The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons

by

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I. Introduction

The criterion used by the International Atomic Energy Agency (IAEA) to assess the proliferation risk of inventory differences routinely encountered during safeguards inspections of weapon-usable nuclear materials is called the "Significant Quantity (SQ)." This quantity is said to represent the minimum amount of fissile material which, if diverted from peaceful nuclear activities, could be used "directly" (without further chemical separation or enrichment) to manufacture a nuclear explosive device. The primary function of safeguards on such "direct-use materials" is to deter their diversion from peaceful use by imposing a high risk of early detection, before the diverted material can be converted to metal, machined into weapon components, and integrated with a nuclear weapon assembly system. This criterion is often referred to as constituting "timely warning" of diversion to weapons use.

The overall level of assurance against diversion also importantly depends on two other factors – the frequency of inspections, and the accuracy of the measurement techniques employed. Containment and surveillance systems limiting access to strategic points within a facility are an important adjunct to the IAEA's materials balance system, but they do not assure detection of a carefully planned diversion by the authorized operators of a facility.

The IAEA's official "SQ" values also form the basis for public, media, and policymaking assessments of the bomb-making potential of nations or terrorist groups seeking to acquire nuclear weapons. Unfortunately, as shown in this report, the IAEA persists in using SQ values that are outdated, technically erroneous, and even dangerous in light of the recent seizures of kilogram quantities of stolen Russian nuclear materials for sale on the black market, and the persistent reports of large accounting discrepancies at plutonium production facilities intended for peaceful use. In August 1994 the Natural Resources Defense Council (NRDC) called upon the IAEA to tighten its criteria for safeguarding weapon-usable material by adopting an eightfold reduction in the agency's "significant quantity" values for plutonium and highly-enriched uranium (HEU). This report represents a revised version of our previous (22 August 1994) report.

II. IAEA Safeguards and the Role of the "Significant Quantity"

In 1953 the United States proposed the establishment of the IAEA to provide a means of verifying that nuclear materials and equipment provided for peaceful purposes would not be used for explosive or military purposes. After three years of debate the IAEA was established in 1957. To carry out the safeguards obligations subsequently assigned to the IAEA under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), and other multinational and bilateral agreements, the IAEA has devised a system of safeguards, one objective of which is to assure the detection of – and thereby deter – the diversion of safeguarded nuclear materials to the production of nuclear explosives.[1]

The principal safeguards documents of the IAEA, both of which have been revised over the years, are "Information Circulars" INFCIRC/66 and INFCIRC/153. Nuclear materials and nuclear facilities in all non-weapon NPT member states, and other states accepting NPT or IAEA safeguards, would be covered under either INFCIRC/66 and INFCIRC/153. The main difference between INFCIRC/66 and INFCIRC/153 is the "full-scope" intent of the latter -- it applies to all nuclear material in all peaceful nuclear activities of the non-nuclear weapon state. The technical objective of safeguards, made explicit in paragraph 28 of INFCIRC/153, is "the timely detection of the diversion of **significant quantities of nuclear material** from peaceful nuclear activities to the manufacture of nuclear weapons or other explosive devices or for purposes unknown and deterrence of such diversion by risk of early detection."[2]

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

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[1] *IAEA Safeguards: An Introduction*, IAEA, IAEA/SG/INF/3, 1981, p. 12.

[2] Ibid., p. 14.

device cannot be excluded."[3] Significant quantity values currently in use by the IAEA are given in Table 2, at the end of this report.[4]

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."[5]

The direct-use values in Table 2, that is, 8 kg of plutonium, 8 kg of uranium-233, and 25 kg of contained U-235, 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.[7] 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 [footnote in original document]."

As seen from Figures 1 and 2 and Table 1 at the end of this paper, the direct-use SQ or threshold values currently used by the IAEA are technically indefensible. The IAEA is clinging to incorrect values 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. The reasons given for this reliance on an invalid

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

[4] Ibid., p. 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., p. 23.

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

standard range from shortfalls in the safeguards budget to the inability of certain fuel cycle facilities under IAEA safeguards to meet even current, much less higher, standards for nuclear material control and accounting.

