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The Problem of Nuclear Energy Proliferation

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THE PROLIFERATION ISSUES RELATED to civil nuclear power have been recognized for almost two decades:

- Very small quantities of plutonium (Pu) and/or highly enriched uranium (HEU) are needed for a nuclear weapon
- It is very difficult to provide adequate security for separated plutonium and HEU at bulk-handling facilities (nuclear fuel reprocessing and fabrication facilities) where separated plutonium and HEU are found in nondiscrete forms
- Stockpiling of these materials in nonweapon states provides a dangerous breakout capability.

The security of fissile material in Russia, the need to dispose of large stocks of fissile materials from retired weapons, and the growing recognition that we must address the long-term proliferation risks associated with spent fuel once the protection afforded by the radioactive fission products has decayed away, represent new dimensions to these issues.

The amount of plutonium and/or highly enriched uranium needed for a nuclear weapon is very small. After almost a half century of living with nuclear weapons, considerable misinformation about the fissile material requirements for nuclear

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weapons still exists. For single-stage pure fission weapons, a spherically symmetric implosion design requires the least amount of fissile material to achieve a given explosive yield, relative to other possible designs. For this kind of device the amount of fissile material required depends primarily upon the type of fissile material used (plutonium or HEU), the desired explosive yield of the device, and the degree to which the fissile material is compressed at the time disassembly of the fissile material begins due to the release of energy from the rapid nuclear chain reaction. The degree of compression achieved depends on the sophistication of the design and degree of symmetry achieved by the imploding shock wave. There are, of course, other factors , such as the timing of the initiation of the chain reaction and the type of neutron reflector used, but we will assume that the proliferant state or subnational group already has acquired the necessary skills so that these factors are of secondary importance.

Figures 1 and 2 show the explosive yield of a pure fission weapon as a function of the quantity of weapon-grade (WG) fissile material (WGPu in figure 1 and HEU in figure 2) for three degrees of compression. In the figures the degree of compression is labeled according to our judgment as to the sophistication of the design; that is, whether it represents low, medium or high technology. As seen in figure 1, the Nagasaki bomb, *Fat Man*, which produced a 20 kiloton (kt) explosion with 6.1 kilograms (kg) of WGPu, falls on the "low technology" curve. However, only three kilograms of WGPu compressed the same amount would still have produced a 1 kt explosion. A 1 kt yield is still a very damaging explosion with the potential to kill tens of thousands of people, depending on the population density and physical characteristics of the targeted area. Many tactical nuclear weapons that were in the U.S. nuclear arsenal had yields in the kiloton, and even sub-kiloton range.

But the bad news does not stop there. A nonnuclear weapons state today can take advantage of the wealth of nuclear weapons design information that has been made public over the past 50 years, and do even better. As seen in figure 1, to achieve an explosive yield of 1 kt, we estimate that from 1 to 3 kg of WGPu are required, depending upon the sophistication of the design. And from figure 2 we can estimate that some 2 to 7 kg of HEU are required to achieve an explosive energy release of 1 kt. Table 1

Figure 1. Yield vs. Pu mass (as a function of technical capability)

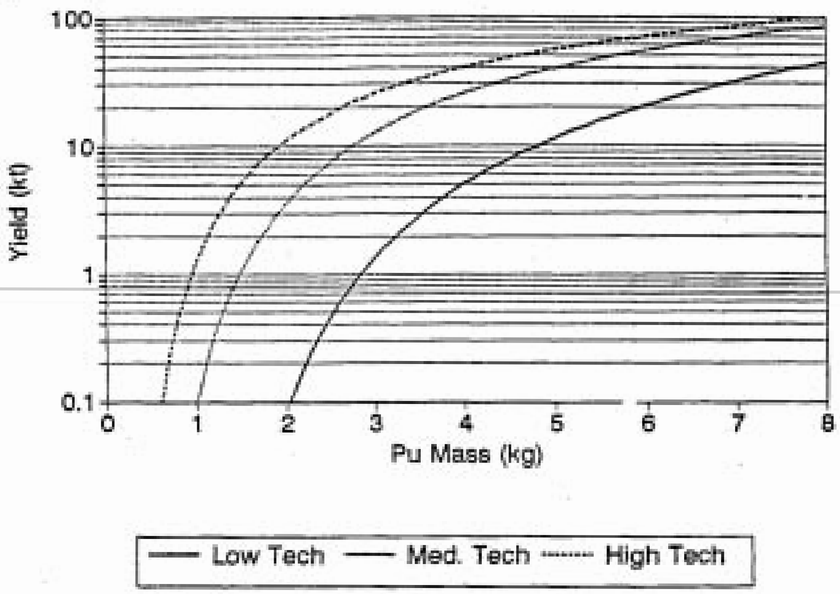

Figure 2. Yield vs. HEU mass (as a function of technical capability)

