Chapter 4

Predetonation and Reactor-Grade Plutonium: No Impediment to Powerful, Reliable Nuclear Weapons

This chapter discusses how the spontaneous fission of plutonium can affect the probability of an unboosted weapon predetonating, thereby reducing the weapon's yield. It shows that the problem of the predetonation of an unboosted levitated implosion fission weapon is not an impediment to the use of reactor-grade plutonium to produce nuclear weapons. Such weapons can have a yield of 5 kilotons with a lethal area about 40% that of a full yield 20 kiloton weapon. By using a reduced quantity of plutonium in the weapon core, this yield could be produced with the same predetonation probability as a full yield weapon using weapon-grade plutonium. Boosted nuclear weapons are immune to predetonation and if boosted nuclear weapons become the norm for early stage nuclear weapon states, they will be able to produce weapons using reactor-grade plutonium that are just as powerful as those using weapon-grade plutonium.

Predetonation of Unboosted Nuclear Weapons

The creation of a nuclear explosion requires the production of a supercritical mass of nuclear material (usually either highly enriched uranium or plutonium or both) from a subcritical configuration. When an unboosted nuclear weapon is fired, the subcritical configuration becomes critical and then increasingly supercritical until it reaches the desired degree of supercriticality.[66] At this point, neutrons are introduced into the system by means of an initiator, and a nuclear explosion soon occurs. In early U.S. implosion nuclear weapons, the initiator was located at the center of the weapon inside the core of nuclear material. It contained beryllium and the short-lived radioactive element polonium. When the shockwave from the implosion reaches the initiator, the polonium and beryllium are mixed together. The alpha particles from the polonium striking the beryllium cause neutrons to be released.

In unboosted nuclear weapons there is a time interval (known as the assembly time) between when the nuclear material first becomes critical to when it reaches the desired degree of supercriticality. If a neutron were to be introduced into the nuclear material during this interval then the weapon could predetonate, reducing the yield of the weapon.[67] Neutrons can be produced by various processes but in plutonium the source of the greatest concern is the spontaneous fission of some plutonium isotopes, in particular Pu-240 (See chapter three).

For some time after World War II, it was believed that the yield of a nuclear weapon that predetonated would be quite small and this belief formed the basis for the notion that plutonium which had a high Pu-240 content was "denatured" (See chapter two). It was only in 1976 that two Manhattan Project memos that had recently been declassified were discovered by researchers at Pan Heuristics.

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66. Samuel Glasstone and Leslie M. Redman, "An Introduction to Nuclear Weapons," WASH-1037, U.S. Atomic Energy Commission, June 1972, originally SECRET, now UNCLASSIFIED but heavily redacted.

67. Any given neutron would only have about a one in three chance of causing a divergent chain reaction, so in fact a number of neutrons would have to be introduced in order to ensure that the weapon predetonates.

These memos gave the predetonation probability and yield distribution of the plutonium-cored Nagasaki implosion nuclear weapon.[68] The memos had been written after the July 1945 Trinity test of the Nagasaki design but before the Nagasaki weapon had been used in combat. The relevant passage from the first memo which was written by Robert Oppenheimer, the head of Los Alamos, stated:

> The possibility that the first combat plutonium Fat Man will give a less than optimal performance is about 12 percent. There is about 6 percent chance that the energy release will be under 5,000 tons, and about 2 percent chance that it will be under 1,000 tons. It should not be much less than 1,000 tons unless there is an actual malfunctioning of some of the components.

The relevant passage from the second memo, which was written by General Groves, the head of the Manhattan Project, stated:

> There is a definite possibility, 12 percent rising to 20 percent, as we increase our rate of production at the Hanford Engineer Works, with the type of weapon tested that the blast will be smaller due to detonation in advance of the optimum time. But in any event, the explosion should be on the order of thousands of tons. The difficulty arises from an undesirable isotope which is created in greater quantity as the production rate increases.

68. Albert Wohlstetter, "Spreading the Bomb without Quite Breaking the Rules," *Foreign Policy*, no. 25, Winter 1976-77, pp. 160-161, available from http://www.npolicy.org/userfiles/file/Nuclear%20Heuristics-Spreading%20the%20Bomb%20without%20Quite%20Breaking%20the%20Rules.pdf.