In concept, the lower the "significant quantity," the more demanding the safeguards system must become in resolving or plausibly explaining nuclear material inventory differences, and in physically recovering material that is said to be temporarily unaccounted for in production machinery, waste tanks, and "losses" to the environment. Moreover, to maintain the timely warning criterion when employing lower SQ values, small inventories of direct-use material would have to be inspected more frequently, to guard against their potential combination into one or more significant quantities.

For the purposes of illustration, consider the following simplified case of a small plutonium fuel fabrication plant in a non-weapon NPT state. This plant might have an annual plutonium throughput of about 700 kilograms. Each year plutonium scrap accumulates in the tightly sealed, remotely operated process lines, where the flow of plutonium through the system is measured indirectly with an inherent and possibly varying degree of error in the measurement. Each year the plant reports a difference of about 15 kilograms between the amount of plutonium oxide entering the plant and the amount of plutonium oxide leaving the plant in "Mixed-Oxide" (MOX) fuel. Containment and surveillance measures – when they are operating -- and remote process line measurements suggest that the material is not really "missing", but is being "held-up" in the production equipment. According to the plant operators, these indirect measurements are accurate to perhaps 10%, assuming the equipment is working and properly calibrated. Under this scenario, when the "SQ" for plutonium is set at 8 kilograms, the IAEA will become seriously concerned about the threat of diversion when the uncertainty in measuring the accumulated plutonium "holdup" reaches or exceeds this level – that is, after about five years of plant operation [0.1 * (15 kg * 5) = 7.5 kg]

If, as we argue in this paper, the SQ is reduced to one kilogram to accurately reflect longstanding technical realities of bomb design now accessible to many nations, the uncertainty in measuring the "plutonium holdup" would exceed the SQ *within one year* of plant operation. The IAEA would have to request a plant shutdown and physical "clean-out inventory" at that point, instead of waiting another four years, during which diversion of another 6 bombs worth of plutonium could be concealed within the cumulative measurement error and secretly withdrawn from the plant for conversion into weapons. As is readily evident from this scenario, timely warning of a diversion is virtually impossible to achieve under such circumstances -- the time lag between diversion and detection must be on the order of 1-3 weeks, not years! In reality, the situation is even worse than this simplified example suggests, because there are additional errors associated with measuring the precise plutonium input to the plant and the exact Pu content of the fuel rods leaving the plant.

III. The Amount of Fissile Material Required to Make a Pure Fission Weapon.

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 type of device the amount of fissile material required depends primarily upon the type of fissile material used, e.g., plutonium, U-233, 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.

In Figures 1 and 2 we plot the explosive yield of a pure fission weapon as a function of the quantity of fissile material (weapon-grade plutonium (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 judgement as to the sophistication of the design; that is, whether it represents low, medium or high technology.

As seen from Figure 1, the Nagasaki bomb, *Fat Man*, which produced a 20 kilotons (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 non-nuclear 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 from Figure 1, to achieve an explosive yield of 1 kt, we estimate that from 1 to 3 kg of WGPu 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 1 kt. Table 1 presents the same results of tabular form. We estimate, for example, that as little as 2 kilograms of plutonium or about 4 kilograms of HEU are required to produce a yield of 10 kilotons.

IV. U.S. Government Requirements.

As noted above the first nuclear weapon developed by the United States -- *Fat Man* -- first tested at the *Trinity* site in New Mexico on July 16, 1945, and dropped on Nagasaki on August 9, 1945, reportedly used 6.1 kg of WGPu. The United States first tested so-called "fractional crit" weapon designs during Operation *Ranger* which took place from 27 January to 6 February 1951. Two of the four "fractional crit" tests during this series involved reducing the amount of fissile material in the *Mark 4* bomb to about 1 to 2 kg of plutonium and about 5 to 6 kg of HEU, respectively. The yields of these two tests were about 1 kt.[8]

Light weight boosted-fission weapons with yields up to about 15 kt can be made with as little as 3.5 kg of plutonium; and in fact, modern boosted-fission primaries of U.S. thermonuclear weapons are made with less than 4 kg of plutonium. U.S. Government classification policy now permits USDOE nuclear weapon experts to acknowledge that nuclear weapons can be constructed with as little as 4 kg of plutonium.

