Canberra Commission Issue Paper

Preventing the Weapons Use of Nuclear Energy

I. Technical Realities Confronting Transition to a Nuclear-Weapon-Free World

by

Christopher E. Paine

Thomas B. Cochran

Robert S. Norris

January 4, 1996

NATURAL RESOURCES DEFENSE COUNCIL, INC
Nuclear Program
1350 New York Avenue, N.W., Suite 300
Washington D.C. 20005

Voice: 202-783-7800 (main)
202-624-9350 (Paine)
202-624-9329 (Cochran)
202-624-9328 (Norris)
Fax: 202-783-5917

Internet: nrdcnuclear@igc.apc.org
Evenings/weekend contact number: 703-527-0306 (Paine)

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So long as intrinsically dangerous activities may be carried on by nations, rivalries are inevitable and fears are engendered that place so great a pressure upon a system of international enforcement by police methods that no degree of ingenuity or technical competence could possibly hope to cope with them.

-- from "A Report on the International Control of Atomic Energy" [the "Acheson-Lilienthal Report"] March 16, 1946.

I. Introduction.

This paper presents an analysis of the underlying technical realities that have to be taken into account in the design and implementation of a control regime to prevent the use of nuclear energy for weapons purposes. The second paper in this series outlines some of the major political obstacles confronting the transition to a NWFW. A third paper analyzes several plausible approaches to organizing a control regime, that embody different combinations of strengths and weaknesses in coping with the technical and political challenges posed by the transition.

II. Underlying Technical Realities Confronting the Transition to a Nuclear Weapons-Free World.

The inherent linkages between the materials and technologies required for nuclear explosives and the controlled release of nuclear energy were fully recognized at the outset of the nuclear age. But over the years recurring bouts of amnesia became the rule as nuclear elites in the U.S., USSR, and other nations sought peaceful applications that could both dampen public fears of the awesome power unleashed by the splitting of the atom and sugar-coat the bitter pill of "defense" via reciprocal threats of thermonuclear incineration.[1]

The gap between "atoms for peace" rhetoric and the underlying technical realities has persisted to the present day, abetting nuclear weapons proliferation and obscuring an accurate understanding of the baseline requirements for transition to a NWFW. These underlying technical realities are summarized in Table 1 and discussed at greater length below.

A. Small Amounts of Plutonium are Required for a Nuclear Weapon.

After a half century of living with nuclear weapons and seeking to prevent their proliferation, misinformation nevertheless persists regarding the *amounts* of fissile material required for nuclear explosive devices. Relative to other possible designs for single-stage fission weapons, a spherically

[1] For example, President Eisenhower's famous "Atoms for Peace" program had its genesis in a White House public education effort called "Project Candor," in which the president had planned to tell the American public the bitter truths about war and survival in the thermonuclear age. But Eisenhower found the draft material for this effort so depressing that he asked his advisers for something more positive and uplifting to say about life in the nuclear age. The result was the famous "Atoms for Peace" speech, and the subsequent program resulted in a dramatic increase in the proliferation of nuclear knowledge, materials and equipment around the globe "for peaceful purposes."

Table 1. Technical Realities Confronting the Transition to A Nuclear Weapons Free World

• The plutonium required to make a pure fission nuclear explosive, with a maximum probable yield in the range, 1-20 kilotons (kt) of chemical high explosive equivalent, is quite small, on the order of 1-8 kilograms (kg), with the exact material requirement within this range depending primarily on the level of expertise employed in the design, and secondarily on the plutonium's isotopic composition and the nominal expected yield chosen for the device. The plutonium cores of modern thermonuclear warheads typically contain only 2 to 4 kg of plutonium.

• Typical stocks of low-enriched uranium fuel (4.5% U-235) represent 71% of the "separative work" required to produce 80%-enriched uranium suitable for use in simple gun-type uranium weapons, such as the weapon that destroyed Hiroshima and the six weapons that were stockpiled by the former white minority government of South Africa, highlighting the importance of close controls on low-enriched uranium and uranium enrichment facilities in a NWFW.

• While less than ideal for military applications, the isotopic composition of the plutonium typically produced in civil power reactors does not represent a serious obstacle to the fabrication of efficient and powerful weapons as well as crude terrorist devices.

• The separation of plutonium from spent nuclear fuel for recycle in fresh fuel results in the availability of large quantities of weapon-usable plutonium; the plutonium breeder-reactor and its fuel cycle provides a technical potential to produce large quantities of separated weapon-grade plutonium; and advanced technologies are under development in several countries that will permit rapid "clean-up" of reactor-grade plutonium inventories to weapon-grade.

• Current levels of international safeguards are not capable of providing timely warning of theft or diversion from bulk handling facilities, e.g., reprocessing, enrichment, and plutonium fuel fabrication facilities, of a "Significant Quantity" (SQ) of material -- the quantity the IAEA uses to represent the minimum amount of material required by a non-weapon state to construct a single nuclear explosive device.

• Basic considerations of critical mass requirements for nuclear explosive material at various levels of compression strongly suggest that the current IAEA SQ values for plutonium (8 kg) and HEU (25 kg) should be reduced eightfold, particularly if the international system is to place primary reliance in the future on safeguards rather than arsenals to deter the use of nuclear materials for weapons purposes.

• The pacing factor in any nation's acquisition of its first nuclear weapon, or a large nuclear arsenal, is the availability of weapon-usable fissile materials.

• Continued pursuit of fast reactors and inertial confinement fusion (ICF) in leading industrial countries worldwide, and the availability of increasingly capable computers and simulation codes, will likely result in the replication of nuclear scientific cadres in numerous countries with relevant skills for the design of nuclear (and possibly thermonuclear) explosives, not all of which would be classified today as "crude" devices.

symmetric implosion system requires the least amount of fissile material to achieve a given explosive yield, and therefore represents the limiting case for assessing the proliferation threat and the effectiveness of safeguards. For this type of device, the amount of plutonium (or HEU) required depends on the desired explosive yield of the device, and the degree to which the fissile material is compressed at "explosion time," i.e., the moment at which explosive disassembly of the fissile material begins due to the energy released by the exponential build-up of the fission chain reaction.

