Technical Appendix to "Reactor-Grade Plutonium and Nuclear Weapons: Ending the Debate" published in the *Nonproliferation Review*, 2019 by Gregory S. Jones

The Evolution of the Methodology for Quantifying the Predetonation Probability and Yield of Unboosted Implosion Nuclear Weapons Using Reactor-Grade Plutonium Cores

The reason most commonly cited as to why reactor-grade plutonium cannot or will not be used to produce nuclear weapons is that the high spontaneous fission neutron background of this plutonium will lead weapons to predetonate, reducing the yield. It has also been argued that the range of yields that might be produced by predetonating weapons will make them "unreliable" and thereby unacceptable to any military. The methodology developed for this article allows, for the first time, the accurate calculation of the predetonation probability and yield of unboosted implosion weapons using reactor-grade plutonium cores. As is discussed in the main article, the results in Table 2 (page 12, Table 2 as well as Tables 1 and 3 are reproduced here from the main text) show that even a nuclear weapon using a near critical reactor-grade plutonium core produced by high burnup in a PWR would be quite destructive. The average yield would be 2 kilotons and the lethal area about 30% that of a 20 kiloton weapon.

This article is also the first to examine the effect of using reduced mass plutonium cores on a weapon's predetonation probability and yield. The article shows that unboosted implosion nuclear weapons using reactor-grade plutonium can be constructed that have the same probability of predetonation as that of weapons using weapon-grade plutonium (Table 3, page 16). This appendix explains in detail the methodology that produced the results in these two tables and how it was developed as an extension of methodology originally developed by Carson Mark and Harmon Hubbard.

Background to the Predetonation Problem

The problem of predetonation was first discovered during World War II. In 1943 the U.S. plan to develop nuclear weapons involved the construction of gun-type weapons where one subcritical piece of nuclear material (either highly enriched uranium [HEU] or plutonium) is fired as an artillery projectile into another subcritical piece of nuclear material. An initiator would then release neutrons into the resulting supercritical mass leading to a nuclear explosion. However, in 1944 it was discovered that plutonium produced in nuclear reactors (the only way to produce large quantities of plutonium) would invariably contain significant quantities of the isotope Pu-240. The spontaneous fission rate of Pu-240 is 40,000 times that of Pu-239. Therefore, the neutron background of plutonium was much higher than was anticipated. In a gun-type nuclear weapon, plutonium would release neutrons starting the chain-reaction long before the plutonium had reached the desired degree of supercriticality. The nuclear explosion from this predetonation would have a much lower yield than intended.

As a result, while the development of the HEU gun-type weapon continued, the work on a plutonium based weapon shifted to the development of an implosion-type weapon, where the plutonium is surrounded by high explosive which compresses the plutonium when it is detonated. An implosion-type weapon produces the desired supercritical mass of plutonium much faster than a gun-type weapon and thereby has a much-reduced chance of predetonation, allowing the use of plutonium. The development of an implosion-type weapon by the Manhattan Project was successful. The weapon was tested at Alamogordo on July 16, 1945 and was used in combat on August 9, 1945. Since implosion-type weapons are more efficient than gun-type ones, all nuclear weapons, even ones using HEU, are now implosion-type weapons.

After the war, this episode formed the basis for the view that plutonium could be denatured, i.e. "make the material unusable by any methods we now know for effective atomic explosives unless steps are taken to remove the denaturants."[1] The 1946 Acheson-Lilienthal Report was one of the more prominent studies to suggest denaturing plutonium as a means of making nuclear electric power available to many countries without providing the means for these countries to produce nuclear weapons. This report did not reveal what the denaturant might be but it did state that to remove the denaturant would require "complex installations," "a large effort," and "scientific and engineering skill of an appreciable order."[2]

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[1] "The Acheson-Lilienthal Report on the International Control of Atomic Energy," Washington, D.C., March 16, 1946, p. 30. http://fissilematerials.org/library/ach46.pdf

[2] *Ibid.*

It was only with the release of the Manhattan Project history in 1961 that the problem with Pu-240 was officially made public.[3] Indeed, the history is divided into two parts, before and after Los Alamos was reorganized to deal with the Pu-240 problem. This revelation made clear that the predetonation of a nuclear weapon caused by spontaneous fission neutrons formed the basis for the belief that plutonium could be denatured.

