Chapter 5

Heat from Reactor-Grade Plutonium: An Outdated Worry

This chapter examines the issue of the heat produced by the decay of plutonium and how this heat might interfere with the production of a nuclear weapon. The chapter shows that reactor-grade plutonium produced by high fuel burnup in current LWRs, by MOX fuel or recycled uranium can be effectively used in fission weapons using early 1950s level of U.S. technology including a levitated design and modern high explosives.

Claims that the heat of plutonium from LWRs denatures that plutonium are based on faulty analysis that looks at only unlevitated nuclear weapon designs using near critical cores and World War II type explosives. These claims also ignore techniques that allow the plutonium heat to be safely dissipated. These techniques include reducing the mass of plutonium in the weapon, using thermal bridges to conduct the heat away from the plutonium, and using in-flight insertion of the plutonium so that it is only contained within the insulating high explosive shell for a short period of time. In addition, more than 50% of the large stocks of separated plutonium that exist worldwide are not nearly as hot as high burnup LWR fuel, having been produced in natural uranium fueled reactors, in reactors that use an enrichment lower than that used in LWRs or in LWRs that did not use the high initial enrichment and high burnup of some current LWRs. By simply reducing the amount of plutonium in the weapon,

all of the current 270 metric ton world stockpile can be used to produce nuclear weapons without any need for special cooling. Claims that the decay heat of plutonium can denature plutonium refer to high Pu-238 plutonium that does not exist and likely never will.

Plutonium Decay Heat

All plutonium produces a significant amount of heat due to its radioactive decay. The plutonium that was used in the 1945 Trinity test consisted mostly of Pu-239 and was noticeably warm to the touch. The isotope Pu-238 is responsible for plutonium with a high heat output. It produces over 200 times as much heat as does Pu-239. (See chapter three) Pu-238's heat dominates the heat output of any plutonium that is more than about 0.5% Pu-238, though for plutonium to have a high heat output it must contain at least several percent Pu-238. Pu-239 as well as the higher plutonium isotopes Pu-240, Pu-241, and Pu-242 have their origin in an initial neutron capture in U-238. Pu-238, however, has its origin mainly in an initial neutron capture in U-235 and requires additional neutron captures in U-236 and Np-237. As a result, not much Pu-238 is produced in natural uranium fuel where the initial U-235 content is low as is the burnup. High Pu-238 plutonium is produced in enriched uranium fuels with a high initial U-235 content and high burnups. It can also be produced in MOX fuel (fuel that initially contains both plutonium and uranium) or recycled uranium fuel that already contains some U-236. There have been proposals to produce plutonium with a very high Pu-238 content by spiking enriched uranium fuel with either neptunium or americium 241. This has never been done, nor is it likely to be done, since this would increase the fuel cost and make the fuel more difficult to handle. Table 10 (drawn from the data in chapter three) shows the heat output of plutonium produced by different types of reactors with different burnups.

For decades it has been suggested that the high heat from Pu-238 would denature plutonium in cases where the Pu-238 content is several percent. Until recently, there was never any specific analysis to delineate how high the Pu-238 content would have to be to result in denatured plutonium. However, Gunter Kessler, a proponent of the false notion of denatured plutonium, has produced some specific analysis.[92] Kessler's analysis suggests that plutonium with a heat output of about 13 watts per kilogram[93] would melt the high explosives that were used in World War II and plutonium with a heat output of about 100 watts per kilogram would be enough to melt the center of the plutonium core.

Plutonium Weapon Core

The plutonium core itself is not going to be a constraint on the acceptable amount of heat from plutonium. Core melting is not an issue, since there is no plutonium with a heat output anywhere close to 100 watts per kilogram. The actual binding constraint is the potential for phase change. Though some still sometimes believe that the plutonium in nuclear weapons is alpha phase which is quite sensitive to heat, it is now well known that plutonium in nuclear weapons is a plutonium alloy containing one percent by weight (3.2 atom percent) of gallium, which stabilizes the plutonium in the delta phase.[94]

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92. G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles: Safeguards and Non-Proliferation*, KIT Scientific Publishing, 2011.