The degree of compression achieved depends on the sophistication of the design and the 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 for the purposes of this analysis, we will assume that the proliferant state or subnational group has already acquired essential design skills from existing open sources or clandestine technology transfers, so 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 fissile material[2] (weapon-grade plutonium in Figure 1 and HEU in Figure 2) for three degrees of compression. In the figures, the numerical factors of compression used in the calculations are assigned qualitative labels according to our judgement of the relative technical sophistication of the designs; that is, whether they represent "low", "medium," or "high" technology. As seen from Figure 1, the Nagasaki bomb, *Fat Man*, which produced a 20 kiloton (kt) explosion with 6.2 kg of weapon-grade plutonium, falls on the "low technology" curve. However, only three kg of weapon-grade plutonium compressed to the same extent would still have produced a one kt explosion. During the "Ranger" series of tests in 1951, the U.S. used an even smaller quantity of plutonium to achieve a yield of one kt from the Mark 4 bomb design, which incorporated the principle of levitation (now declassified), first demonstrated by the United States in 1948.[3]

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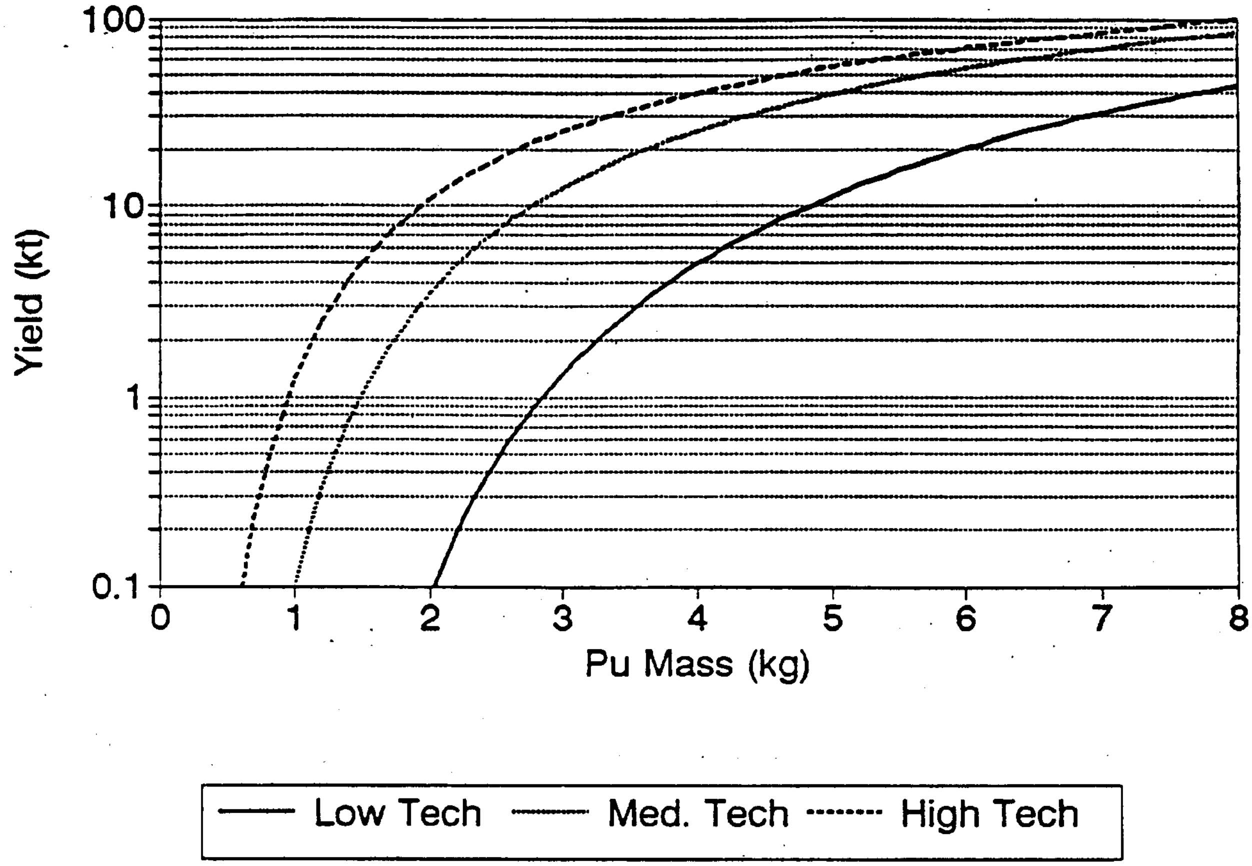
[2] The United States categorizes plutonium stocks in terms of the concentration of the major isotopic contaminant, Pu-240: super-grade (2-3% Pu-240), weapon-grade (<7% Pu-240), fuel-grade (7 to <19% Pu-240), and reactor-grade (≥19% Pu-240). Uranium is not so categorized. *Little Boy*, dropped on Hiroshima, was made with uranium enriched to about 80% U-235. Today, to the extent that it is used in fission warheads, and the fission triggers of thermonuclear warheads, the uranium is enriched to about 93-94% U-235. The secondaries of thermonuclear warheads contain uranium of various enrichments up to about 94% U-235.