By the 1970s, the possession of plutonium and the reprocessing technology needed to separate plutonium from spent fuel threatened to become widespread. This plutonium would generally be reactor-grade with a relatively high Pu-240 content, making it more prone to predetonation. There was no public information on what the yield of a predetonating implosion-type weapon might be. Europeans defended their sale of reprocessing technology and their possession of reactor-grade plutonium by arguing that weapons produced from this plutonium would be "weak," "unreliable" and have "highly questionable military value."[4]

In September 1976, a research team at Pan Heuristics led by Albert Wohlstetter discovered two declassified memos from 1945 that revealed the predetonation characteristics of the Nagasaki nuclear weapon.[5] These memos gave the predetonation probability and yield distribution of the plutonium-cored Nagasaki implosion nuclear weapon. 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

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[3] David Hawkins, "Manhattan District History, Project Y, The Los Alamos Project, Volume I. Inception Until August 1945," LAMS-2532 (Vol. I), Los Alamos Scientific Laboratory, Los Alamos, New Mexico, written 1946, released December 1, 1961. https://www.osti.gov/opennet/manhattan-project-history/publications/LANLMDHProjectYPart1.pdf

[4] "Spent nuclear fuel and radioactive waste," A summary of a report given by the Swedish government committee on radioactive waste, SOU 1976:32, Stockholm, 1976, p. 43.

[5] In addition to Albert Wohlstetter, the key persons involved in this discovery were Arthur Steiner and myself.

> 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.[6]

The relevant passage from the second memo, which was written by General Leslie 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.[7]

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. The predetonation probability was going to increase to 20% as the Pu-240 content of the plutonium was increased, in order to improve the rate of plutonium production.

The earliest possible predetonation occurs if a neutron causes a divergent chain reaction just as the nuclear core becomes critical.[8] This results in the lowest possible nuclear yield which is somewhat misleadingly termed the "fizzle" yield. These memos show that the fizzle yield of the Nagasaki weapon was a little less than a kiloton. Since the lethal area of a 1 kiloton weapon has about one-quarter the lethal area of the 16 kiloton weapon that destroyed Hiroshima, implosion-type nuclear weapons that predetonate can hardly be termed weak and reactor-grade plutonium is not denatured. The publication of these memos helped to change U.S. plutonium policy in the 1970s.

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

[7] *Ibid*. p. 161.

[8] Samuel Glasstone and Leslie M. Redman, "An Introduction to Nuclear Weapons," WASH-1037, U.S. Atomic Energy Commission, June 1972, pp. 32-33, originally SECRET, now UNCLASSIFIED but heavily redacted. http://fissilematerials.org/library/aec72.pdf

Carson Mark's Methodology

In 1990, J. Carson Mark who had been the Director, Theoretical Division, Los Alamos National Laboratory between 1947 and 1972, published an analysis of the predetonation probability of Nagasaki type weapons using the information in the two memos discovered by the Pan Heuristics team.[9] Mark showed that for weapons with a neutron background n times that of the Nagasaki weapon, the probability of achieving a particular yield would be the probability that the Nagasaki weapon would achieve that yield raised to the nth power.

For example, the overall predetonation probability of the Nagasaki weapon was 12%, meaning that its probability of achieving the full yield was 88%. If a weapon had a neutron background 10 times higher than that of the Nagasaki weapon, then the probability of the weapon achieving the full 20 kiloton yield is 0.88^{10}= 0.28. Similarly the probability of such a weapon achieving a yield of 5 kilotons or more is 0.94^{10} = 0.54 and the probability of achieving a yield of 1 kiloton or more is 0.98^{10} = 0.82.

Mark performed calculations for weapons with neutron backgrounds 10, 20, 30 and 40 times that of the Nagasaki weapon. These calculations showed that even for a quite high neutron background, a weapon of the Nagasaki design would have a significant probability of producing a yield higher than that of the fizzle yield. In addition, Mark stated that the fizzle yield of the Nagasaki weapon was about 0.7 kilotons.

Mark published an expanded version of his article in 1993.[10] In it, Mark calculated the predetonation probabilities not only for the Nagasaki weapon but also for a hypothetical weapon with an assembly speed twice that of the Nagasaki weapon. Mark did not provide an analytical explanation for these latter calculations. Mark also described a technique for handling the higher heat of reactor-grade plutonium in a nuclear weapon.