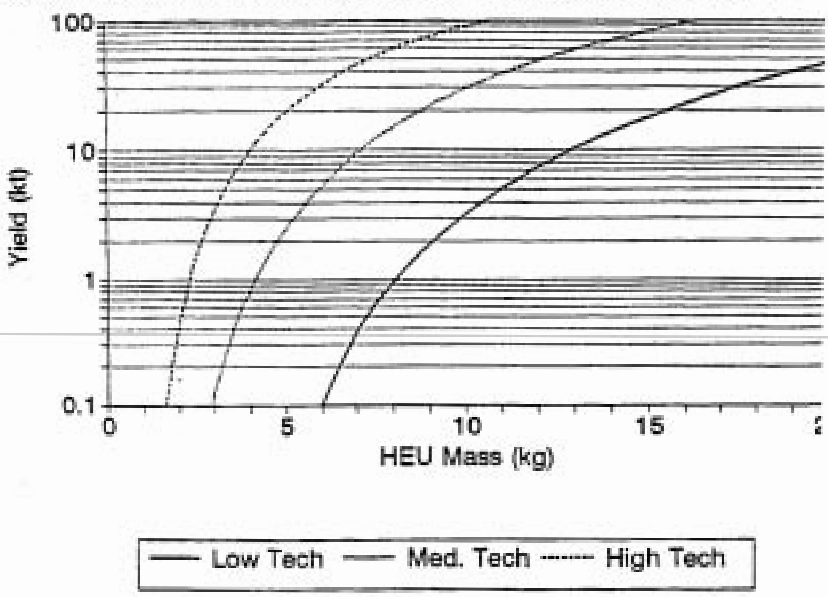

Table 1. Approximate fissile material requirements for pure fission nuclear weapons

	Weapon-grade Plutonium (kg)			**Highly enriched Uranium (kg)**		
Yield	*Technical Capability*			*Technical Capability*		
(kt)	Low	Med	High	Low	Med	High
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5

presents some of the results of our calculations in a different form. We estimate, for example, that as little as 2 kilograms of plutonium, or about 4 kilograms of HEU, is required to produce a yield of 10 kilotons. The curves in figure 1 apply to weapon-grade plutonium where the Pu-240 content is less then 7 percent. Most of the plutonium in the civil world is reactor-grade with a Pu-240 content in the range of 20-35 percent. The critical mass of reactor-grade plutonium falls between that of weapon-grade plutonium and HEU.

Plutonium with a high Pu-240 content is less desirable for weapons purposes than weapon-grade plutonium, because for low-technology weapons designs the neutrons generated by the high rate of spontaneous fusion of Pu-240 can increase the statistical uncertainty of the yield by "preinitiating" the chain reaction before the desired compression of the plutonium core has been achieved. In spite of this, militarily useful weapons, with predictable yields in the kiloton range can be constructed based on low technology designs with reactor-grade plutonium. According to the conclusions of a recent study by the National Academy of Sciences in the United States, based in part on a classified 1994 study by scientists at the Lawrence Livermore National Laboratory,

> even if pre-initiation occurs at the worst possible moment (when the material becomes compressed enough to sustain a chain reaction), the explosive yield of even a relatively simple device similar to the Nagasaki

> bomb would be on the order of one or a few kilotons. This yield is referred to as the " yield " a one kiloton bomb would still have a destruction radius roughly one third that of the Hiroshima weapon; making it a potentially fearsome explosive. Regardless of how high the concentration of troublesome isotopes is, the yield would not be less. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.[1]

By making use various combinations of advanced technologies, including improved implosion techniques, the use of beryllium as a neutron reflector, boosting with deuterium and tritium, and two stage weapon designs, it is possible to offset the problems created by the high rate of spontaneous fusion of Pu-240. Using sophisticated designs well within the capability of the declared weapon states, reliable light weight efficient weapons and high-yield weapons whose yields have small statistical uncertainties can be constructed with plutonium regardless of the Pu-240 content. NRC Commissioner Victor Gilinsky best summed up the issue in 1976:

> Of course, when reactor-g-ade plutonium is used there may be a penalty in performance that is considerable or insignificant, depending on the weapon design. But whatever we once might have thought, we now know that even simple designs, albeit with some uncertainty in yield, can serve as effective, highly powerful weapons - reliably in the kiloton range.[2]

Existing physical security measures provide insufficient insurance against theft of weapons-usable nuclear material. Adequate physical security is essential to prevent the theft of any quantity of materials even as little as one bomb's worth. Highly accurate material accounting and control measures are essential to determine whether a theft has taken place and provide timely warning to prevent the material from being used for illicit purposes. From experience at existing civil and military chemical separation (reprocessing) plants, naval fuel facilities, and mixed-oxide fuel facilities, it is well established that it is extremely difficult (some would argue impossible) to provide in practice a sufficient level of physical security and material accounting and control at bulk handling facilities that process large amounts of nuclear weapons-usable material.