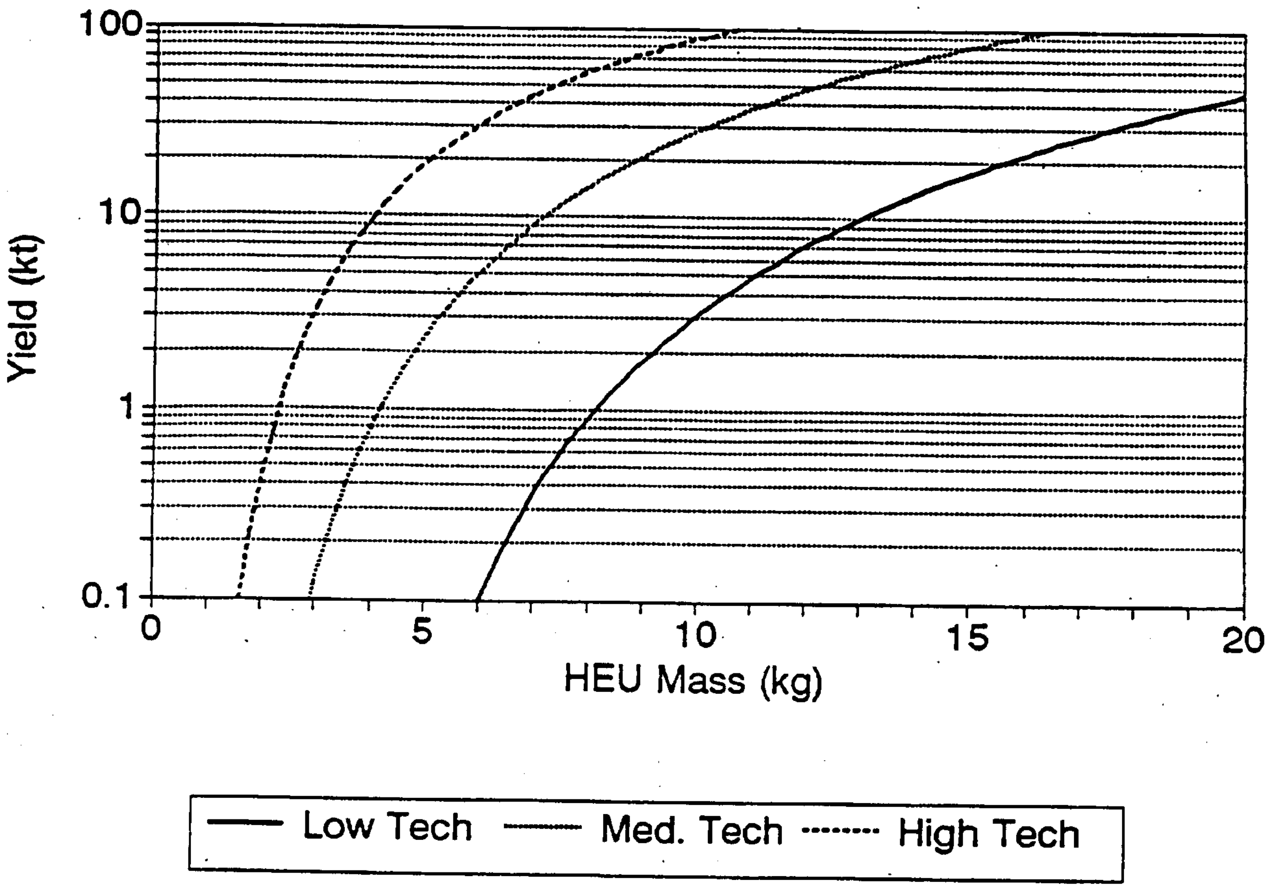
[3] R.S. Norris and T.B.Cochran, "United States Nuclear Tests: July 1945 to 31 December 1992," Natural Resources Defense Council, Washington, D.C., Nuclear Weapons Databook Working Paper NWD 94-1, 1 February 1994, p.22.

Figure 1.[4]
Yield vs. Plutonium Mass
(as a function of technical capability)



[4] T.B. Cochran and C.E. Paine, "The Amount of Plutonium And Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," *Nuclear Weapons Databook* monograph series, Natural Resources Defense Council, Washington, D.C., 13 April 1995.

Figure 2.[5]
Yield vs. HEU Mass
(as a function of technical capability).



[5] T.B. Cochran and C.E. Paine, "The Amount of Plutonium And Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons," *Nuclear Weapons Databook* monograph series, Natural Resources Defense Council, Washington, D.C., 13 April 1995.

Table 2.
Approximate Fissile Material Requirements for Pure Fission Nuclear Weapons.

	WEAPON-GRADE PLUTONIUM (kg)			HIGHLY-ENRICHED URANIUM (kg)		
Yield	Technical Capability			Technical Capability		
(kt)	Low	Medium	High	Low	Medium	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

A one kt yield is still an 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 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 technically advanced non-nuclear weapon state today can take advantage of a wealth of technical information on the physics of nuclear explosives that has found its way into the open literature over the past 50 years, and do even better. As seen from Figure 1, to achieve an explosive yield of one kt, an estimated 1 to 3 kg of weapon-grade plutonium is required, depending upon the sophistication of the design. And from Figure 2, we estimate that some 2 to 7 kg of HEU is required to achieve an explosive energy release of one kt. Table 2 presents some of the results of our calculations in a different form. It is estimated, for example, that as little as 2 kg of plutonium, or about 4 kg of HEU, is required to produce a yield of 10 kt.[6]

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[6] These calculations recently received independent indirect corroboration from two unexpected sources. Russia revealed in May 1995 that destruction was imminent for a nuclear effects test device, -- originally emplaced in a horizontal tunnel at the Kazakh test site in May 1991 -- that contained "a total mass of almost 1 kg of plutonium" with a planned yield of "0.3 kilotons." These specifications are very close to those at the low end of the "high-tech" weapon design curve in Figure 1. Recently declassified documents in the U.K. reveal that its first test of an air-dropped weapon, on October 11, 1956, produced a yield of 3 kilotons from a 2 kg Pu core. These specifications lie extremely close to a point on the "medium-tech" weapon design curve in Figure 1. See Victor Litovkin, "Destroy Nuclear Device!..." *Moscow Izvestiya*, 23 May 1995, p. 1.; R.S. Norris, et al., Nuclear Weapons Databook Volume V, *British, French and Chinese Nuclear Weapons* (Boulder, CO: Westview Press 1994), p. 400; and Letter to NRDC from D. Forster, 28 October 1995, citing letter from R. Cook of AWRE to the Director General Atomic Weapons, 27 June 1956, on file in the U.K. Public Record Office.

B. "Civil Plutonium" of Widely Varying Isotopic Composition Can Be Used to Make an Efficient Nuclear Explosive.

The curves in Figure 1 apply to weapon-grade plutonium -- that is, plutonium containing less than 7 percent of the isotope Pu-240. Most of the plutonium in the civil sector is reactor-grade, with a Pu-240 content in the range of 20-35 percent.