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[9] J. Carson Mark, "Reactor-Grade Plutonium's Explosive Properties," Nuclear Control Institute, August 1990. http://www.nci.org/new/NT/rgpu-mark-90.pdf

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

Mark's work represented a major advance in our understanding of predetonation probabilities and yield distribution of simple fission weapons using reactor-grade plutonium. However, it also had some important limitations. Mark's calculations are in terms of multiples of the neutron background of the Nagasaki weapon. But Mark does not indicate what the Nagasaki neutron background was and therefore it is impossible to use his papers to calculate the predetonation probability of a Nagasaki type weapon for any specific spontaneous fission neutron background. Also, though he gives calculations for both the Nagasaki weapon and for a weapon with twice the assembly speed of the Nagasaki weapon, Mark gives no indication which of these two types of weapons would likely be used by a new nuclear weapon state today.

Von Hippel and Lyman Appendix

Frank von Hippel and Edwin Lyman, both of Princeton University, wrote an appendix to Mark's 1993 article in which they attempted to calibrate Mark's predetonation calculations.[11] Von Hippel and Lyman made estimates of the mean neutron lifetime and the assembly speed of the weapon. They found that the neutron background produced by a Pu-240 concentration of 1% approximately reproduces Oppenheimer's estimates for the predetonation probabilities of the Nagasaki weapon. They plotted curves showing the probability of attaining a specific yield for weapons that have a spontaneous fission neutron background equal to that of the Nagasaki weapon, 6 times that of the Nagasaki weapon and 40 times that of the Nagasaki weapon. They only considered weapons with an assembly speed equal to that of the Nagasaki weapon.

There are a number of problems with von Hippel's and Lyman's analysis. First, they find that the Nagasaki weapon with a Pu-240 content of 1% had a predetonation probability of 20.3%, even though Oppenheimer's memo says 12%. Certainly, von Hippel and Lyman could have chosen different weapon parameters to produce a 12% result. Why they did not is unclear. As a result, all their calculations are calibrated incorrectly. Second, the shape of their predetonation curves does not match the data given by Oppenheimer. Even if they were adjusted to give a

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[11] Frank von Hippel and Edwin Lyman, "Appendix: Probabilities of Different Yields," *Ibid.*, pp. 125-128.

predetonation probability of 12%, they would not give the correct probability of attaining the yields of 5 kilotons or 1 kiloton.

Third, they ignore the increase in the plutonium neutron background produced by subcritical neutron chains. For plutonium masses that are an appreciable fraction of a critical mass, the neutron background is increased by the inverse of 1 minus the fraction of the critical mass.[12] For example, if one has a plutonium mass that is 0.5 of a critical mass, the neutron background is doubled [1/(1 – 0.5) = 2].

It is known that the Nagasaki weapon used a near critical mass of plutonium. For such a plutonium core, the neutron background increase would be substantial and would depend strongly on exactly how close to critical the plutonium core was. For example, if the core were 0.9 of a critical mass then the enhancement would be a factor of 10, if 0.95, it would be a factor of 20, if 0.98, it would be a factor of 50. It is obvious that the neutron background used in von Hippel's and Lyman's analysis would need to be increased substantially. This would require a significant revision to the mean neutron lifetime and/or the weapon assembly speed to reproduce the 12% predetonation probability found by Oppenheimer. The exact revision would depend on just how close to critical the Nagasaki core was but this was unknown in the 1990s.

Harmon Hubbard's Methodology

In 2004, Harmon Hubbard, a former nuclear weapon designer, significantly improved Mark's methodology.[13] Hubbard calibrated Mark's calculations by using a 1.0% Pu-240 content for the Nagasaki weapon. Hubbard implied that Los Alamos had published information on the critical mass of a weapon that is actually the Nagasaki weapon but he gave no reference. Hubbard also provided a formula for calculating the critical mass in kilograms for the core used in a Nagasaki

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[12] Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering*, D. Van Nostrand Company Inc., Princeton New Jersey, 1963, p. 222.

[13] 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, Appendix 3. https://www.iranwatch.org/sites/default/files/perspex-npec-lwr-102204.pdf

type weapon for plutonium with different Pu-240 contents. His formula is 5.5 + 9.02 x where x is the fraction of Pu-240 in the plutonium.