The difficulty in providing adequate physical security is that theft of materials can involve a collusion of individuals, including the head of the guard force, the head of the company, or even the state. Despite having guards at every bank, employees at the Bank of Credit and Commerce, Inc. (BCCI) were able to steal billions of dollars from bank customers because the thieves were running the bank—the collusion was at the top. If the threat includes the potential for collusion involving the guard force and facility directors, providing adequate physical security in the West would require turning the facility into a heavily armed site occupied by an independent military force. In Russia, physical security has relied on heavily guarding not only the facilities, but also the towns where the work force resides. These closed cities are anathema to a democratic society.

Of course, the principal role of physical security is completely reversed when the collusion involves elements of the government itself. In this case the primary mission of the security apparatus is to hide the program from outside scrutiny. It is now known that at various times in the past, the governments of the United States, Japan (during World War II, Soviet Union, United Kingdom, France, China, Israel, India, South Africa, Sweden, Argentina, Brazil, Taiwan, Pakistan, North Korea, South Korea, and Iraq have had secret nuclear weapons development programs.

The collapse of the Soviet Union and the current economic conditions in Russia have severely challenged the physical security of weapons-usable fissile material there. Russian President Boris Yeltsin has said that 40 percent of individual private businessmen and 60 percent of all Russian companies have been corrupted by organized crime. Reports of illegal activities in Russia associated with nuclear materials—offers to sell and successful and unsuccessful attempts to steal nuclear materials—are now appearing regularly in the Russian and European press. On average there is about one new case per week. Low-enriched uranium fuel has been stolen, and four tons of beryllium and a small quantity of HEU, thought to be less than 1 kilogram, was stolen from a Russian nuclear facility, perhaps Obninsk. These materials were recovered last year by Lithuanian authorities in Vilnius. This may be the case involving the theft of several hundred grams of HEU that has been confirmed by the Russian Ministry of Atomic Energy (Minatom).

In another case, a Russian nuclear scientist from the Luch Production Association, which manufactures nuclear space reactors, was apprehended in October 1992 at the Podolsk train station with 1.5 kilograms of HEU in his suitcase. In February of this year 3 kilograms of HEU (90 percent U-235) were stolen from a plant near Moscow. Subsequently, a St. Petersburg butcher was apprehended in an attempt to sell it. Between May 10 and August 12 of this year German authorities intercepted four small samples of weapon-usable materials, one having 300 to 350 grams of plutonium. These are some of cases we know about because the materials were intercepted. We know for certain that kilogram quantities of weapons-usable materials are being stolen from Russian nuclear institutions and that some of it has crossed international borders. The most serious cases to date have involved weapons-usable materials in the civil sector. There may have been other diversions of nuclear weapons-usable materials that were successful and have gone undetected.

Plutonium-239 has a half-life of 24,000 years, and uranium-235 has a half-life of 700 million years. The lifetimes of weapon-usable materials greatly exceed the lifetimes of the institutions that must prevent their misuse. The situation in Russia today makes this abundantly clear.

IAEA safeguard measures are incapable of detecting diversion of weapons-usable fissile material from bulk handling facilities. The international community's principal tool for penetrating the secrecy of nuclear facilities is the power of the International Atomic Energy Agency (IAEA) to conduct inspections and require adherence to strict materials accounting and control procedures, collectively referred to as "safeguards." These are meant to provide timely detection of the diversion of significant quantities of weapons-usable material.

While there are numerous shortcomings in the design and implementation of IAEA safeguards, we focus here on three technical flaws: (a) the IAEA's "significant quantity" (SQ) values are technically flawed—they are far too high; (b) detection of the diversion of a SQ amount applies to a material balance area, instead of the entire facility, or even country; and (c) the IAEA's timely detection criterion cannot be met.

For safeguards purposes the IAEA defines a "significant quantity" (SQ) of nuclear material as "the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded."[3] Significant quantity values currently in use by the IAEA are given in table 2.[4] The SQ values were recommended to the IAEA by a group of experts, namely, the IAEA's Standing Advisory Group for Safeguards Implementdtion (SAGSI), and "relate to the potential acquisition of a first nuclear explosive by a non-nuclear weapon state."[5]

Table 2. IAEA significant quantities

Material	Quantity of Safeguards Significance	Safeguards Apply to:
Direct-use material		
Plutonium	8kg	Total element
Uranium-223	8 kg	Total isotope
Uranium enriched to 20 percent of more	25 kg	U-235 isotope
Indirect-use nuclear material		
Uranium ((20 percent U-235)	75 kg	U-235 isotope
Thorium	20 t	Total element