Plutonium with a high Pu-240 content is less desirable for weapons purposes than weapon-grade plutonium for four reasons: (a) it has a larger critical mass; (b) it presents a greater radiation hazard to workers and weaponeers; (c) it gives off more thermal energy (heat) as a consequence of radioactive decay of the shorter-lived plutonium isotopes; and (d) it has a greater rate of spontaneous fissions due to the higher concentration of Pu-240. Regardless of its Pu-240 content the critical mass of reactor-grade plutonium falls between that of weapon-grade plutonium and HEU. Hence from the standpoint of critical mass alone, reactor-grade plutonium is superior to HEU as a weapon-usable material. The added radiation and thermal effects can be alleviated through shielding and design modifications.

Some advocates of civil plutonium use have argued erroneously that the higher rate of spontaneous fissions effectively "denatures" the explosive characteristics of reactor-grade plutonium.[7] For low-technology weapon designs the neutrons generated by the high rate of spontaneous fission of Pu-240 can increase the statistical uncertainty of the yield by "pre-initiating" the chain reaction before the desired compression of the plutonium core has been achieved. In spite of these difficulties, *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 first 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. *While this yield is referred to as the "fizzle 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*

[7] The likely source of this mistaken view is discussed in the Appendix to this issue paper.

> *less*. With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.[8]

By making use various combinations of advanced technologies, including more rapid implosion techniques, the use of beryllium as a neutron reflector, "boosting" the fission reaction with additional high energy (14 MeV) neutrons from deuterium-tritium fusion, and using two-stage weapon designs, it is possible to offset the problems created by the high rate of spontaneous fission of Pu-240. As long ago as 1976, then NRC Commissioner Victor Gilinsky summed up the situation as follows:

> Of course, when reactor-grade 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.[9]

More recently, the Los Alamos National Laboratory released the following unclassified statement regarding the weapon-usability of reactor-grade plutonium:

> Except for high purity Pu-238, plutonium of any isotopic composition, including that in spent fuel from commercial power reactors, can be used to make a nuclear weapon that is capable of significant nuclear yield. Design and construction of any nuclear weapon is a difficult task -- but is a task that can be accomplished with a level of sophistication and computational capability that existed in the early 1950s at the nuclear-weapons design laboratories.
>
> Examination of designs typical of 1950s nuclear weapons indicate that replacing weapons grade plutonium with plutonium of other isotopic composition could have two results: it might decrease slightly the maximum yield of the weapon, and it might reduce the probability that the maximum yield would be obtained in an explosion. *However, even in extreme cases [i.e., involving high concentrations of Pu-240 and other non-fissile isotopes] yields on the order of kilotons would result* [emphasis added].[10]

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[8] Management and Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, National Academy of Sciences (Washington, D.C.: National Academy Press, 1994), Prepublication Copy, p.37.

[9] 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).

[10] Cited in Frank von Hippel, "Weapons-Usable Nuclear Materials Security after the Cold War," revised text of opening speech at a Symposium at the Konrad-Adenauer House, Bonn, May 9, 1995, p.4.

Assuming an advanced design were attempted using reactor-grade Pu-240 plutonium of 24%, the nominal yield potential of a modern 2-3 kg weapon-grade plutonium core could be maintained by increasing the mass of the core by about 25% -- the ratio of the respective reflected critical masses -- and a corresponding increase in the amount of chemical high explosive. Similarly, to obtain the same nominal yield from a modern boosted primary, the mass of the core and chemical high explosive would have to be slightly increased if reactor-grade plutonium were used instead of weapon-grade plutonium.

C. The Plutonium Breeder Fuel Cycle Potentially Affords Access to Large Quantities of High-Quality Plutonium for Weapons.

By giving sanction to spent-fuel reprocessing the world is confronted with large flows of recovered plutonium and plutonium stockpiles. Each tonne (t) of separated reactor-grade plutonium in civil reactor programs represents the equivalent of 160 Nagasaki-type plutonium cores, or 270 to 400 modern nuclear weapon cores. As noted in accompanying Canberra Commission issue paper, "The Arsenals of the Nuclear Weapons Powers: An Overview," a large commercial reprocessing plant, such as THORP in the U.K. or the proposed Rokkasho-mura Plant in Japan, is capable of separating 6-7 t of reactor-grade plutonium per year. This represents roughly 800 to 900 Nagasaki-type plutonium cores, or 1600-2800 modern plutonium cores, annually. As explained in Section D below, there is at present no technically credible means of safeguarding this material to prevent strategically significant quantities from being diverted for use in nuclear weapons.

Commercial deployment of plutonium fast breeders would entail staggering amounts of nuclear weapons-usable plutonium in the reactors and the supporting fuel cycle.[11] If only 10 gigawatts of nation's 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

[11] The plutonium inventory in the once planned U.S. commercial-scale breeder would have been about 5 t (of which 3.5 t would have been "fissile") -- sufficient for about 800 Nagasaki-type weapons each using 6.2 kg of plutonium. Assuming a smaller, more efficient advanced design were attempted using reactor-grade (24% Pu-240) plutonium, the plutonium inventory in the planned U.S. commercial breeder of the early 1980's would have been sufficient for at least 5t/.00375, or 1330 fission weapons. A Russian BN-800 breeder reactor, under construction in the late 1980's but currently deferred, would require a plutonium inventory of over 4 t, sufficient to fabricate about 1070 weapons. 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 fast breeder reactor 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 needed to support a single commercial-size plutonium breeder is 11-18 t -- sufficient for about 2900-4800 reactor-grade plutonium implosion weapons.

their supporting fuel cycle would be on the order of 100-200 t, sufficient for *20,000 to 40,000 modern nuclear weapons*.[12]

However, those nations -- or agencies within nations -- having access to reprocessing technology, *would not be limited to reactor-grade plutonium weapons*. In civil spent fuel stocks, even those in which most of the fuel is reactor-grade, there is usually some low Pu-240 content ("low burnup") fuel from which significant quantities of weapon-grade plutonium can be extracted if the low burnup fuel is processed separately. For example, about one half of the new plutonium created in a typical liquid metal breeder reactor is super-grade, bred in the outer uranium "blanket" rods surrounding the core. This super-grade plutonium has a Pu-240 concentration lower than that used in U.S. and Russian weapons. *To produce a ready stock of low-burnup plutonium that is optimally suited for weapons*, a country has only to reprocess the blanket assemblies separately from the core assemblies.[13]

More than sufficient plutonium has already been separated to date to meet the needs of worldwide breeder development and demonstration programs, so at a minimum there is no technical requirement to continue separating plutonium for this purpose. If plutonium breeders some day prove to be economically competitive for electricity generation, and if the breeder fuel cycle can be made secure against proliferation under stringent international controls, then commercial deployment could begin with cores of non-weapons usable 20%-enriched uranium. *In other words, from a technical perspective, there is no need to separate large stocks of plutonium today to insure the possibility of deploying breeders at some point in the future.* In this respect the world *can* have its cake and eat it too -- the international community can preserve both the option of a NWFW and the long-term prospect of extracting energy from plutonium-based fuels, but only if the nuclear weapons elimination process is not short-circuited by a premature proliferation of chemical separation or isotopic enrichment capabilities under essentially national ownership and control.