Hubbard's method of calculating the predetonation probability of a nuclear weapon is similar to that of Mark but he changes the exponent used in the calculation to take into account the different critical masses of plutonium with varying Pu-240 concentrations. He also uses the Pu-240 fraction to specify the plutonium's spontaneous fission neutron background.

To illustrate Hubbard's method, take, as an example, a weapon with the assembly speed of that of the Nagasaki weapon with plutonium that is 6% Pu-240. The critical mass is then 5.5 + (9.02 x 0.06) = 6.04 kilograms. For 1% Pu-240 the critical mass is 5.59 kilograms.[14] The exponent used in Hubbard's calculations is then (6.04 x 0.06) / (5.59 x 0.01) = 6.48. The probability of attaining the full 20 kiloton yield is then found by $0.88^{6.48}$ = 0.44. Similarly based on the data in the Oppenheimer memo, the probability of attaining a 5 kiloton yield is $0.94^{6.48}$= 0.67 and the probability of attaining a 1 kiloton yield is $0.98^{6.48}$ = 0.88.

Hubbard further states that to perform this calculation for weapons with assembly speeds n times that of the Nagasaki weapon, one simply divides the above exponent by n. In the case of a weapon that had an assembly speed three times that of the Nagasaki weapon, and plutonium with a 6% Pu-240 content, the exponent would be 6.48/3 = 2.16. The probability of attaining the full 20 kiloton yield would be $0.88^{2.16}$ = 0.76, attaining a 5 kiloton yield, $0.94^{2.16}$ = 0.87 and attaining a 1 kiloton yield, $0.98^{2.16}$ = 0.96.

Hubbard has calculated the probability of attaining yields of 20 kilotons, 5 kilotons and 1 kiloton, for cases where the plutonium has a Pu-240 content of 4.5%, 6% and 14% and for weapons with assembly speeds equal to, twice and three times that of the Nagasaki weapon. Unlike von Hippel's and Lyman's methodology, Hubbard's methodology ensures that his results match the values given in the Oppenheimer memo. Note that Hubbard does not need to take into account the increase in the neutron background due to subcritical chain reactions, since the

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[14] As will be seen below the actual critical mass for the Nagasaki weapon was 6.46 kilograms of plutonium. Hubbard is aware of this fact and attributes the difference to the void in the actual weapon for the initiator. He says that for his calculations it is the relative critical masses, not the absolute ones that are relevant. *Ibid.*, p. 59.

increase would appear in both the numerator and the denominator of the exponent and cancel itself out.[15]

As useful as Hubbard's work is, it has its limitations. Though Hubbard has calculated the predetonation probabilities for plutonium that is up to 14% Pu-240, this plutonium is not reactor-grade. Since his calculation of the critical mass is limited to just Pu-239 and Pu-240, his formula is only valid for plutonium compositions where those two isotopes are the principal components. Hubbard represents the spontaneous fission neutron background in terms of the Pu-240 content but for reactor-grade plutonium, Pu-242 and Pu-238 are significant contributors to the spontaneous fission neutron background. Due to these limitations, one cannot use the Hubbard methodology to calculate the predetonation probability of reactor-grade plutonium. Further though Hubbard has calculated the predetonation probability for weapons with assembly speeds equal to, twice and three times that of the Nagasaki weapon, he provides no guidance as to which of these three alternatives would most likely represent the type of weapon that a new nuclear weapon state would likely use today.

Methodology of the Current Work: Near-Critical Plutonium Core

This article has improved the Mark/Hubbard methodology so as to remove these limitations. The first improvement is to note though Hubbard uses the percentage of Pu-240 in his calculation of the predetonation probability, this is just a proxy for the neutron background. In my calculations, I use the spontaneous fission neutron background directly which allows the calculation of the predetonation probability of any plutonium, including reactor-grade plutonium.

The second improvement is to generalize Hubbard's calculation of the critical mass to any plutonium composition. Hubbard's formula includes only Pu-239 and Pu-240. However, the fast critical mass of Pu-238 and Pu-241 are close to that of Pu-239 and they can be treated as equivalent to Pu-239. The fast critical mass of Pu-242 is significantly larger than that of Pu-240. I have conservatively treated the Pu-242 as an inert component and divide Hubbard's critical

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[15] For the same reason Mark does not need to account for this increase in the neutron background, though as discussed previously, von Hippel and Lyman do.

mass formula by 1 minus the Pu-242 fraction. Since the fraction of Pu-242 is always less than 0.12, the error produced by this assumption is not large.