These memos provide a number of important facts about the Nagasaki weapon. With the plutonium that was available in August 1945, the weapon had a 12% predetonation probability. It is now known that the plutonium for this weapon had a 1% Pu-240 content.[69] The predetonation probability was going to increase to 20% as the Pu-240 content of the plutonium was raised, in order to improve the rate of plutonium production. It has since been declassified that this plutonium had a 2% Pu-240 content. (See appendix)

The earliest possible predetonation occurs if a neutron causes a divergent chain reaction just as the nuclear core becomes critical. This results in the lowest possible nuclear yield which is somewhat misleadingly termed the "fizzle" yield. These memos showed that the fizzle yield of the Nagasaki weapon was a little less than a kiloton.

Mark performed a simple calculation which showed that the fizzle yield of the Nagasaki weapon would have been roughly 0.5 kilotons.[70] In his discussion, he stated that the actual fizzle yield was probably higher, more likely about 0.7 kilotons. Such a yield would already be devastating since it would have a lethal area about 25% of that of the 16 kiloton weapon that destroyed Hiroshima. The actual value of the fizzle yield is not that important since, as I will show, even for plutonium with a very high spontaneous fission rate, the average yield of a simple fission implosion weapon using a near critical plutonium core and early 1950s U.S. technology would be about 2 kilotons. By reducing the amount of plutonium in the weapon, a 5 kiloton yield can be produced with a predetonation

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69. Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lesson from the Manhattan Project," December 16, 2015, p. 10, available from http://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

70. J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security* 4, 1993, available from http://scienceandglobalsecurity.org/archive/sgs04mark.pdf.

probability that is the same as that of a weapon using weapon-grade plutonium.

Calculating the Predetonation Probability

Mark developed a methodology for calculating the predetonation probability of a simple fission implosion weapon for various levels of spontaneous fission neutrons.[71] This methodology was expanded and improved by Hubbard.[72] Mark/Hubbard considered not only weapons with higher levels of spontaneous fission neutrons but also parametrically weapons with assembly speeds twice or three times greater compared to those of the Nagasaki weapon.

From the declassified World War II memos it is apparent that weapons with a predetonation probability of 12% to 20% were considered acceptable. As is shown in the appendix, by the early 1950s, the United States was using plutonium with a 5.5% Pu-240 content. That the United States was able to use plutonium with this high a Pu-240 content implies that U.S. weapons of that era had assembly speeds three times greater than that of the Nagasaki weapon since, as can be seen in Table 8, such weapons would provide acceptable predetonation probabilities. Since it is known that U.S. weapons in the early 1950s used a levitated design, which significantly improved their assembly speed, such a result seems reasonable. Further such weapon performance is likely typical of an early nuclear device that a nuclear

71. J. Carson Mark, "Reactor-Grade Plutonium's Explosive Properties," *Nuclear Control Institute*, August 1990.

72. Victor Gilinsky, Marvin Miller, and Harmon Hubbard, "A Fresh Examination of the Proliferation Dangers of Light Water Reactors," *The Nonproliferation Policy Education Center*, October 22, 2004.

weapon state might produce today since even 50 years ago the first French and Chinese nuclear test devices were apparently levitated.[73]

Yield	5.5% Pu 240 50 n/g-s[74]	20% Pu 240 182 n/g-s	Full Burnup CANDU fuel[75] 264 n/g-s	Full Burnup PWR fuel[76] 432 n/g-s
Full Yield 20 kilotons	78%	33%	17%	5%
Greater than 5 kilotons	89%	58%	43%	23%
Greater than 1 kiloton	96%	84%	76%	62%

TABLE 8: Probability of an Unboosted Nuclear Weapon Achieving Various Yields for Different Plutonium Spontaneous Fission Neutron Backgrounds (Near Critical Plutonium Core, Early 1950s U.S. Implosion Technology[77])

I have extended the Mark/Hubbard methodology to calculate the probability that an unboosted nuclear weapon using a near critical plutonium core and early 1950s U.S. implosion technology will achieve various yields given different levels of spontaneous fission

73. The yield to weight ratio of these devices was significantly improved compared to that of the Nagasaki weapon.

74. Neutrons per gram-second.

75. Natural uranium fuel with a burnup of 7,000 MWD/Te

76. 4.3% initial enrichment, burnup 51,000 MWD/Te.