U.S. Nuclear Regulatory Commission (USNRC) regulations define a *formula quantity* as "strategic special nuclear material in any combination in a quantity of 5,000 grams [5 kg] or more computed by the formula, grams = (grams containing U-235) + 2.5*(grams U-233 +

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[8] Robert Standish Norris and Thomas B. Cochran, "United States Nuclear Tests: July 1945 to 31 December 1992," NRDC, Nuclear Weapons Databook Working Paper NWD 94-1, 1 February 1994, p. 22.

plutonium)," where *strategic special nuclear material* means "uranium-235 (contained in uranium enriched to 20 percent or more in the U-235 isotope), uranium-233, or plutonium."[9] Thus, considered separately 2 kg of plutonium constitutes a formula quantity, since 2.5*(2000 grams of Pu) = 5000 grams; and similarly 5 kg of contained U-235 is a formula quantity. USNRC applies its most stringent physical security and material control and accounting (MC&A) requirements to licensees possessing or transporting formula quantities of strategic special nuclear materials.

The U.S. Department of Energy (USDOE) has a more detailed categorization of nuclear materials in terms of the attractiveness of the materials for weapon purposes (defined in terms of Attractiveness Levels A through E) and the level of safeguards applied (defined in terms of Categories I through IV).[10] USDOE's most stringent physical security and MC&A requirements (Category I) apply to assembled weapons and test devices (Attractiveness A), and "Pure Products," defined as weapon pits, major components, buttons, ingots, recastable metal, and directly convertible materials (Attractiveness B) containing 2kg or more of Pu/U-233 or 5 kg or more of contained U-235. This is similar to the USNRC definition of a formula quantity. The USDOE defines high-grade plutonium, U-233 and contained U-235 in other chemical forms (including solutions, oxides and carbides) as Attractiveness C materials, and here the Category I safeguards are triggered at 6 kg or more of Pu/U-233, and 20 kg or more of contained U-235.

V. Conclusion.

The IAEA "threshold amounts" and "significant quantities" are not technically valid. If one took the same *Fat Man* design, first tested at the *Trinity* site in New Mexico and dropped on Nagasaki in 1945, and substituted a three 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 one kiloton, a very respectable atomic bomb. *Thus, the IAEA is in error to assert that "highly*

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[9] USNRC Regulations as reproduced in 10 CFR 70.4, 73.2 and 74.4.

[10] USDOE Order 5633.3B.

sophisticated techniques available to NW States" are needed to make nuclear weapons with "significantly reduced" quantities of materials. Also, 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 designed safeguards program for a given country or group of countries would set the "significant quantity" levels at values considerably 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 non-weapon 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 sophisticated technologically, the key technical information needed to establish a program for achieving a high degree of compression by implosion techniques is now available in the unclassified literature. The quantities defining safeguards significance, therefore, must be based on the assumption that the proliferator has access to advanced technology. As a consequence, NRDC believes the IAEA's significant quantities should be lowered 8-fold to the values in Table 3 -- 1 kg of plutonium and U-233 and 3 kg of contained U-235.

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	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

Values rounded to nearest 0.5 kilograms.

Table 2. IAEA Significant Quantities.

Material	Quantity of Safeguards Significance	Safeguards Apply to:
Direct-use nuclear material		
Plutonium	8 kg	Total element[1]
Uranium-233	8 kg	Total isotope
Uranium enriched to 20% or more	25 kg	U-235 isotope
Indirect-use nuclear material		
Uranium (<20% U-235)	75 kg	U-235 isotope
Thorium	20 t	Total element

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[1] Does not apply to plutonium containing >80% Pu-238, e.g. in radioisotope thermoelectric generators (RTGs).

Table 3. NRDC's Proposed Significant Quantities.

Material	Quantity of Safeguards Significance	Safeguards Apply to:
Direct-use nuclear material		
Plutonium	1 kg	Total Element[1]
Uranium-233	1 kg	Total isotope
Uranium enriched to 20% or more	3 kg	U-235 isotope

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[1] Does not apply to plutonium containing >80% Pu-238, e.g. in radioisotope thermoelectric generators (RTGs).

