the fissile material until one wishes to use the weapon for military reasons, however, one may need a fast response—i.e. a weapon mounted on a missile that can be launched on short notice. If a proliferant country goes to such a readiness posture, there should be great concern for the reliability of its command and control systems and the safety features which prevent accidental nuclear detonation of its warheads. Beginning proliferants are not apt to be able to cope well with such issues. In many situations if a lightning strike, or collapse of a missile carriage were to trigger a nuclear detonation, one could foresee the disaster being immediately blamed on an enemy and a retaliatory strike being launched immediately.

• **One point safety**—in implosion system design it was mentioned that the outer surface of the high explosive must be initiated simultaneously. The system that does this is called the "lighting system" and usually requires multiple electrical signals to occur with precise timing—ideally if they are not timed correctly there will be no nuclear yield. Some designs however, while requiring precise timing to insure high yield, have a significant probability of significant nuclear yield even if only a single point on the high explosive surface is initiated; i.e., accidentally dropping the weapon might cause a nuclear detonation. Systems where this cannot happen are referred to as "one point safe". All U.S. weapons meet these criteria but designing to such criteria would be difficult for a proliferant particularly without a full-scale nuclear testing program.

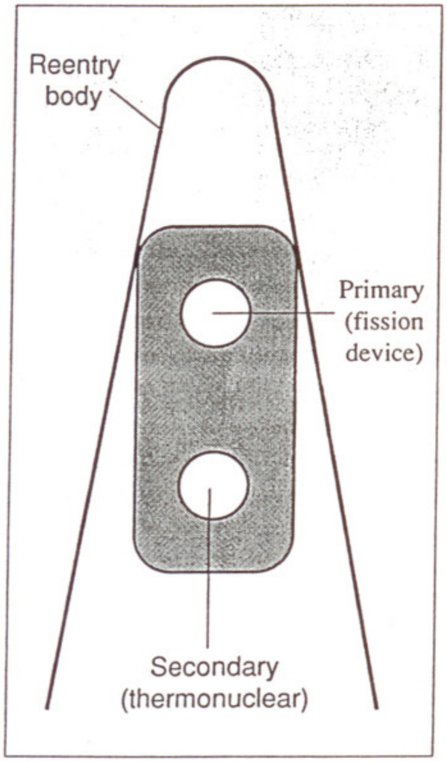


Diagram of a thermonuclear device.

VII. Thermonuclear and boosted weapons

• **Thermonuclear weapons** use nuclear fusion reactions, such as between deuterium and tritium, to produce energy. High temperatures and pressures are required and the only known way to generate the conditions is to use a fission bomb as the trigger. Skillful design is required to couple the energy of the fission bomb into the fusion fuel. Most designers believe proliferant country design teams would be unable to do such a design with confidence without a full-scale nuclear test or without access to data from a nuclear test. Thermonuclear weapons can rather easily be scaled to arbitrarily large sizes—greater than 50 Mt was demonstrated by the U.S.S.R..

• Solid-salt **lithium-6 deuteride** can be used as the **fuel for thermonuclear weapons**. Fast nuclear reactions taking place with the lithium create tritium, which then reacts with deuterium. A program to separate large quantities of the lithium-6 isotope is a strong indicator of thermonuclear weapon interest. The separation is much simpler than uranium isotope separation. The common method requires large amounts of liquid mercury, which can also be an indicator.

• **Boosted weapons** use thermonuclear reactions within a fission weapon's imploding core to generate neutrons to fission even more uranium-235. Tritium and deuterium are used in the reaction. Boosting gives many desirable features, including additional safety features, but the process is very difficult to computer model and most designers think that full-scale nuclear test data is essential for confident design.

• **Tritium** (an isotope of hydrogen not found in nature in significant separable quantities) used in boosted weapons, is made by irradiating lithium (natural or Li-6 enriched may be used) targets in a production reactor. Producing tritium reduces the plutonium production rate in the same reactor—both consume neutrons to produce. Tritium has a 12 year half-life and must be periodically replenished if used in weapons.