Table 1

Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced in Different Types of Reactors with Different Burnups (Ten Years After Discharge)

Reactor Type and Burnup (MWD/Te)	Pu-238%	Pu-239%	Pu-240%	Pu-241%	Pu-242%	Spontaneous Fission Neutrons (n/g-s)	Decay Heat (watts per kilogram)
Weapon-Grade Pu		93.4	6.0	0.6		55	2.2
CANDU 7,000	0.07	69.2	26.4	3.0	1.3	264	3.6
MAGNOX 5,000	<0.1	69.9	25.5	3.4	1.2	254	3.6
PWR 33,000	1.3	58.8	25.9	8.7	5.4	361	10.4
PWR 20,000	0.6	69.8	20.6	6.9	2.2	240	6.4
PWR 51,000	2.6	54.3	25.8	9.7	7.6	432	17.8
PWR 1st Discharge	0.1	77.8	18.1	3.5	0.5	176	3.4
PWR MOX 51,000	3.3	41.3	33.0	10.7	11.6	583	22.0
PWR Recycled U 46,300	6.3	61.5	19.4	8.8	4.0	408	38.1

Consider, for example, reactor-grade plutonium produced by a burnup of 51,000 MWD/Te in a PWR, whose composition is given in Table 1, in a weapon with twice the assembly speed of the Nagasaki weapon. The plutonium has a Pu-240 fraction of 0.258. From Hubbard's critical mass formula 5.5 + (9.02 x 0.258) = 7.83 kilograms. Since the plutonium has a Pu-242 fraction of 0.076, divide this number by 1 – 0.076 which results in 8.47 kilograms. As in the prior example, the critical mass for the plutonium used in the Nagasaki weapon is 5.59 kilograms. The reactor-grade plutonium has a neutron background of 432 n/g-s and for plutonium that is 1% Pu-240, the neutron background is 9.1 n/g-s.[16]

The calculation of the exponent is: (8.47 x 432) / (5.59 x 9.1) = 71.9. For a weapon with twice the assembly speed of the Nagasaki weapon, divide this number by 2 to get 36.0. The probability that the weapon achieves the full 20 kiloton yield is then $0.88^{36.0}$ = 1.0%, the probability that the yield is at least 5 kiloton, $0.94^{36.0}$ = 11% and the probability that the yield is at least 1 kiloton, $0.98^{36.0}$ = 48%. This example shows, that for these assumptions, the weapon would predetonate almost all of the time but that it would achieve a yield greater than 1 kiloton almost half the time.

But what assembly speed would be typical for a weapon developed by a new nuclear power today? As is discussed in the text, even the first nuclear weapons of nuclear powers today would use weapons that employ a levitated design, which would significantly increase the assembly speed of the weapon. But to perform predetonation calculations, this increase needs to be quantified. Neither Mark, von Hippel and Lyman nor Hubbard provide any insight into this matter.

Elsewhere I have produced a history of the Pu-240 content of U.S. nuclear weapons.[17] I found that by the early 1950s the U.S. was already using plutonium with a Pu-240 content of 5.5% (spontaneous fission neutron background of 50 n/g-s) in its levitated unboosted fission weapons. Using Hubbard’s methodology, one can calculate that such plutonium would have a probability of 47% of attaining the full yield if a weapon has an assembly speed equal to that of the Nagasaki weapon, a probability of 69% of attaining the full yield if a weapon has an assembly speed twice that of the Nagasaki weapon and a probability of 78% of attaining the full yield if a weapon has an assembly speed three times that of the Nagasaki weapon. General Groves implies in his 1945 memo that a predetonation probability of 20% is acceptable in a nuclear weapon.[18]

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[16] Mark, 1993, p. 115.

[17] Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons: Exploding the Myths*, Nonproliferation Policy Education Center, 2018, Appendix. https://nebula.wsimg.com/3fd1e3cfbbf101d6c4f562e17bc8604c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[18] Wohlstetter, p. 161.

Taking this predetonation probability as the standard, it is clear that U.S. levitated unboosted fission weapons, even in the early 1950s, would have had an assembly speed three times that of the Nagasaki weapon.