The direct-use values in table 2—that is, 8 kg of plutonium, 8 kg of uranium-233, and 25 kg of HEU—are also referred to by the IAEA as "threshold amounts," defined as "the approximate quantity of special fissionable material required for a single nuclear device."[6] The IAEA cites as a source for these threshold amounts a 1967 United Nations document:

> These threshold amounts include the material that will unavoidably be lost in manufacturing a nuclear explosive device. They should not be confused with the minimum critical mass needed for an explosive chain reaction, which is smaller. (IAEA footnote: Using highly sophisticated techniques available to NW states, the critical mass and the corresponding threshold amount can also be significantly reduced, but these are special cases that need not be considered here.)[7]

As seen from figures 1 and 2, the direct-use SQ or threshold values currently used by the IAEA are technically indefensible. The IAEA is making false claims as to the minimum quantity of nuclear material needed for a nuclear weapon, even for a low-technology first nuclear explosive by a nonnuclear weapon state, including consideration of unavoidable losses. If one took the same *Fat Man* design, first tested at the site in New Mexico and dropped on Nagasaki in 1945, and substituted a 3-kilogram plutonium core for the 6.1-kilogram core that was used in 1945, the yield of this device would be on the order of 1 kiloton, a very respectable atomic bomb. Thus, the IAEA is in error to assert that "highly sophisticated techniques available to NW States" are needed to make nuclear weapons with "significantly reduced" quantities of material.

The so-called "highly sophisticated techniques available to NW States" were known to U.S. weapons designers in the late 1940s and early 1950s, and nuclear devices using very small quantities of plutonium and HEU—so-called "fractional crit" weapons—with yields on the order of one kiloton were tested during the Ranger series in 1951. Furthermore, a well-advised safeguards program for a given country or group of countries would set the "significant quantity" levels at values less than the minimum amount needed for a weapon, in recognition of the fact that materials can be diverted from more than one source. The practice of setting higher levels to account for manufacturing losses is imprudent, particularly in view of the fact that a significant fraction of these "losses" are technically recoverable.

In sum, safeguards apply to all nonweapons countries, irrespective of their technological sophistication. Many countries, such as Japan, Germany, Israel, India and Pakistan, have highly developed nuclear infrastructures and must be considered technologically sophisticated. Even for countries that are in general not terribly sophisticated technologically, the key technical information needed to establish a program for achieving substantial compression by implosion techniques is now available in the unclassified literature. The quantities defining safeguards significance, therefore, must be based an the assumption that the proliferator has access to advanced technology. As a consequence, NRDC believes the IAEA's significant quantities should be lowered at least 8-fold to the values in table 3.

Table 3. NRDC's proposed significant quantities

Material	Quantity of safeguards signifcance	Safequards apply to:
Direct-use nuclear material		
Plutonium	1 kg	Total Element
Uranium-233	1 kg	Total Isotope
Uranium enriched to 20 percent or more	3 kg	U-235 isotope

In the parlance of nuclear material accounting the inventory difference (ID) is defined as ID = BI + I - R - EI, where BI is the beginning inventory, EI is the ending inventory, and I and R are, respectively, the material added and removed during the inventory period.[8] For the minimum amount of diverted plutonium (assumed by the IAEA to be the SQ value (currently 8 kg of plutonium) to be distinguished from measurement noise with detection and false alarm probabilities of 95 percent and 5 percent, respectively, it can be shown that 3.3 σ_0 must be less than the SQ value, where σ_0 is the uncertainty in the inventory difference.[9] This means if the SQ value for plutonium were lowered to 1 kg, σ_0 should not exceed about 300 grams.

At reprocessing plants that handle tons of weapons-usable plutonium, σ_0 is dominated by the error in measuring the plutonium input into the plant, which is about one percent of the throughput. The Japanese Tokai Mura reprocessing plant, one of the smallest plants in the West, has an average output of about 90 t of heavy metal per year (the/t)), and the LWR spent fuel processed has an average total plutonium content of about 0.9 percent. Thus, σ_0 for Tokai Mura is about 8 kg of plutonium per annual inventory. Even if inventories were taken every 6 months, σ_0 would be about 4 kg, which is an order of magnitude too high. One simply cannot detect the diversion of several bombs' worth of plutonium annually from Tokai Mura. The inventory difference would be larger at the plants in the United Kingdom and France because they have a greater throughput of plutonium.

We are told that material accounting and control at Russian plants handling nuclear fuel in bulk form is rudimentary at best. The RT-1 chemical separation plant at Chelyabinsk-65 has a capacity of about 400 the/y, and until 1991 had been operating at about 200 the/y. Therefore, the situation at RT-1 would be two to six times worse than at Tokai Mura, even if it were brought up to current Western standards.[10] It is difficult to imagine running a bank in which you counted the money only a few times a year, and then only counted the notes larger than 10,000 rubles. Yet the Russian nuclear establishment sanctions the commercial use of nuclear weapons-usable material under safeguards that are no better.