77. Assembly speed three times that of the Nagasaki weapon.

neutrons. The results are shown in Table 8. For a nuclear weapon having a 20% Pu-240 content (182 neutrons per gram-seconds), about two-thirds of the weapons would predetonate. Yet the average yield would still be about 8 kilotons. The plutonium from low burnup power reactor fuels (including MAGNOX, CANDU, and LWR) routinely has a similar spontaneous neutron output. (See chapter three)

For plutonium from full burnup CANDU fuel, about five sixths of the weapons would predetonate but the average yield would still be about 5 kilotons. Even for plutonium from high burnup PWR fuel, though most weapons would predetonate, the average yield would still be about 2 kilotons.

Gunter Kessler, a leading proponent of the false notion that plutonium can be denatured, has published his own estimates of the distribution of yields produced by the predetonation of implosion nuclear weapons using a near critical plutonium core and plutonium with different isotopic compositions.[78] Kessler limits himself to weapons using Nagasaki level technology which is unrealistic since any nuclear state today would use significantly improved technology. Though Kessler has performed what appear to be sophisticated calculations, his results are clearly in error. Table 9 compares results using the Mark/Hubbard methodology with those of Kessler for plutonium with a 3% Pu 240 content. Even for this low Pu-240 content, Kessler has calculated that the probability of predetonation would be 100%. In contrast, calculations using the Mark/Hubbard methodology show that only about one-third of weapons would predetonate. As is shown in the appendix, in 1949 the United States was already using plutonium with a 3.8% Pu-240 content. Therefore, Kessler's results are erroneous since the United States would not have increased the Pu-240 content if it expected its nuclear weapons

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78. G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles: Safeguards and Non-Proliferation*, KIT Scientific Publishing, 2011, see in particular figures 9.46b and 9.47, pp. 244-245.

to always predetonate.[79] Similarly, all of Kessler's other calculated predetonation probabilities appear to be in error.

Yield	Mark/Hubbard	Kessler
Full Yield 20 kilotons	67%	0%
Greater than 5 kilotons	83%	15%
Greater than 1 kiloton	94%	80%

TABLE 9: Comparison of Mark/Hubbard Predetonation Yield Probabilities with that of Kessler, Near Critical Plutonium Core, 3% Pu 240 Content, Nagasaki Weapon Technology Level

A Technicality?

A number of the proponents of the false notion that reactor-grade plutonium can be denatured will grudgingly admit that reactor-grade plutonium can be used to produce explosions in the low kiloton range. However, they argue that this is just a technicality. They claim that no country would actually use reactor-grade plutonium to produce weapons. In part their argument is that militaries would demand weapons that are "reliable" and that no military force would accept a weapon where the yield could range between 0.7 kiloton and 20 kilotons.

79. It is likely that in 1949, in the aftermath of the 1948 Sandstone nuclear test series, the U.S. was already using weapons with assembly speeds twice that of the Nagasaki weapon. Such weapons using plutonium with a Pu-240 content of 3.8% would have a predetonation probability of 22%.

This argument has a number of problems. By necessity, militaries must deal with great uncertainties. As the 19th century German military strategist Helmuth von Moltke said, "No plan of operations extends with any certainty beyond the first contact with the main hostile force."

Further, the United States developed and used the Nagasaki weapon even though its yield was quite unknown. Before the Trinity test of the Nagasaki design, the Manhattan Project scientists considered the yield so uncertain that they created a betting pool. Most of the scientists' picks were well below the actual estimated yield of 20 kilotons.[80] As we have seen, even after the Trinity test, it was expected that the weapon would have a 12% chance of predetonating and this chance was raised to 20% to increase the rate of plutonium production by raising the Pu-240 content from 1% to 2%.

In addition, in terms of lethal area, the range of weapon destruction uncertainty is far less than one might imagine given a range of yields between 0.7 kiloton and 20 kilotons. A 0.7 kiloton weapon has a lethal area about one fifth that of a 20 kiloton weapon, so that the actual uncertainty range is only about 5 to 1 instead of 29 to 1.