93. Kessler states that a plutonium core with a total heat output of 120 watts would begin to melt World War II type explosives. Though he is not explicit, it appears he is referring to a core which contains 9.24 kilograms of plutonium. See Ibid. p. 265.

94. For a discussion of plutonium phases see: Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhat-

The properties of this alloy are shown in Figure 2.[95] The alloy is very heat resistant and is stable from room temperature to over 500 degrees centigrade. It has a very low coefficient of expansion over this range. Above about 530 degrees centigrade the plutonium transitions from delta phase to epsilon phase and contracts which could possibly damage the plutonium core of a nuclear weapon.

By Kessler's own calculations, achieving a temperature of over 530 degrees centigrade would require plutonium that had a heat output of about 67 watts per kilogram. By simply lowering the amount of plutonium in the device, this limit could be raised to 109 watts per kilogram. Kessler assumes that the plutonium in a nuclear weapon is near critical and that the weapon contains 12.9 kilograms of reactor-grade plutonium recovered from MOX fuel so that the total plutonium heat output would is 858 watts.[96] As I showed in chapter four, quite satisfactory nuclear weapons can be produced using just 0.6 of a critical mass instead of the 0.98 incorrectly assumed by Kessler. For the inferior reactor-grade plutonium that forms the basis of Kessler's calculations, about 7.9 kilograms of plutonium would be 0.6 of a critical mass. If this plutonium is made into a shell having the same outer diameter as 12.9 kilograms of plutonium, then the 7.9 kilograms of plutonium could have a heat output of about 109 watts per kilogram and match the outer temperature of a 12.9 kilogram plutonium sphere with a heat output of 67 watts per kilogram. Reactor-grade plutonium with such a high heat output does not exist and likely never will.

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tan Project," December 16, 2015, available from http://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

95. Siegfried S. Hecker, "Plutonium and Its Alloys," *Los Alamos Science*, no. 26, 2000, p. 293. Figure reproduced with permission, available from http://www.sciencemadness.org/lanl1_a/lib-www/pubs/00818035.pdf.

96. G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles: Safeguards and Non-Proliferation*, KIT Scientific Publishing, 2011, pp. 190 & 262-263.

Plutonium From Nuclear Reactors Using Natural or Slightly Enriched Uranium Fuel

Even if Kessler were correct regarding the proper limits for the heat from plutonium, as can be seen from Table 10, significant amounts of plutonium are far cooler than the Kessler's 13 watts per kilogram limit for World War II type explosives. Most notable is the plutonium produced by power reactors fueled with natural uranium (CANDU and MAGNOX). Currently there are 47 power reactors in operation fueled with natural uranium.[97] The majority of these are in either Canada or India but there are some in Argentina, China, Pakistan, Romania, and South Korea. At the present time, only the spent fuel from the reactors in India is being reprocessed but the spent fuel from these other reactors could also be reprocessed.

97. There is also a heavy water nuclear power reactor in Argentina (Atucha 1) which uses 0.9% enriched uranium fuel. The plutonium produced by this reactor is only slight hotter than that produced in a natural uranium fueled reactor.