Table 2 is the culmination of these developments in quantifying of the predetonation probability of unboosted fission weapons using a near critical plutonium core. This table, for the first time, provides the predetonation probability of reactor-grade plutonium when used in a levitated unboosted fission weapon of the type that new nuclear powers would use today. The calculations in Table 2 are also consistent with the information in Oppenheimer’s original memo.

Table 2

Probability of a Simple Fission Nuclear Weapon Achieving Various Yields for Different Plutonium Spontaneous Fission Neutron Backgrounds
(Near Critical Plutonium Core, Early 1950s U.S. Implosion Technology with an Assembly Speed Three Times that of the Nagasaki Weapon)

Yield	Weapon-Grade 5.5% Pu 240 50 n/g-s	1st Discharge PWR 176 n/g-s	CANDU 264 n/g-s	PWR 51,000 MWD/Te 432 n/g-s
Full Yield 20 kilotons	78%	35%	17%	5%
5 kilotons or more	89%	60%	42%	23%
1 kiloton or more	96%	85%	76%	62%

For a weapon having a 5.5% Pu-240 content, which was weapon-grade in the early 1950s, the predetonation probability would be 22%. For plutonium from the first discharge from a PWR, almost two-thirds of the weapons would predetonate. Yet the average yield would still be about 9 kilotons. For plutonium from CANDU fuel, about five-sixths of the weapons would predetonate but the average yield would still be about 5 kilotons. For plutonium from high burnup PWR fuel, though most weapons would predetonate, the average yield would still be about 2 kilotons. Even for this latter plutonium, the average yield would be substantial and significantly higher than that of the fizzle yield.

Methodology of the Current Work: Reduced Mass Plutonium Cores

The results from Table 2 show that unboosted fission weapons using near critical plutonium cores produced by high burnup in a LWR, even with an assembly speed three times that of the Nagasaki weapon, would predetonate most of the time. Proponents of the view that a country would not ever base a nuclear weapon program on reactor-grade plutonium have seized upon this fact to support their case. They argue that militaries would not accept weapons with such uncertain yields. Even Mark has stated his belief that "a military organization" would "wish to have a set of warheads with a reliable known yield."[19]

As stated in the main article, I am less convinced that this is the case, since the yield of the predetonating weapon would be in the nuclear range and the weapon's lethal area would be substantial. Nevertheless, this raises the issue of whether it is possible to produce unboosted fission weapons using reactor-grade plutonium that have a predetonation probability the same as that of a weapon using weapon-grade plutonium. This issue is not addressed by either Mark, von Hippel and Lyman or Hubbard.

The British have stated that the predetonation probability can be reduced by simply decreasing the amount of plutonium in the weapon.[20] In the 1990s, the Natural Resources Defense Council first publicly suggested that nuclear weapons could be manufactured with amounts of nuclear material that are significantly less than that of a critical mass.[21] Since then the North Korean public statement that it had used only 2 kilograms of plutonium in its 2006 nuclear test and information released by the Russians that in its 1953 nuclear test series it used 2 kilograms and 0.8 kilograms of plutonium to produce yields of 5.8 and 1.6 kilotons respectively have confirmed this fact.[22]

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[19] Mark, 1990, p. 5.

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

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

[22] "North Korea Declares 31 Kilograms of Plutonium," *Global Security Newswire*, October 24, 2008. Pavel Podvig, "Amounts of fissile materials in early Soviet nuclear devices," International Panel on Fissile Materials Blog, October, 1, 2012, http://fissilematerials.org/blog/2012/10/amounts_of_fissile_materi.html

A reduced plutonium mass will decrease the predetonation probability because of a major reduction in the increase in neutron background that is the result of subcritical neutron chain reactions. But in order to quantify this reduction, it is necessary to know how close to critical the Nagasaki weapon was. The British, at the start of their nuclear weapon program, produced a general description of the entire Nagasaki weapon, based on their Manhattan Project experience.[23] Using the information in this document and Hubbard's statement that Los Alamos had published critical mass data on the Nagasaki weapon, I was able to track down the information.[24] The plutonium in the Nagasaki weapon was 6.15 kilograms, making it 0.952 of a critical mass.[25] As a result, the spontaneous fission neutron background was increased by a factor of 21.[26]

As was stated above, the weapon-grade plutonium used in U.S. nuclear weapons in the early 1950s had a spontaneous fission neutron background of 50 n/g-s (Pu-240 content of 5.5%). The neutron production from an entire plutonium core that was 0.952 of critical would be 6,460,000 n/s.[27] As was shown in Table 2, the predetonation probability of this weapon would be 22%.