The IAEA permits facilities to reduce inventory uncertainties in two ways. First, the plutonium entering a reprocessing plant is not measured until after the spent fuel has been chopped up and dissolved, thereby sidestepping the large uncertainties in measurements o; the amounts of plutonium entering the plant. Second, the facilities are subdivided into numerous material balance areas. The facilties in fact should be so subdivided, and this provides added protection against a single insider threat. But it must be recognized that this does not afford adequate protection against a collusion of individuals, particularly in scenarios where the state is engaging in the diversion.

In May 1994 the Nuclear Control Institute disclosed that there was a 70 kg discrepancy in the plutonium inventory balance at the Tokai Mura fuel fabrication plant The Japanese claimed the plutonium was not missing but was stuck to the surfaces of the glove boxes. Nevertheless, the uncertainty in the estimate of this plutonium holdup is on the order of 10-15 percent, one or more nuclear weapons worth. Astonishingly, the IAEA has given Japan months to resolve this discrepancy.

Detection time (the maximum time that should elapse between diversion and detection of a significant quantity) should be in the same range as the conversion time, defined as the time required to convert different forms of nuclear material into components of nuclear weapons. For metallic plutonium and HEU, the conversion time is 7 to 10 days; for other compounds of these materials, 1 to 3 weeks. These times are already much shorter than the period between inventories at any fuel reprocessing plant

Unfortunately the mission of the DOE effort is too narrow. It is limited to improving the national physical security and material accounting programs in Russia. Unfortunately, the rate at which improvements will be made is funding limited: $2 millon in FY 1994, $15 million in FY 1995, and $40 million in FY 1996. Also, only a few facilities will be covered by the cooperative effort, and there will be little capability for the U.S. to observe the effectiveness of the U.S. assistance when applied to sensitive military facilities.

The mission of the lab-to-lab effort needs to be expanded to construct a comprehensive nondiscriminatory safeguards regime that covers all nuclear weapons and weapon-usable fissile material. Only then will the parties be forced to address methods for adequately safeguarding the most sensitive facilities and materials. There is no reason this should not be one of the mainline mission of the U.S. and Russian labs.

As seen from table 4, all the nuclear weapons and most of the fissile material facilities are not covered by the IAEA or even bilateral safeguards. As shown in table 5, even with the Clinton administration objectives of a global cutoff in the production of fissile material for weapons, and with IAEA safeguards placed over fissile materials declared "excess" to national security requirements, all nuclear warheads and many fissile material inventories and production facilities will remain outside any bilateral or international safeguards, including the weapons-usable material inventories in Russia. If we hope to achieve deep reductions in the global nuclear weapons arsenals, we will need a comprehensive safeguards regime covering all nuclear weapons and weapon-usable material (table 6). The U.S. and Russian nuclear weapons labs should begin constructing such a regime on a bilateral basis.

Proliferation risks associated with the closed fuel cycle. The United Kingdom, France, Russia, and Japan are reprocessing spent civil reactor fuel for waste management and to separate plutonium for recycle as a nuclear fuel in light water reactors and breeders. France, Russia, and Japan continue to develop plutonium breeder reactors. Not only is there no adequate means of safeguarding large bulk-handling facilities to prevent weapon-usable plutonium from being stolen, but also reprocessing of spent fuel and the recycling of plutonium[11] into fresh fuel for reactors permit nonnuclear weapons states to justify the

TABLE 4. CURRENT SAFEGUARDS

	WEAPON STATES		NON-WEAPON STATES
	DECLARED	UNDECLARED	
MILITARY:			
Warheads:			
Operational			
Reserve			
Retired			
Fissile Material:			
In Warheads			
Reserved for Warheads			
Declared Excess			
Facilities:			
Weapon Production			
Material Production			
Excess Material Storage			
NAVAL FUEL CYCLE:			
Facilities			
Fuel			
CIVIL NUCLEAR:			
Reactors		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Fuel Cycle Facilities		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
HEU/Pu		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
LEU		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Spent Fuel		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]

TABLE 5. FISSILE CUTOFF FOR WEAPONS AND EXCESS STOCKS UNDER IAEA SAFEGUARDS

	WEAPON STATES		NON-WEAPON STATES
	DECLARED	UNDECLARED	
MILITARY:			
Warheads:			
Operational			
Reserve			
Retired			
Fissile Material:			
In Warheads			
Reserved for Warheads			
Declared Excess	[illegible] IAEA [illegible]		
Facilities:			
Weapon Production			
Material Production	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	
Excess Material Storage	[illegible] IAEA [illegible]		
NAVAL FUEL CYCLE:			
Facilities			
Fuel			
CIVIL NUCLEAR:			
Reactors		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Fuel Cycle Facilities	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
HEU/Pu	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
LEU		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Spent Fuel		[illegible] IAEA [illegible]	[illegible] IAEA [illegible]