• Supercomputers, if available, are apt to play a key role in advanced weapon designs but do not do away with the need for full-scale nuclear test data. Supercomputers are not essential; most of the U.S. stockpile was designed with computers that are not in today's supercomputer class—indeed with computing power now readily available in desktop machines.

VIII. Proliferation Controls

• **The Nuclear Nonproliferation Treaty (NPT)** is one of the most widely supported treaties in history. It will expire in 1995 after 25 years and is expected to be renewed.

• **The International Atomic Energy Agency (IAEA) Safeguards** regime, developed to satisfy the treaty, gives confidence that nuclear materials are not being diverted in declared facilities—it is designed to give "timely" warning of diversions, not to prevent them. It was one of the first international arms control agreements to permit routine inspections of a country's facilities by citizens of another country acting on behalf of an international agency. The fortunate fact that there is no international black market in fissile materials can be credited to the Safeguards regime.

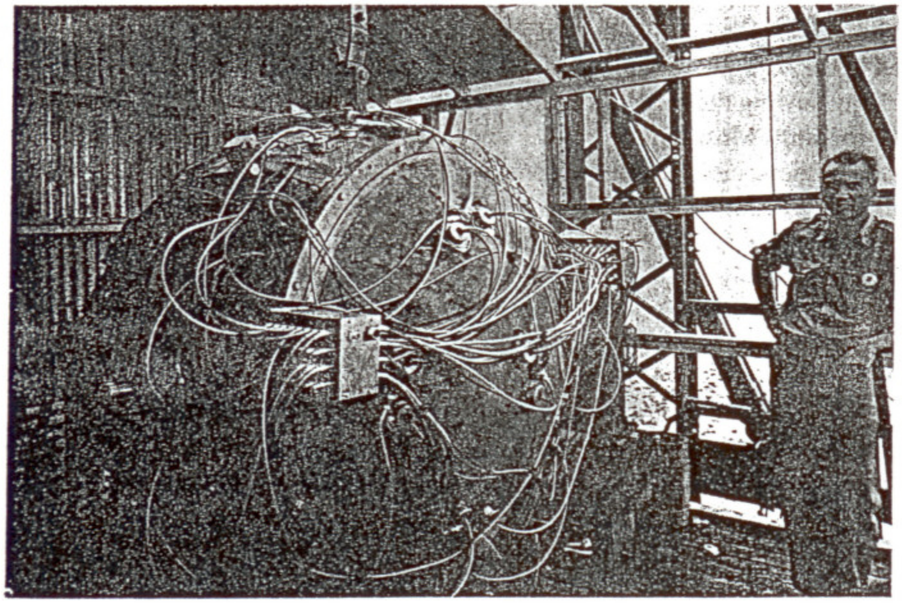
• Export controls play an important role in slowing the spread of key commodities needed for nuclear weapon programs. Most of the international controls apply only to fuel cycle items, i.e. fissile material production. The oldest nuclear controls are the so-called **Zangger Committee (Nuclear Exporters' Committee) Trigger List** implemented to meet Article III.2. of the NPT. The list includes only "especially designed or prepared" (EDP) nuclear items and the participating countries (15 originally, 23 now) agree not to sell these items to any facilities not under IAEA Safeguards; i.e. their sale will trigger safeguards. Similar nuclear controls with more stringent guidelines and controls on nuclear technology are implemented under the auspices of the **Nuclear Suppliers Group** (NSG, 27 countries). Membership in the NSG consists of western and eastern Europe; the former Soviet Union; U.S. and Canada; Japan, and Australia. Newer supplier nations like Brazil, China, and India are not represented—in fact they are both suppliers and importers and present special policy dilemmas.