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[12] Calculation based on an estimated U.S.-Russian average of about 3 kg of weapon-grade plutonium per core adjusted to 4 kg to reflect the slightly larger reflected critical mass requirement of reactor-grade plutonium, and including an allowance for manufacturing "losses" of 20 percent.

[13] A case in point is Japan, which from 1987-1993 acquired advanced "centrifugal contactor" technology for separating *low-burnup* plutonium from the U.S. Department of Energy for installation in PNC's Recycle Equipment and Test Facility (RETF) at Tokai -- technology that was originally developed and tested at two U.S. nuclear weapons production facilities -- the Savannah River Plant and the Oak Ridge National Laboratory. To maximize output of weapon-grade material, a country could blend super-grade plutonium ($<3\%$ Pu-240) from the breeder blanket with existing inventories of reactor-grade plutonium ($\geq 19\%$ Pu-240) plutonium to create a larger quantity of weapon-grade material ($< 7\%$ Pu-240).

Since the perspective of a nuclear weapons free world is a longer term one (i.e., 20 -50 years) one must also entertain the prospect that advanced isotopic separation techniques, such as Atomic Vapor Laser Isotope Separation (AVLIS), will be available to any country with the nuclear technology and capital sufficient to support construction of breeders and reprocessing plants. The availability of such technology would erase whatever operational and technical deficiencies attend the use of reactor-grade plutonium in weapons, by allowing inventories of already separated reactor-grade material to be "cleaned-up" to weapons-grade. Indeed, the U.S. was on the verge of constructing a large plant of this type in 1989 to clean-up Department of Energy stocks of fuel-grade plutonium (~12% Pu-240) when the Berlin Wall came down. Both France and the U.S. are continuing to develop production-scale AVLIS technology for commercial uranium enrichment, and Israel is suspected of having built a small pilot-scale AVLIS facility in connection with its secret nuclear weapons program.

D. Current Levels of IAEA Safeguards Do Not Provide a Capability for Timely Warning of the Theft or Diversion of Weapon-Usable Materials from Several Important Types of Nuclear Facilities.

Adequate physical security measures are essential to prevent the theft of fissionable material. Under the present international safeguards system these are entrusted to the individual nation state, which in turn may delegate the task to private commercial entities licensed for the purpose. The difficulty in placing total reliance on physical security measures is that theft of materials can involve a collusion of individuals, including the head of the guard force, or even the head of the company or agency.[14]

Moreover, the nonproliferation function of physical security is largely reversed when the collusion involves elements of the government itself. In this case the primary mission of the security apparatus is not only to prevent theft, but also 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), former 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

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[14] Despite having guards at every bank, employees at the Bank of Credit and Commerce, Inc. (BCCI) were able to steal millions 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 the former USSR, and now Russia, the security of fissile materials has relied heavily on guarding not only the facilities, but also the secret towns and cities where the nuclear work force resides. These large "closed" areas are anathema to a democratic society.

programs. *In light of this history, successfully combatting the "norm of secrecy" surrounding the operations of nuclear research and development complexes can be seen as an integral part of any serious nuclear weapons elimination strategy.*

The international community's principal tool to date for penetrating the secrecy of nuclear facilities has been the power of the International Atomic Energy Agency (IAEA) to conduct inspections of declared nuclear facilities and to require adherence to strict material accounting and control procedures. Because the possibility of collusion exists between guard forces and facility operators, particularly when both are controlled by the same (usually unaccountable) state entity, frequent and accurate material control and accounting (MC&A) measures are essential to provide both other national authorities and the international community with a timely determination of whether any significant theft or other loss of material has occurred. This determination should in theory afford the international community the opportunity to undertake actions aimed at preventing any diverted, stolen, or otherwise missing material from being used for destructive or coercive purposes, or from posing an unrecognized threat to the environment and human health.

Given the technical difficulty and cost of making the repeated measurements that are often necessary to provide a high degree of assurance that all material remains accounted for, MC&A measures are supplemented by "containment and surveillance" (C&S) techniques -- mainly seals and cameras -- that are intended to maintain the integrity of measured quantities or storage areas between inspections. C&S techniques are also used to monitor access to areas where direct measurements cannot be taken, or where the error in making remote measurements is large. Together with periodic inspections, the MC&A and C&S techniques routinely employed by the IAEA at declared nuclear facilities are collectively referred to as "IAEA Safeguards."

It is well established -- from experience at existing civil and military chemical separation (reprocessing) plants, naval fuel facilities, and mixed-oxide fuel facilities -- that one cannot detect -- through independent MC&A measurements alone -- the diversion of several bombs worth of plutonium annually, even from a small plant such as Japan's Tokai-mura reprocessing facility.[15] Given the

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[15] At existing reprocessing plants in the West that handle tons of plutonium, the error in measuring the plutonium input into the plant (about 1% of the throughput) dominates the degree of inaccuracy in the IAEA's determination of the difference between beginning and ending plutonium inventories, known as the "inventory difference" or "material unaccounted for" (MUF). The current MUF for Tokai Mura is on the order of 8 kg per annual inventory -- the IAEA's current "significant quantity" for plutonium. However, for this amount of (continued...)

continuing political instability in Russia and the real possibility of significant diversions, it is hard to argue that the location of plutonium bulk-handling facilities in a nuclear weapons state makes them any less of a security threat than a similar plant located in Japan, and yet these facilities remain outside of the international safeguards regime.