Figure 1. Yield vs. Pu Mass

(As a Function of Technical Capability)

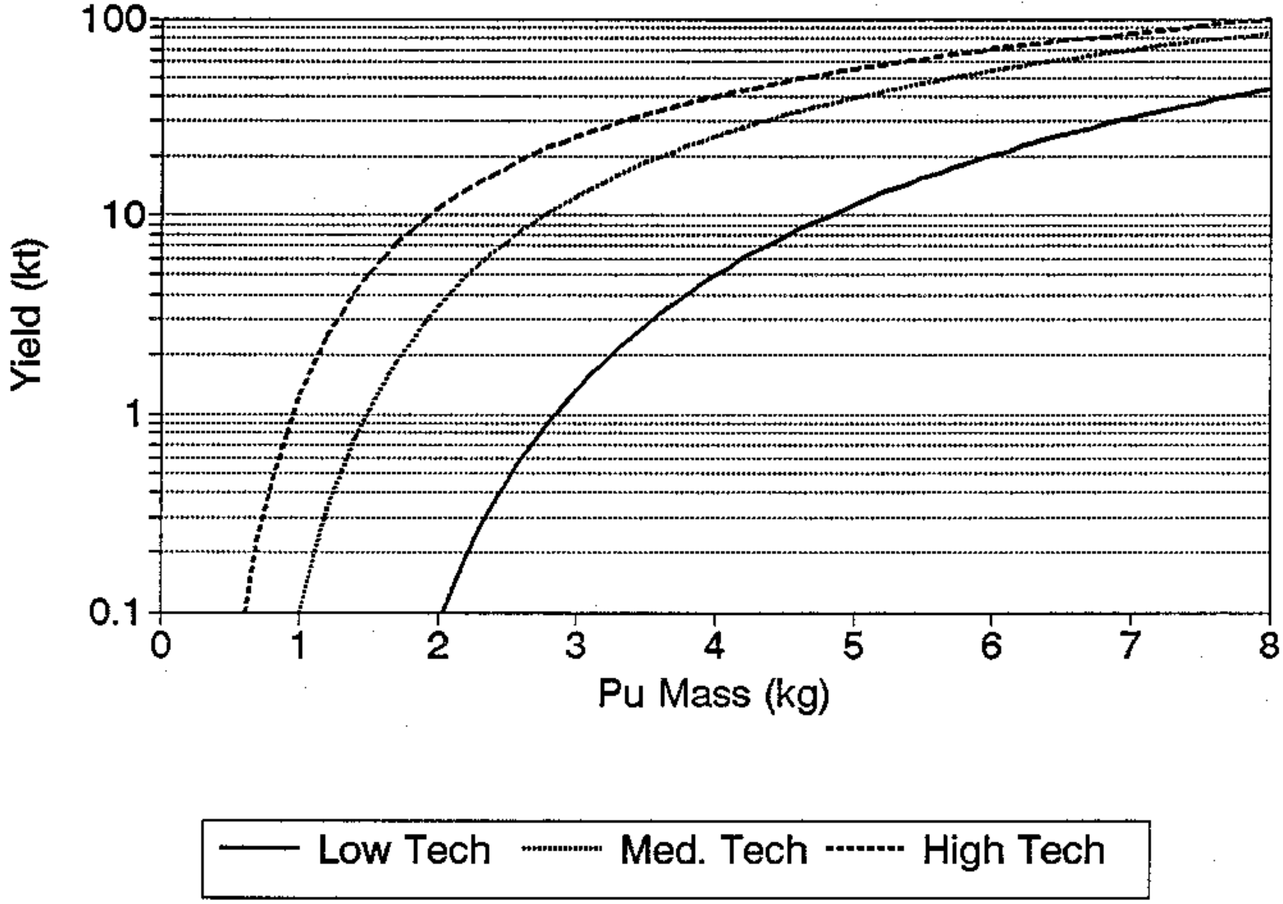

Figure 2. Yield vs. HEU Mass
(As a Function of Technical Capability)