• The newest control effort (by the NSG countries) is to control **dual-use commodities,** which have valid civil uses but also are key in nuclear weapons development. These **Nuclear Dual-Use List** controls are aimed at both fuel cycle and weaponization activities and are expected to go into effect this calendar year. There is not a list of prescribed countries but a set of "tests" to be applied to end users prior to approving shipments to them.

• Some commodities are controlled to China and many of the former Soviet bloc countries by **COCOM.** However, recent COCOM initiatives, namely the creation of the COCOM Cooperation Forum, have been undertaken to reflect changes in East-West relations.

• The U.S. government has been a leader in the development of nuclear export controls and implements some controls unilaterally. U.S. controls are administered by the Nuclear Regulatory Commission (nuclear EDP controls), the Department of Energy (assistance to foreign nuclear programs), the Department of Commerce (nuclear dual-use controls—the Nuclear Referral List), and the Department of State (International Traffic in Arms Regulations). A complex set of interagency committees, involving also the Arms Control and Disarmament Agency and the Department of Defense coordinates the control activities. The primary legislative mandates come from the Atomic Energy Act of 1954, as amended, and the Nuclear Non-Proliferation Act of 1978.

• Because of the accelerating worldwide spread of technology, it is anticipated that export controls, except to very underdeveloped countries, will have markedly less effect in another decade. Technology spread is inevitable if countries are to develop (and we generally wish to foster development). Also, the continual development of new dual-use



Norris Bradbury, the second director of Los Alamos National Laboratory, atop the 100-ft tower on which the Trinity device, the first nuclear weapon, an implosion device using plutonium-239, was mounted.

technology (which eases steps in the nuclear development cycle) and new technology suppliers tend to reduce export control effectiveness. Effectiveness relative to new suppliers can be maintained if the new suppliers can be convinced to join the control regimes. Export controls also have less effect on the weapon programs of countries with a high level of technological development, i.e., less effect on an Israel than a Libya.

• Proliferants **all need technology imports** for their programs but more and more they start from more basic levels by using more dual-use commodities and fewer nuclear items, per se; i.e., **they are indigenously designing and building their own systems.**

• Some countries that previously pursued or appeared about to pursue weapons programs have realized that it is not in their best interest to do so; i.e. Sweden, Taiwan, South Korea, South Africa, possibly Argentina, and Brazil. Can other program rollbacks be fostered?

• We depend on **intelligence agencies** for timely warning of covert nuclear proliferation activities.

• When nuclear weapon programs can be publicly and credibly exposed, world opinion tends to be strongly against them.

• The U.S. government operates detection systems (seismic arrays, satellite detectors, atmospheric samplers, etc.) that are expected to detect any full-scale nuclear testing with significant yield.

Perhaps one of the most effective ways of stemming the flow of nuclear, or other weapons of mass destruction, remains in international cooperative measures that promote greater transparency of national objectives.

—Arvid Lundy
International Technology Division
Los Alamos National Laboratory

A Proliferation Related Chronology (proliferation "shocks" in bold)