Because traditional MC&A measures have inherent technical deficiencies in safeguarding bulk handling facilities, safeguards agencies have increased their reliance on C&S measures to ensure against unauthorized or unrecorded access to the process lines and storage areas. However, unless such measures provide comprehensive and continuous coverage under the control of a credible independent authority, including coverage during frequent maintenance outages, ultimate confidence in safeguards effectiveness once again reposes, as it does in the case of physical security, in the overtly *political* judgement that successful collusion to defeat the system is highly improbable.

The IAEA permits facilities to reduce inventory uncertainties by subdividing the facility into numerous "material balance areas." The facilities in fact should be so subdivided, because this provides added protection against a single insider threat. But it must be recognized that this system does not afford adequate protection against a collusion of individuals, particularly in scenarios where inspections are infrequent and elements of the state apparatus itself may be engaged in the diversion.

The "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 7-10 days; for other compounds of these materials, 1-3 weeks. These times are already much shorter than the period between inventories at any fuel reprocessing plant operating today, or the period between inspections of research facilities containing one

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[15](...continued)
diverted plutonium to be distinguished from measurement noise with detection and false alarm probabilities of 95% and 5%, respectively, the MUF value must be on the order of 2.4 kg, less than a third of what it is today. If the SQ value were lowered to the technically indicated 1 kg, the MUF should not exceed about 300 grams, and the Tokai plant would fail to meet the IAEA standard *by an order of magnitude*. Material accounting and control at Russian plants handling nuclear fuel in bulk form is rudimentary at best. At the civil RT-1 chemical separation plant at Chelyabinsk-65, the MUF alone is almost twice the IAEA's current SQ value for plutonium, meaning that the ability to detect diversions at this plant falls short of the current (inadequate) international standard by a factor of six.

or a few significant quantities of HEU fuel.[16] *Thus, in many instances there is not technical assurance that the primary objective of safeguards -- the timely detection of the loss or diversion of significant quantities of plutonium or HEU -- is now being, or can be, met.*[17]

In Western Europe and Japan, consideration is being given to Near-Real-Time Accountancy (NRTA) as a means of improving the sensitivity and timeliness of detection. NRTA involves taking inventories at frequent intervals, typically once a week, without shutting down the facility. Effective implementation of NRTA and similar concepts may well be opposed by plant operators due to the added costs that would be imposed. In any case the methods and adequacy of practical NRTA system implementation are open questions.[18] In a recently published analysis of safeguards, the U.S. Congressional Office of Technology Assessment observed:

[16] It is now known that between November 1990, the date of the last IAEA inspection of Iraq's inventory of HEU fuel before the Gulf War, and April 1991, the date of the next scheduled inspection, Iraq moved some 26 kilograms of fresh and lightly irradiated HEU fuel without informing the IAEA and sought to use it in a crash weapon development program ordered in August 1990. The IAEA failed to detect either of these developments before the war began in January 1991, even though the safeguards violation occurred before the war began.

[17] To meet the timely detection criteria, reprocessing plants would have to undergo clean-out inventories every few days, or weeks. But this would reduce their annual throughput -- and utility -- practically to zero. It would also drive up the cost of reprocessing. Plutonium recycle -- the use of MOX fuel in standard commercial light-water reactors (LWRs) -- is already uneconomical due to the high costs of reprocessing and fuel fabrication even when conducted without a technically adequate level of safeguards. Similarly, the cost of the fast breeder fuel cycle is already vastly greater than that of the LWR operating on the once-through cycle. Ensuring adequate safeguards on the breeder fuel cycle would only widen this cost disparity.

[18] A case in point is Japan's Tokai Plutonium Fuel Production Facility (PFPF) where MOX fuel has been fabricated for Japan's Joyo and Monju fast-breeder reactors since 1988. The PFPF's production line consists of 17 interconnected glove boxes monitored by unattended, tamper proof instruments, such as neutron coincidence counters. Following an April 1994 inspection conference with the IAEA, Japanese sources disclosed that on the order of 70 kg of plutonium was "held up" in the remotely monitored process line, and that the uncertainty in the NRTA system's measurement of this hold-up material exceeded at least 8 kilograms, enough material for several nuclear explosive devices. PNC agreed to design new glove boxes that reduce the amount of plutonium deposited in the process line, but astonishingly the IAEA did not order the immediate shutdown of the plant and a comprehensive clean-out inventory. Given that 1-2 kg is sufficient for a weapon, the IAEA's intervention was technically four years too late to provide timely warning of a theft or diversion should an eventual physical inventory demonstrate that kilogram quantities of plutonium remain unaccounted for. This initial application of NRTA, and the IAEA's sluggish response to the difficulties encountered, does not justify confidence in successful implementation of NRTA techniques in larger and more complex facilities with vastly greater flows of material.

> To date, the IAEA has not considered the possibility that it cannot safeguard large facilities such as the Rokkasho-mura reprocessing plant, but neither has it demonstrated that it can.[19]

E. The IAEA's Definition of "Significant (i.e., Explosive) Quantities" for Plutonium and HEU Nuclear are Technically Incorrect.

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."[20] Significant quantity values currently in use by the IAEA are given in Table 3.[21]

Table 3.
IAEA Significant Quantities.

Material	Quantity of Safeguards Significance	Safeguards Apply to:
Direct-use nuclear material		
Plutonium (<80% Pu-238)	8 kg	Total element
Uranium-233	8 kg	Total isotope
Uranium enriched to 20% or more	25 kg	U-235 isotope
Indirect-use nuclear material		
Uranium	75 kg	U-235 isotope
(<20% U-235)		
Thorium	20 t	Total element

[19] "Nuclear Safeguards and the International Atomic Energy Agency," OTA-ISS-615, Washington, D.C. June 1995, p. 73.

[20] *IAEA Safeguards Glossary, 1987 Edition*, IAEA/SG/INF/1 (Rev. 1), 1987, p. 23.

[21] Ibid., p. 24.

The SQ values were recommended to the IAEA by a group of experts, namely, the IAEA's Standing Advisory Group for Safeguards Implementation (SAGSI), and "relate to the potential acquisition of a first nuclear explosive by a non-nuclear weapon state."[22] The direct-use values in Table 3, 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."[23] The IAEA cites as a source for these threshold amounts a 1967 United Nations document.[24] The IAEA states:

> 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.[34]
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>
> [34] 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.