Producing Reliable Yields from High-Burnup Pu: Reduced Pu Cores

If indeed a military were troubled by this range of uncertainty, it could easily be significantly reduced. The simplest way would be to deliberately predetonate the weapon by flooding the weapon with neutrons just as it is detonated. Such weapons would only produce the fizzle yield of about 0.7 kilotons but the yield would be quite consistent.

80. Today it is believed that the yield was 21 kilotons with an uncertainty of plus or minus one kiloton.

Nor would it be necessary to go to this extreme. The British have stated that the predetonation probability can be reduced by simply decreasing the amount of plutonium in the weapon.[81] The 6.15 kilogram plutonium core of the Nagasaki weapon was close to being critical (95.2% of critical, making the critical mass 6.46 kilograms)[82] but it did not have to be. In the 1990s the Natural Resources Defense Council (NRDC) suggested that nuclear weapons using what it called "low technical capability" could produce yields in the low kilotons with only 3 or 4 kilograms of weapon-grade plutonium.[83] The NRDC work was largely ignored.

In June 2008, as part of the six-party negotiating process, North Korea issued a declaration of its nuclear operations and materials. The most surprising part of this declaration was North Korea's claim that it used only 2 kilograms of plutonium in its 2006 nuclear test.[84] This statement was greeted with widespread skepticism. However, in 2012 an old Soviet document revealed that in 1953, the Soviet Union tested simple fission weapons using only 2 kilograms and 0.8 kilograms of plutonium and produced yields of 5.8 and 1.6 kilotons respectively.[85] In 2016 the former deputy director general of the

81. Margaret Gowing, *Independence and Deterrence: Britain and Atomic Energy*, 1945-1952, Volume 2: Policy Execution, New York: St. Martin's Press, 1974, pp. 456-457.

82. Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lesson from the Manhattan Project," December 16, 2015, p. 10, available from http://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

83. Thomas B. Cochran, "Technological Issues Related to the Proliferation of Nuclear Weapons," *Natural Resources Defense Council*, August 23, 1998, available from http://npolicy.org/Articles/Tech%20Issues%20Related%20to%20Prolif.pdf.

84. "North Korea Declares 31 Kilograms of Plutonium," *Global Security Newswire*, October 24, 2008.

85. Pavel Podvig, "Amounts of fissile materials in early Soviet nuclear devices,"

IAEA called for this agency to reduce its "significant quantity" for plutonium from the current 8 kilograms to only 2 to 4 kilograms.[86]

Suppose the amount of plutonium in a simple fission weapon were to be reduced so that it was only about 60% a critical mass. For weapon-grade plutonium, this would reduce the amount of plutonium by about a factor of 1.6 (0.952/0.6). For plutonium from high burnup LWR fuel, the critical mass would be about 1.5 times as large and therefore the amount of plutonium in the core would be about 5.8 kilograms (6.15 x 1.5/1.6).

Kessler has pointed out that since the plutonium core in the Nagasaki weapon was near critical, the neutron background was significantly increased due to subcritical chain reactions. Kessler incorrectly believed that the plutonium core in the Nagasaki weapon was within 98% of being critical so that the neutron increase would be a factor of 50.[87] Since the weapon was actually 95.2% of being critical, the neutron increase was a factor of 21.[88] A weapon that was only 60% of critical would have a neutron increase of only a factor of 2.5, so that the neutron increase due to subcritical chain reactions would be decreased by a factor of 8.4.

For a Nagasaki sized core with 5.5 % Pu-240, the spontaneous fission neutron production in the entire core would be 50 n/g-s x 6,150

International Panel on Fissile Materials Blog, October, 1, 2012, available from http://fissilematerials.org/blog/2012/10/amounts_of_fissile_materi.html.

86. Olli Heinonen, "North Korea's 5th Nuclear Test—What Now?" *Foundation for Defense of Democracies Policy Brief*, September 16, 2016, available from http://www.defenddemocracy.org/media-hit/olli-heinonen1-north-koreas-5th-nuclear-test-what-now/.

87. 1/ (1 - 0.98) = 50, See: Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering*, D. Van Nostrand Company Inc., Princeton New Jersey, 1963, p. 222.