TABLE 6. A COMPREHENSIVE SAFEGUARDS REGIME FOR THE 21ST CENTURY

	WEAPON STATES		NON-WEAPON STATES
	DECLARED	UNDECLARED	
MILITARY:			
Warheads:			
Operational	MONITORED		
Reserve	MONITORED		
Retired	MONITORED		
Fissile Material:			
In Warheads	MONITORED		
Reserved for Warheads	MONITORED		
Declared Excess	[illegible] IAEA [illegible]	[illegible]	
Facilities:			
Weapon Production	MONITORED		
Material Production	[illegible] IAEA [illegible]	[illegible]	
Excess Material Storage	TIM/IAEA [illegible]		
NAVAL FUEL CYCLE:			
Facilities	MONITORED	MONITORED	MONITORED
Fuel	MONITORED	MONITORED	MONITORED
CIVIL NUCLEAR:			
Reactors	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Fuel Cycle Facilities	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
HEU/Pu	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
LEU	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]
Spent Fuel	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]	[illegible] IAEA [illegible]

acquisition and stockpiling of nuclear weapons-usable material, ostensibly for peaceful purposes. At the same time, without violating any international safeguards agreements, these countries can design and fabricate nonnuclear weapon components. By moving to a point of being within hours of having nuclear weapons, perhaps needing only to introduce the fissile material into the weapons, a nascent weapons state would have all of its options open. Under these conditions, international safeguards agreements can serve as a cover by concealing the signs of critical change until it is too late for diplomacy to reverse a decision to "go nuclear." India recovered the plutonium for its first nuclear device in a reprocessing plant that was ostensibly developed as part of its national breeder program.

Acceptance of the plutonium breeder as an energy option provides the justification for the early development of a reprocessing capability by any country. A nonnuclear weapons country would always have the option to shift its "peaceful" nuclear program to a weapons program, but this would require the politically difficult decision to attempt evasion or overtly abrogate IAEA safeguards. Without national reprocessing facilities and breeder reactors, countries wishing to develop nuclear weapons capacity face very considerable political problems and cost. Obtaining large quantities of weapon-usable plutonium requires that they build one or more specialized production reactors and chemical separation facilities. By establishing their nuclear weapons option through a plutonium-using nuclear electric generation program, they can circumvent these obstacles.

Were plutonium fast breeder reactors ever to become economical (I seriously doubt this will happen), their deployment would entail staggering amounts of nuclear weapons-usable plutonium in the reactors and the supporting fuel cycle. [12] If only 10 gigawatts of electric capacity were supplied by breeders, hardly enough to justify the R&D effort in any country even if the economics were otherwise favorable, the plutonium inventory in the reactors and their supporting fuel cycle would be on the order of 100-200 t—sufficient for 17,000 to 33,000 nuclear weapons each using 6 kg of plutonium. By comparison, U.S. nuclear weapons stockpiles in 1987 consisted of 23,400 warheads, and the weapon-grade plutonium inventory, most of which was in weapons, was about 90 t. The Russian warhead plutonium stockpile consists of an estimated 135-170 t of plutonium in a total stockpile which peaked in 1985 at about 45,000 warheads.

Moreover, about one-half of the plutonium created in a breeder reactor is bred in the blanket rods. The burnup of the blanket material is low. Consequently, the resulting plutonium is weapon-grade, with a Pu-240 concentration lower than that used in U.S. and Russian weapons. Thus, any nonweapons country that has large stocks of breeder fuel has the capacity to produce a ready stock of weapon-grade plutonium. It only has to segregate and reprocess the blanket assemblies separately from the core assemblies.

Consequently, remaining breeder research and development programs, if not deferred altogether, should be limited to conceptual design efforts only, with an emphasis on advanced proliferation resistant fuel cycles that do not require mastery of the technology for isolating and fabricating weapons-usable nuclear materials. To the extent that this is politically impossible, sufficient plutonium has already been separated to meet the needs of R&D programs, so at a minimum there is no requirement to continue separating plutonium for this purpose. In this connection it should be noted if plutonium breeders some day prove to be economically competitive, and if the breeder fuel cycle can be safeguarded with high confidence under stringent international controls, then commercial deployment could begin with cores of nonweapons usable 20 percent enriched uranium. *In other words, there is no need to accumulate a stockpile of separated plutonium today to insure the possibility of deploying breeders at some point in the future.*