As evident from Figures 1 and 2 and the earlier discussion, the direct-use SQ or threshold values currently used by the IAEA are technically indefensible. For decades the IAEA has set invalid technical thresholds for the minimum quantity of nuclear material needed for a nuclear weapon, even for a low-technology first nuclear explosive by a non-nuclear weapon state, including consideration of unavoidable losses.

First, the current 8 kg SQ value for plutonium is consistent with assuming a 30% loss in fabricating a solid 6.2 kg plutonium core similar to the Trinity device or the Nagasaki bomb -- equivalent to losing the outer 0.4 cm of the 4.5 cm core during casting and machining. This degree of imprecision seems exceptionally high for the numerically controlled techniques now available in the commercial marketplace. Second, as noted earlier, if one took the same *Fat Man* design, first tested at the *Trinity* site in New Mexico and dropped on Nagasaki in 1945, and simply substituted a three kg plutonium core for the 6.2 kg core that was used in 1945, the yield of this device would be on the order of one kt, still a very respectable atomic bomb that could create catastrophic losses in dense urban areas. Thus, based

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

[23] Ibid., p. 23.

[24] *Effects of the Possible Use of Nuclear Weapons* ..., United Nations, A/6858, 6 October 1967.

on this evidence alone 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 materials.

Third, as discussed in Section A, since the early 1950's, the nuclear weapon states have been producing nuclear weapons with yields of several kilotons range from as little as 2 kg of plutonium. The so-called "highly sophisticated techniques available to NW States" referenced by the IAEA were known to U.S. weapons designers in the late-1940s and early 1950s -- and are now available to anyone with the patience and skills to search the open technical literature. Nuclear devices using very small quantities of plutonium and HEU--so-called "fractional crit" weapons--with yields on the order of one kt 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, to guard against the fact that materials can be diverted from more than one source. The practice of setting higher levels to account for manufacturing losses is likewise imprudent, particularly in view of the fact that a significant fraction of these "losses" are technically recoverable. In sum, *safeguards apply to all non-weapons countries, irrespective of their technological sophistication, and safeguards effectiveness should be assessed with this fact in mind.*

Many IAEA-member countries that are not declared nuclear weapon states, such as Japan, Germany, South Korea, Israel, India and Pakistan, have highly developed nuclear infrastructures, and must be considered technologically sophisticated. Even for countries that are in general not sophisticated technologically, such as North Korea, the key technical information needed to establish a program for achieving substantial compression via implosion techniques is now accessible in the unclassified literature. The quantities defining safeguards significance, therefore, must be based an the assumption that the proliferator has access to "advanced" (i.e., at least 1950's era) technology. Whatever the nonproliferation "disinformation benefit" that may have flowed from the IAEA is mistaken SQ values in the past, it is now far too late in the proliferation game to base the international nuclear control regime on flawed technical premises. As a consequence, the IAEA's significant quantities should be lowered at least 8-fold to the values in Table 4.

Table 4.
Technically Indicated Significant Quantities.

Material	Quantity of Safeguards Significance	Safeguards Apply to:
Direct-use nuclear material		
Plutonium (<80% Pu-238)	1 kg	Total Element
Uranium-233	1 kg	Total isotope
Uranium enriched to 20% or more	3 kg	U-235 isotope

F. Enrichment Capabilities.

There are many ways to enrich uranium. Early attempts at separating isotopes employed thermal diffusion, gaseous diffusion, electromagnetic separation (calutrons), and gas centrifuge technologies. From World War II to the present the dominant technologies deployed were gaseous diffusion (U.S., Russia, U.K., France, China, Argentina), gas centrifuge (Russia, U.K., France, India, Pakistan, Brazil), and aerodynamic separation (South Africa, Brazil). Atomic vapor laser isotopic separation (AVLIS) is under development and being actively researched in several countries, and a wide variety of separation techniques have been the subject of various levels of research and development: molecular laser isotope separation (MLIS), and several other laser enrichment technologies, plasma and chemical separation and several combined techniques.

Diversion of HEU for unauthorized use from safeguarded enrichment plants designed to produce HEU can be difficult to detect because of the large inventory differences--a few percent of throughput. This diversion scenario is best resolved by an agreed ban on the isotopic separation of weapon-usable uranium, i.e., uranium enriched above 20% U-235.

Aside from direct diversion of HEU from a safeguarded plant, there are three additional technical paths for obtaining weapon-usable uranium through clandestine enrichment: (a) develop a new enrichment plant designed for HEU production, (b) alter an existing plant designed for low-enriched uranium (LEU) production, and (c) divert LEU for subsequent enrichment to HEU in a smaller enrichment plant. Some enrichment technologies, e.g., AVLIS, require relatively little space and consequently locating clandestine facilities represents a challenge to the IAEA and National Technical Means. Conversion of some enrichment technologies, e.g., centrifuge plants, is not a difficult operation physically, but could be detected by in-plant inspectors.

The diversion of LEU for subsequent enrichment also represents a potential breakout scenario and a challenging safeguards problem. Typical stocks of low-enriched uranium fuel (4.5% U-235) represent 71% of the "separative work" required to produce 80%-enriched uranium suitable for use in simple gun-type uranium weapons, such as the weapon which destroyed Hiroshima and the six weapons that were stockpiled by the former white minority government of South Africa. Since nuclear power based on the thermal reactor's "once-through" fuel cycle is likely to persist at least 40-50 years into the future -- the expected lifetime of new nuclear plants currently approved for construction -- close controls on enrichment as well as reprocessing capabilities will have to be maintained during the transition to a NWFW, and perhaps indefinitely, depending on the future of nuclear power.