1945	**U.S. Trinity test, bombs dropped on Hiroshima and Nagasaki**
1946	U.S. proposed Baruch Plan rejected in the U.N.; U.S. passes Atomic Energy Act
1949	**U.S.S.R. detonates first device**
1952	**U.K. detonates first device**
1953	"Atoms for Peace" program, proposed by President Eisenhower, calls for establishment of an International Atomic Energy Agency (IAEA) under the U.N.
1954	U.S. Atomic Energy Act revised to foster commercial development, and permit international cooperation
1957	IAEA created to promote worldwide sharing of peaceful uses of nuclear energy and to develop Safeguards for peaceful facilities
1960	**France detonates first device**
during 1960s	Rapid development of nuclear power technology
1961	First IAEA Safeguards system approved (covers small reactors) (INFCIRC/26)
1962	First IAEA Safeguards inspection takes place
1963	President Kennedy predicts 15 to 25 nuclear weapon states in the 1970s
1963	Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space, and Under Water (LTBT)
1964	**China detonates first device**
1965	New Safeguards system approved covering all sizes of reactors (INFCIRC/66)
1968	Treaty for the Prohibition of Nuclear Weapons in Latin America (Treaty of Tlateloco) enters into force
1968	Swedish Parliament stops nuclear weapons program
late 1960s	probable Israeli nuclear weapon capability
1970	Nuclear Nonproliferation Treaty (NPT) enters into force; significant holdout states: China, France, South Africa, Argentina, Brazil, India, Israel, Pakistan, Algeria
during 1970s	European suppliers contract to supply sensitive nuclear technology and equipment to Argentina, Brazil, Pakistan, and South Korea. Argentina, Brazil, Libya, and Pakistan believed to start nuclear weapons programs
1971	NPT Safeguards system approved (INFCIRC/153)
1974	**India detonates "peaceful nuclear device" (used "peaceful" nuclear assistance from Canada and the U.S.)**
1974	First publication of the Zangger Committee on export controls (INFCIRC/209)
1977	Agreement of the London Nuclear Suppliers Group (NSG) on guidelines for nuclear commerce; 15 members (published as INFCIRC/254)
1977	**Soviets report South Africa's Kalahari test site**
1978	U.S. Nuclear Non-Proliferation Act
1979	**U.S. Vela satellite detects flash in the South Atlantic believed by some technologists to be a nuclear test; U.S. government unable to confirm; Israel and/or South Africa suspected by some.**
1981	**Israel bombs French built Iraqi research reactor at Tuwaitha**
1985	North Korea signs NPT
1985	Missile Technology Control Regime (MTCR) agreed to by seven countries; controls technology for missiles of 300 km or greater range and 500 kg or greater throw-weight

1985 South Pacific Nuclear Free Zone Treaty signed, entered into force 1986
mid 1980s Probable South African nuclear weapon capability
1986 Mordecai Vanunu discloses large Israeli nuclear weapons program at Dimona–Israel may have >50 weapons
1989 CIA Director Webster reports 15 countries may be able to produce ballistic missiles by 2000
1989? Probable Pakistani nuclear weapon capability; Abdul Qadeer Khan believed to have stolen centrifuge technology from Urenco plant in the Netherlands; China suspected of assisting Pakistan
1990 U.S. aid to Pakistan stopped; President Bush unable to certify they do not have a nuclear device
1990 Argentine-Egyptian-Iraqi Condor missile project terminated
1991 NSG countries meet (at The Hague) for the first time in 12 years; now 26 members
1991 Large Iraqi nuclear program revealed by U.N./IAEA inspections and Iraqi defectors–program may have cost $10 billion and employed 10,000 (U.N. Security Council Resolution 687 mandates intrusive inspections and dismantlement of Iraqi program)
1991 South Africa renounces any ambition to become a nuclear weapons state
1991 China, France, and South Africa announce intent to sign the NPT; 144 states now adhere
1991 Germany revamps and strengthens its export laws
1991 Concern about Chinese export sales to Algeria (research reactor) and Iran (electromagnetic separator and research reactor)
1992 NSG members (27 countries) agree to "nuclear dual-use" control regime
1992 North Korea still has not allowed IAEA Safeguard inspections mandated by its 1985 signing of the NPT; world concern grows and economic sanctions and preemptive military strikes are discussed
1992 MTCR now has 16 members but does not include China or the former Soviet Union
1992 Soviet Union disintegration ('91) triggers new proliferation concerns:
—Security and disposal of strategic weapons located in Russia, Ukraine, Byelorussia, and Kazakhstan
—The adherence of the new states to international nonproliferation arrangements and the adequacy of their export controls
—Nuclear technology leakage and black market sale or theft of weapons or fissile material; the possible move of nuclear weapons specialists to proliferant countries
1995 NPT extension to be decided by member nations

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