Civil Plutonium Stockpiles are a potential barrier to achieving deep reductions in the global nuclear arsenals. The accumulation of large stockpiles of separated plutonium and weapon-usable expertise in nominally civil programs will act as a barrier to deep reductions and eventual elimination of nuclear weapons held by declared and undeclared weapon states. One need only ask how far China, for example, might be willing to go in accepting limits on, or reductions in its nuclear weapons stockpile if Japan is poised to accumulate an even larger inventory of weapons-usable fissile materials in pursuit of a civil plutonium program with no clear commercial rationale. Similarly, Russia's continued operation of reprocessing plants and potentially large-scale commitment to the breeder reactor fuel cycle could abort U.S. political support for continuing toward very deep reductions and ultimate abolition of nuclear weapons stockpiles. The lack of such a commitment by the United States and other nuclear weapons states could, in turn, lead to continued erosion of the nonproliferation regime. Hence the need to forthrightly address the mistaken legitimacy afforded civil plutonium programs under the current system of international controls. In any case, nations having civil nuclear energy programs with closed fuel cycles can make an important contribution to the disarmament process by deferring further separation of plutonium until the global inventories of plutonium are substantially reduced.

Plutonium economics. Development efforts worldwide have demonstrated that plutonium fast breeders are uneconomical—unable to compete with thermal reactors operating on a once through uranium cycle—and that breeders will remain uneconomical for the foreseeable future. The putative benefits of the plutonium breeder, associated with its ability to more efficiently utilize uranium resources, are not diminished if commercial breeder development is postponed for decades, and the spent fuel from existing conventional reactors is stored in the interim. As thoroughly documented by Paul Leventhal and Steve Dolley of the Nuclear Control Institute, energy security in the nuclear sector can be achieved more cheaply and more quickly by stockpiling uranium.

The use of plutonium in the form of MOX fuel in conventional power ("thermal") reactors is likewise uneconomical because the costs of using MOX fuel cannot compete with those of enriched fresh uranium fuel for the foreseeable future. A recent study by the RAND Corp. estimates that, at the current cost for reprocessing services, the price of uranium feedstock for enrichment would have to increase by a factor of 16 before plutonium recycle in LWRs becomes competitive.

At current reprocessing costs and an FBR/LWR capital cost ratio of 1.5, the yellowcake price would have to increase by a factor of 45 before the breeder becomes competitive. When might this happen? The earliest date, based on the most optimistic assumptions about nuclear energy growth, reprocessing costs, and breeder capital costs, is at least 50 years away, and the more likely case is 100 years away. On the timescale for technology development, a period of 50 to 100 years is a very long time, during which more efficient fission options may emerge, to say nothing of advanced solar and new energy technologies not yet invented.

Accumulating a plutonium inventory today is not required to insure a sufficient startup fuel supply for breeders. If the time ever comes when plutonium breeders are both economically competitive and proliferation resistant, startup cores can be made from reserves of uranium enriched to about 20 percent U-235 (Because the critical mass of 20 percent enriched uranium metal is 14 times that of 93.5 percent enriched HEU metal, it would require on the order of 35 times or more, 20%-enriched HEU compared with the amount of weapon-grade plutonium needed, and the same increase in the amount of high explosive, to achieve a comparable yield). *Consequently, there is no sound economic or energy security justification for continued commercial reprocessing.*

Despite these realities, however, by the end of 1990, France, the United Kingdom and Japan alone had separated about 90 t of civil plutonium, and these countries plan to separate an additional 170 t by 2000. The global inventory of separated civil plutonium (i.e., not fabricated into fuel or in use in reactors) will rise to an estimated 170 t by the turn of the century—that is, almost two times the size of the U.S. weapons plutonium stockpile at its peak. This amount would be in addition to more than 100 t of plutonium likely to be removed from retired U.S. and former Soviet weapons.

Conclusion. At the dawn of the nuclear age, the authors of the famous Acheson-Lilienthal plan for international control of atomic energy clearly recognized the inherent military potential of fissile materials used for ostensibly peaceful purposes. Indeed, they believed that no widespread use of nuclear energy for civil purposes was possible or desirable without international ownership and control of the full nuclear fuel cycle.

Today it remains the unanimous opinion of the weapons design and arms control communities that the pacing consideration in a country's acquisition of a nuclear weapon is not the capability to design a nuclear device, but the availability of fissile materials that can be turned to weapons purposes. Ending, as opposed to managing, nuclear weapons proliferation will likely prove impossible as long as production of HEU and chemical separation of plutonium for national security needs remain legitimate activities in a particular class of "nuclear weapon states." The international control regime permits civil nuclear fuel reprocessing in any state that asserts a peaceful interest in plutonium recycle and future deployment of plutonium breeder reactors for energy production.