G. The Nuclear Fuel Cycle and Fusion Technology Base.

Without civil reprocessing facilities, breeder reactors, or enrichment plants, countries wishing to develop to develop an option for producing nuclear weapons capacity face very considerable political obstacles and costs. Obtaining significant quantities of fissionable material for weapons would require that they build one or more specialized production reactors and chemical separation facilities outside of safeguards, using indigenous or black market technology, or seek international acceptance for the acquisition of a safeguarded uranium enrichment plant. This plant could produce either HEU, or excess stocks of unirradiated LEU that could be rapidly enriched to weapon-grade coincident with withdrawal from the NPT. However, in the absence of a well-developed civil nuclear power program with sizable fresh fuel requirements, there is now virtually zero international legitimacy for a country's efforts to pursue the uranium enrichment route -- the only recent exception being Russia's "agreement in principle" -- now withdrawn -- to negotiate the sale of a centrifuge plant under safeguards to Iran. By establishing a nuclear weapons option through a "peaceful" plutonium-using nuclear electric generation program, current and future proliferators could circumvent these obstacles.

A "peaceful" fast breeder reactor program also justifies the acquisition of a whole panoply of specialized research facilities, training, and data applicable to nuclear weapons design that would otherwise not be easily acquired, such as: fast critical assemblies, including significant quantities of weapon-grade material with which to perform reactor safety and criticality experiments in the laboratory with minimal health risk to personnel; nuclear diagnostic instrumentation and recording equipment; elaborate Monte-Carlo neutronic codes, and data on material properties at high temperatures and pressures, needed for controlling the same fast-neutron spectrum used in nuclear weapons; data on plutonium metallurgy and alloys for producing plutonium fuel elements and evaluating their performance; and so on. In short, a peaceful plutonium fuel cycle program represents an enormous head start on a nuclear weapons program. Indeed, it represents a "legal" path to a nuclear weapons potential under the NPT.

Inertial confinement fusion (ICF) involves imploding small pellets of nuclear fusion fuel with the objective of achieving thermonuclear burn. The ICF target materials and shapes can be similar to those of the secondary components of thermonuclear weapons, and the densities and temperatures sought in the laboratory approach conditions achieved in thermonuclear weapon tests. Consequently the pursuit of ICF even for peaceful purposes, provides a means for a country to develop or retain a cadre of experts knowledgeable about a wide range of topics relevant to thermonuclear weapon physics, including hydrodynamics, material properties at high densities and temperatures, radiation flow, radiative properties, and related computer codes.

An advanced country that does not have nuclear weapons, or that has given them up, but wishes to retain an effective nuclear weapon breakout capability, will likely wish to maintain a robust closed nuclear fuel cycle and a robust ICF research and development program.

APPENDIX

A brief description of the differences between bombs and reactors can perhaps explain why some were led to a mistaken belief in the non-explosive character of plutonium having a substantial concentration of the isotope Pu-240. The odd plutonium isotopes (239 and 241) are said to be "fissile" -- meaning their nuclei can be fissioned by low-energy (so-called "thermal") neutrons that have been slowed by a "moderator," such as the water moderator-coolant in most civil power reactors. A reactor that relies on this thermal neutron spectrum takes advantage of the higher "cross section" of U-235 and Pu-239 atoms for fission by slow neutrons, allowing low concentrations (0.7% to 4.8%) of these materials to be used as fuel. The time required for the fast neutrons produced in fission to be slowed down -- by non-fission, non-capture collisions with the moderator nuclei -- introduces a lag in the growth of the chain reaction. This lag prevents the chain reaction from reaching explosive proportions before its own heat expands the fuel to "subcritical" density, shutting off the reaction.

Nuclear reactors have the further property that they are designed to achieve a self-sustaining chain reaction (called "criticality") in the fuel with the assistance of so-called "delayed neutrons," (i.e., those that are not produced "promptly" by the fission reaction itself, but rather in subsequent radioactive decay of some of the shorter-lived fission products.) This affords a much longer time -- on the order of minutes rather than microseconds -- between neutron generations, allowing the power of the reaction to be regulated by withdrawal or insertion of neutron absorbing control rods.

By contrast, nuclear explosives and a class of power reactors that also rely on a "fast neutron" spectrum, -- the so-called "fast reactors" -- compensate for the lower fission cross-sections available at higher neutron energies by using higher densities of chain-reacting material, and a low density of neutron absorbing materials. The isotopes Pu-240 and Pu-242 have a threshold for fission at neutron energies approaching one million electron volts (MeV), well above the thermal neutron spectrum used in most civil power reactors. Hence the origin of the (misguided) notion that Pu-240, the useless "nonfissile" isotope that builds up steadily with fuel exposure in a thermal reactor, could serve to "denature" the explosive properties of the plutonium produced in the spent fuel.

However, in *a nuclear explosive the thermal neutron spectrum plays no role*, and unlike a fast reactor, criticality and then an exponentially multiplying chain reaction ("supercriticality") is achieved in the fissionable material *with prompt neutrons alone*. The time between neutron generations is drastically reduced by reliance on the prompt neutrons, leading to an explosive growth in the fission reaction. The average initial energy of a fission neutron, before collisions with other nuclei, is almost 2 MeV, and the average energy of a fission neutron moving in plutonium metal after a few "scatterings" (collisions), is about one MeV. For neutron energies above about 0.7 MeV, the fission "cross-section" of Pu-240 is smaller than that for Pu-239, *but larger than that for U-235.*

As Los Alamos weapons designer Robert Selden emphasized in a briefing to senior IAEA officials in November 1976 : "*The most useful comparison of fissile materials for nuclear explosives is the comparison of fast neutron (prompt) critical masses* (emphasis added)." Since the bare critical mass of Pu-240 as metal is about 40 kg -- *less* than the 52 kg needed for a bare critical mass of weapon-grade uranium (94% U-235) -- Pu-240 may be said to be *a more effective fissionable material than weapons-grade uranium* in a metal system.

"In practice," observes J. Carson Mark, former director of the Theoretical Division of the Los Alamos National Laboratory, "at all burn-up levels and at any time following discharge [from the reactor] the critical mass of reactor-grade plutonium metal is intermediate between that of Pu-239 and Pu-240, which is more reactive than weapons-grade uranium." He observes that reactor-grade plutonium can be brought to a supercritical -- and hence explosive -- state, by any assembly system that can handle U-235."[25] While this inconvenient fact has been studiously overlooked by the advocates of civil plutonium use, its relevance to the nonproliferation problem is beyond dispute.

[25] J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, 1993, Vol. 4, p. 115.