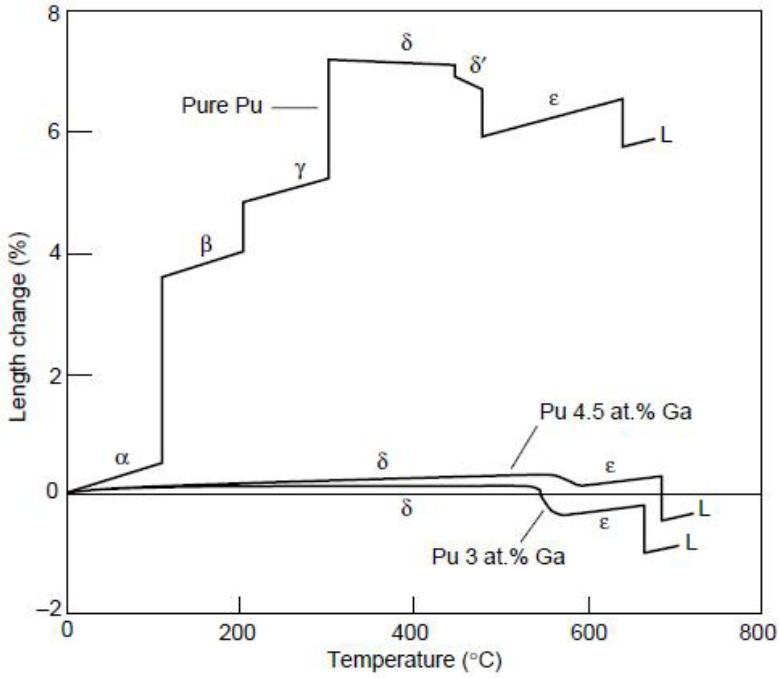

FIGURE 2: The Benefits of a Plutonium-Gallium Alloy

All of the current natural uranium fueled power reactors are heavy water reactors (mainly CANDU) but in the past there were 38 natural uranium fueled graphite power reactors (MAGNOX[98]). 26 of these reactors were in the UK, 9 were in France and 1 each in Spain, Italy, and Japan. The last of these reactors operated in the UK and was shut down in December 2015. All of the spent fuel from these reactors has been or is going to be reprocessed. Due to its low heat and Pu-241 content (a source of radiation exposure), this plutonium is preferred for the production of MOX fuel. As a result, it is likely that most if not all of the plutonium produced by

98. Strictly speaking, only the reactors in the UK, Japan, and Italy were MAGNOX. The reactors in France and Spain were UNGG (uranium naturel-graphite-gaz) but the designs were quite similar.

the reactors in France, Spain, Italy, and Japan has been consumed as MOX fuel. This is not the case for the plutonium produced in the UK, where most if not all of the plutonium produced by the natural uranium fueled graphite reactors (roughly 75 metric tons) is being stored as part of the UK's massive plutonium stockpile.

In addition, there are nuclear power reactors which use low enriched uranium fuel where the initial enrichment is significantly less than that used in modern LWRs and the burnup is less as well. One group of such reactors is the 14 advanced gas cooled reactors (AGRs) in operation in the UK. The initial enrichment of the fuel for these reactors is only about 2.5% and the burnup is about 18,000 MWD/Te. Up to now the spent fuel from these reactors has all been reprocessed (though this may end in the next few years) and has resulted in about 30 metric tons of plutonium whose the heat output is about 7 watts per kilogram (see Table 10).

The remainder of the 129 metric ton UK plutonium stockpile is from foreign LWRs, mainly Japan.[99] Not only was this fuel generated at a time when fuel burnup was not as high as it is today but the British have indicated that this LWR fuel was not reprocessed in dedicated campaigns but rather was commingled with the British AGR fuel.[100] Therefore, this plutonium is a blend of the plutonium from the two reactor types and likely only has a heat output of about 8 watts per kilogram. It is probable that the entire massive 129 metric ton stockpile of separated plutonium stored in the UK is low heat plutonium. The UK has no plans for the disposal of its stockpile of plutonium.

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99. "Annual figures for holdings of civil unirradiated plutonium as at 31 December 2015," UK Office for Nuclear Regulation, available from http://www.onr.org.uk/safeguards/civilplut15.htm.

100. Adrian M. Simper, "Plutonium Management," UK Nuclear Decommissioning Authority, February 2014, available from https://www.cnec.group.cam.ac.uk/presentations/NDA13Feb2014.pdf.

Another group of reactors similar in fuel enrichment and burnup to the AGRs are the RBMK reactors, all of which were built in the Soviet Union. The Chernobyl reactor was an RBMK. Today 11 such reactors are operating, down from a total of 17. Of Russia's current civil stockpile of separated plutonium of 52 metric tons, roughly 20 metric tons were produced in this type of reactor. Combined with the approximately 129 metric tons of separated plutonium in the UK, this means that roughly 150 metric tons of the 270 metric ton world stockpile of separated civil plutonium (over 50%) has a heat output well below Kessler's 13 watt per kilogram limit.