88. 1/(1 - 0.952) = 21.

grams x 21 = 6,458,000 n/s. For a high burnup LWR plutonium core which was 60% of a critical mass, the spontaneous fission neutron production in the entire core would be 432 n/g-s x 5,800 grams x 2.5 = 6,264,000 n/s. This latter number is less than the former and demonstrates that with a smaller core, the predetonation probability would a bit less than that of a weapon using a near critical weapon-grade plutonium core. Using 1950s implosion technology, weapon's predetonation probability would be about 20% which was considered acceptable in 1945 (see Table 8).

Mark has given a formula for calculating the efficiency of the fissioning of the nuclear material in a nuclear weapon.[89] It is K x $(N^{1/3} - 1)^3$, where N is the number of critical masses produced by the compressed nuclear material and K is a constant. Since the efficiency of the Nagasaki weapon was about 20% (about 20% of the plutonium in the weapon fissioned), N was equal to about 4 and K equal to about 1.[90] Reducing the starting plutonium from 0.952 of a critical mass to 0.6 of a critical mass would reduce N to about 2.5. This would give an efficiency of about 5% and a yield of about 5 kilotons. The lethal area of such a weapon is about 40% that of the 20 kilotons full yield and this yield would be produced with a predetonation probability that was considered acceptable by General Groves. Therefore, by using a reduced amount of plutonium in the weapon core, a yield of about 5 kilotons could be produced with a predetonation probability about the same as that of a full yield weapon using weapon-grade plutonium.

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89. J. Carson Mark, "Some Remarks on Iraq's Possible Nuclear Weapon Capability in Light of Some of the Known Facts Concerning Nuclear Weapons," *Nuclear Control Institute*, May 16, 1991.

90. From published data I have calculated that N for the Hiroshima gun weapon was about 2.6. Since it is known that implosion is more efficient than gun assembly, N = 4 seems reasonable.

Boosted Nuclear Weapons Are Immune to Predetonation

Thus far I have only discussed unboosted implosion fission weapons. In the past, it was thought that boosting was a technology that would be beyond the capability of an early stage nuclear weapon state but this view is beginning to change. Many analysts have suggested that North Korea's fourth nuclear test in January 2016 was a boosted device. Boosted fission weapons are "immune" to predetonation (see chapter two). Boosted weapons would produce the same yield whether they were manufactured from weapon-grade plutonium or reactor-grade plutonium.

Pakistan has claimed to have equipped short-range ballistic missiles with small light-weight nuclear warheads consistent with boosted warheads. Pakistan has also built four plutonium production reactors which could be providing substantial amounts of tritium for nuclear weapons. Pakistan may well possess boosted nuclear weapons and could have spread this technology to other countries including North Korea. Even if North Korea has developed boosted nuclear weapons indigenously, it could now spread this technology to other countries. If boosted nuclear weapons become the norm for early stage nuclear weapon states, then they will be able to produce weapons with reactor-grade plutonium that are just as powerful as those using weapon-grade plutonium.

In sum, the problem of the predetonation of an unboosted implosion fission weapon is not an impediment to the use of reactor-grade plutonium to produce nuclear weapons. Such weapons can reliably have a yield of 5 kilotons with a lethal area about 40% that of a full yield weapon. By using a reduced amount of plutonium in the weapon core, this yield could be produced with a predetonation probability about the same as that of a full yield weapon using weapon-grade plutonium.

Boosted nuclear weapons are immune to predetonation and if boosted nuclear weapons become the norm for early stage nuclear weapon states, they will be able to produce weapons using reactor-grade plutonium that are just as powerful as those using weapon-grade plutonium. Recently there have been calls in South Korea for that country to develop its own nuclear weapons. Any such program would need to rely on the reactor-grade plutonium produced by its large nuclear power program. South Korea has already amassed a large tritium stockpile and could easily develop boosted nuclear weapons.[91]

91. Gregory S. Jones, "Heavy Water Nuclear Power Reactors: A Source of Tritium for Potential South Korean Boosted Fission Weapons," February 29, 2016, available from http://nebula.wsimg.com/344f048726407b8951892db91c98a0b1?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.