For the reactor-grade plutonium produced by high burnup in a PWR (Table 1) the spontaneous fission neutron output would be 432 n/g-s. Due to the poorer quality of the plutonium, it would require about 9.3 kilograms of plutonium to make 0.952 of a critical mass.[28] However, if the reactor-grade plutonium core were reduced to only 0.60 of a critical mass, then the plutonium core would only contain 5.9 kilograms of plutonium and the background neutrons would only be increased by a factor of 2.5. Therefore, the total neutron production from the entire core would be 6,370,000 n/s, which is slightly less than that of the near critical core using weapon-grade plutonium.[29] As a result, its predetonation probability would also be slightly less than 22%.

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[23] UK Public Record Office File AVIA 65 "Implosion." Written by William G. Penney, July 1, 1947. https://nuclearweaponarchive.org/Library/DocumentArchive/Resources/PenneyPuWeapon.html

[24] H.C. Paxton, "Los Alamos Critical-Mass Data," LAMS-3067, Los Alamos Scientific Laboratory, April 1964, p. 45. https://digital.library.unt.edu/ark:/67531/metadc867974/m2/1/high_res_d/4054646.pdf

[25] Paxton gives the critical mass as 6.46 kilograms.

[26] 1 / (1 – 0.952) = 21

[27] 6,150 x 50 x 21

[28] As was shown above, using my adaptation of Hubbard's formula, this plutonium has a critical mass of 8.47 kilograms and the Nagasaki weapon a critical mass of 5.59. The ratio of these two critical mass estimates, times the 6.15 kilograms of plutonium that was actually in the weapon plutonium gives 9.3 kilograms (8.47/5.59) x 6.15 = 9.3.

[29] 5,900 x 432 x 2.5

Mark has published a formula for calculating the efficiency of the fissioning of the nuclear material in a nuclear weapon.[30] 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.[31] 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.[32] 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. Therefore, by using 0.60 critical mass of high burnup reactor-grade plutonium, a weapon can be constructed with a 5 kiloton yield that has a predetonation probability a little less than that of a weapon using weapon-grade plutonium.

For plutonium from CANDU fuel, the spontaneous fission neutron output is 264 n/g-s. By performing a similar calculation, one can show that by using 0.72 of a critical mass (in this case 6.65 kilograms of plutonium), a weapon would produce a yield of 9 kilotons with a predetonation probability a little less than that of a weapon using weapon-grade plutonium. For the first discharge plutonium from the Iranian Bushehr PWR, the spontaneous fission neutron output is 176 n/g-s. By using 0.81 of a critical mass (in this case 6.7 kilograms of plutonium), the analogous yield would be 13 kilotons.

The results in Table 3 provide the basis for the conclusion in the main article that powerful, reliable nuclear weapons can be manufactured using reactor-grade plutonium simply by using reduced mass plutonium weapon cores. These weapons would have the same predetonation probability as weapons using weapon-grade plutonium and would be the exact same design, size and weight, requiring no special cooling. Depending on the specific spontaneous fission neutron rate, an unboosted fission weapon design that would produce 20 kilotons using weapon-grade

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[30] 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.

[31] Mark notes that K is related to the nuclear properties of the fissile material used in the weapon and is different for plutonium and HEU. Mark uses this formula to calculate the efficiency of possible Iraqi nuclear weapons with different masses of HEU, illustrating that K does not vary significantly due to different masses of the same fissile material.

[32] 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.

plutonium could reliably produce a yield between 5 and 13 kilotons using reactor-grade plutonium.

Table 3

Yield Produced by Plutonium with Different Spontaneous Fission Neutron Backgrounds Using Fractional Critical Mass Cores
Equal Predetonation Probability

Plutonium Type	Spontaneous Fission Neutrons n/g-s	Fraction of Critical Mass	Yield Kilotons
Weapon-Grade 5.5% Pu-240	50	0.952	20
1st Discharge PWR	176	0.81	13
CANDU	264	0.72	9
PWR 51,000 MWD/Te	432	0.60	5