Even if one believed that high heat plutonium was denatured, what should be done about the 73 nuclear power reactors that do not produce high heat plutonium? Should they all be shut down? Proponents of the notion that heat can denature plutonium are silent on this issue.

Nor do all LWRs necessarily use high initial fuel enrichment and high fuel burnup (for example 4.3% enriched with a burnup of 51,000 MWD/Te) resulting in plutonium with a high heat output. Iran's Bushehr LWR, which started operation in 2012, is one of the LWRs of highest proliferation concern. Yet the reactor uses fuel with an initial enrichment of only 3.6%, resulting in a full burnup of only 37,000 MWD/Te.[101] The plutonium produced in such fuel after just 20 years of decay would have a heat output of about 12.6 watts per kilogram which is less than Kessler's 13 watts per kilogram limit. This issue applies to any LWR since there is no requirement that reactors use the highest initial fuel enrichment possible.

101. Gregory S. Jones, "Iran's Bushehr Nuclear Power Reactor: A Potential Source of Plutonium for Nuclear Weapons," March 24, 2016, available from http://nebula.wsimg.com/0bde4bc34f1c736b5d635c12f23bec87?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

Even for LWRs that use uranium fuel with a high initial enrichment, not all of the fuel will have a high burnup. Most notably, when any LWR starts initial operation, it will use some fuel whose enrichment is well below its normal enrichment. When a reactor has been in sustained operation, it contains a mixture of fuel with different burnups. But when a reactor starts for the first time, it must use fuel with different levels of enrichment. Fuel with the lowest enrichment is burned for only a relatively short time before being permanently discharged. This first discharge fuel will contain plutonium which may not even be reactor-grade but rather fuel-grade. Its heat output will be no more than 3 to 4 watts per kilogram.[102] This is similar to plutonium produced by full burnup natural uranium fuel. It is certainly not denatured by heat, since its heat output is far less than Kessler's 13 watt per kilogram limit. This first reactor discharge might contain close to 100 kilograms of plutonium, enough for at least 15 nuclear weapons.

Low burnup is not necessarily an issue only when a power reactor starts operation for the first time. Even when operating normally, some reactor fuel from modern LWRs is discharged with less than full burnup (figure 1, chapter three). It would be easy for a country to claim some technical fault in reactor fuel and discharge the fuel with far less than full burnup. This plutonium could be fuel-grade or even weapon-grade. Iran temporarily discharged the entire fuel core from the Bushehr reactor during reactor testing in 2012. The reason for this discharge was never explained. The IAEA might detect such early discharge but would have no reason to declare a safeguards violation.

102. Ibid.

High Heat Plutonium is Not Denatured

Even when plutonium is produced by high burnup enriched uranium fuel in LWRs, the heat will not denature the plutonium. The easy expedient of using a reduced plutonium mass in the weapon would allow high heat plutonium to be used in a simple nuclear weapon without melting even World War II type high explosives. If 5.8 kilograms of plutonium were made into a shell with the same diameter as the 9.24 kilograms that Kessler uses in his calculations, then Kessler's 13 watts per kilogram limit would become 21 watts per kilogram (13 x 9.24/5.8). As can be seen from Table 10, this is significantly higher than the 17.8 watts per kilogram heat output of plutonium produced by high burnup enriched uranium LWR fuel. Since almost all of the world's current stockpile of separated plutonium produced in LWRs was produced using enriched uranium fuel uncontaminated by U-236 (i.e. did not use recycled uranium), this means that all this plutonium is not denatured by its decay heat. What little plutonium that has been recovered from MOX fuel or fuel using recycled uranium has been diluted by other plutonium to make it more manageable. Since the remainder of the world's separated plutonium has come from natural uranium fueled reactors and reactors that used a lower enrichment than that of current LWR's this means that the *entire* 270 metric ton current world stockpile of separated plutonium is not denatured by its decay heat. This plutonium could be used in nuclear weapons without any need for special cooling systems.