With the end of the Cold War, and the reductions in the superpower arsenals, the United States and Russia have huge surpluses of weapon-grade plutonium and highly enriched uranium. Undoubtedly, there is no need for additional weapons plutonium production in other declared weapons states. *By completely renouncing the production, separation, and isotopic enrichment of weapons-usable nuclear materials, declared weapons states can put pressure on undeclared weapons states to do the same.* Weapon-usable fissile materials have no legitimate application in today's energy marketplace and can always be produced in the future should the appropriate market and international security conditions emerge.

Despite the fact that all types of plutonium in relatively small quantities, irrespective of their designation as civil or military, have an inherent capability to be used in weapons, the current nonproliferation regime allows national separation and acquisition of plutonium (and highly enriched uranium) under an internationally monitored commitment of peaceful use. A more effective nonproliferation approach would be a global ban on the production, transfer, acquisition, or isotopic enrichment of separated plutonium and on the isotopic enrichment of uranium to greater than 20 percent U-235.

The heavy commitment of United Kingdom, France, Japan and Russia to spent fuel reprocessing and recycle of plutonium and the lingering hopes of a future revival of the plutonium fast-breeder programs have effectively barred consideration of such a direct step as outlawing production and acquisition of weapons-usable fissile materials globally. While there are obvious technical advantages in such a comprehensive approach, tangible political progress will more likely be achievedby adopting parallel approaches that seek separate controls (in the initial stages at least) on the military and civil applications of weapon-usable fissile materials.

Notes

1. *Management and Disposition of Excess Weapons Plutonium*, *Committee on National Security and Arms Control*, National Academy of Sciences, Washington, DC 1994, (prepublication copy) 37.

2. Victor Gilinsky, Plutonium, Proliferation and Policy, Commissioner, Nuclear Regulatory Commission, Remarks given at Massachusetts Institute of Technology, November 1, 1976 (Press Release No. S-14-76).

3. *IAEA Safeguards Glossary, 1987 Edition*, IAEA/sg/int/1 (REV. 1), 1987, P 23.

4. Ibid., 24.

5. Thomas Shea, "On the Application of IAEA Safeguards to Plutonium and Highly Enriched Uranium from Military Inventories," IAEA (June 1992, with additions December 1992).

6. Ibid., 23.

7. *Effects of the Possible Use of Nuclear Weapons*, United Nations, 6 October 1967.

8. In the literature, "inventory difference" is sometimes called "material unaccounted for," or MUF.

9. Marvin Miller, "Are Safeguards at Bulk-Handling Facilities Effective?" Nuclear Control Institute, Washington DC, August 1990.

10. According to Evgeni Dzekun, chief engineer of the Mayak civil reprocessing plant at Chelyabinsk-65, a plutonium input-output balance for the plant is calculated every 3.4 months when the plant is cleaned out between reprocessing campaigns. About one percent of the plutonium is lost to waste streams, and a lesser amount to plateout in the plant's plumbing. The ID is typically 15 kilograms of Pu per campaign, amounting to a total ID of about 3% percent of throughpt In other words, the ID is almost twice the IAEA's significant quantity for plutonium. According to Dzekun, if the ID in a given campaign is larger than can be explained by measurement errors, a 'special investigation' is carried out, but what this consists of is not known. To assure detection of an 8 kg. diversion at this plant with 95 percent confidence and a 5 percent false alarm rate, 3.3 x ID must be less than 8 kg, so this plant apparently falls short of the minimum IAEA standard by a factor of six. If 4 kilograms is regarded as the amount needed for a weapon, then the 'safeguards' at Mayak need to be improved by a factor of twelve in order to provide confident detection of diverted material See "Report on an International Workshop on the Future of Reprocessing, and Arrangements for the Storage and Disposition of Already Separated Plutonium" (Moscow, 14-16 December 1992) by F. v .Hippel, Princeton University, and T.B. Cochran, C. E. Paine, Natural Resources Defense Council, 10 January 1993, 5.

11. Or any other weapons material, such as HEU or Uranium-233.

12. With a plutonium breeder economy the quantity of plutonium involved would be enormous. The plutonium inventory in a commercial-size breeder is about 5 t, of which 3.5 t is fissile—sufficient for 800 atomic bombs using 6 kg Pu each. A Russian BN-800 breeder would require over 4 t. Although the net amount of plutonium produced in a fast breeder reactor annually is generally less than that produced in a conventional thermal power reactor of the same size, one-third to one-half of the FBR fuel must be removed annually for reprocessing, plutonium recovery, and remanufacture into fresh fuel. Since the fuel will be outside of the reactor for 3.5 to 7 years the plutonium inventory to support a single plutonium breeder is 11-22 t—sufficient for 1,800 to 3,600 atom bombs using 6 kg Pu each.