But what about plutonium produced in MOX fuel or in enriched uranium fuel that has been contaminated by high levels of U-236 (recycled uranium)? Plutonium produced from these fuels, if undiluted, might have a heat output in the range of 30 to 40 watts per kilogram. The first point to note is that up to now very little plutonium has been separated from these types of fuels. This is unlikely

to change in the future.[103] The high heat (and the relatively high radiation) from this plutonium make it undesirable for use as MOX fuel. The characteristics of this plutonium may exceed what current MOX fabrication plants are licensed to handle and as a result, reprocessing plant operators dilute this plutonium with much cooler plutonium to make it easier to handle.

Second, Kessler's 13 watts per kilogram limit applies only to World War II type explosives and more modern explosives are less sensitive to heat. World War II explosives might melt at temperatures of less than 100 degrees centigrade, whereas more modern explosives might not melt until 190 degrees centigrade. In addition, more modern explosives have somewhat better heat transfer characteristics.

Consider the case of 6 kilograms of reactor-grade plutonium with a heat output of 40 watts per kilogram. The total heat output is 240 watts. Kessler has performed a calculation for a case where the core has a total heat output of 240 watts for a weapon using modern high explosives (his "medium technology" case). He finds that the inner edge of the high explosive layer would have a temperature of about 240 degrees centigrade, higher than 190 degrees centigrade. Kessler then concludes that such a nuclear weapon could not function.

But Kessler's calculation is based upon a solid pack nuclear weapon design where every layer of the weapon is in contact with the next layer. However, U.S. nuclear weapons of the early 1950s used "levitation" where a void is introduced into a weapon (i.e. there is an empty space is between two of the layers) to improve weapon performance. From their weight and yield, it appears that even 50 years ago, the first French and Chinese nuclear weapons employed levitation.

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103. France, the only country to recycle uranium in a significant way, stopped producing fuel using this uranium in 2012, in part because the French utility (EDF) objected to the high cost. See: International Panel on Fissile Materials, "Plutonium Separation in Nuclear Power Programs," July 2015, p. 34.

If one uses a 10 centimeter void in Kessler's design, expanding the outer shell of the weapon by this amount, then there is a dramatic temperature drop. The inner edge temperature of the high explosives layer would only be about 140 degrees centigrade, well below 190 degrees centigrade, and there should be no problem with the functioning of the weapon.[104] Therefore, simply by reducing the mass of plutonium, using a levitated design and modern high explosives, it is quite possible to use reactor-grade plutonium with a heat output of at least 40 watts per kilogram. This heat output exceeds that of plutonium produced in MOX fuel or plutonium produced by recycling uranium.

Nor are these the only techniques to deal with high heat plutonium. J. Carson Mark has suggested using an aluminum thermal bridge to conduct heat away from the plutonium core which could result in halving the plutonium core temperature.[105] Simple calculations show that the aluminum segments running through the high explosives would be less than one tenth of one millimeter thick, which would be unlikely to interfere with the functioning of the high explosives. Therefore the use of a thermal bridge might allow the acceptable heat level of plutonium for nuclear weapons to be as high as 80 watts per kilogram. Various proponents of the concept of denatured plutonium have suggested that the aluminum running through the high explosive implosion system would interfere with the weapons functioning. They have made these claims even though they have no background in nuclear weapon design, unlike

104. The lower temperature is achieved because with a larger diameter, the high explosive shell has a larger surface area. For the case where the plutonium has a heat output of 20 watts per kilogram, the inner edge temperature of the high explosives layer would be less than 90 degrees centigrade. As noted, almost all separated plutonium, including that produced by high burnup in LWRs has a heat output of less than 20 watts per kilogram.

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

Mark who was Director, Theoretical Division, Los Alamos National Laboratory from 1947 to 1972.

Further, in the early 1950s the United States did not store its plutonium cores inside the high explosives but rather stored them separately for safety and security reasons. Pakistan is reported to use the same system today. U.S. 1950s era weapons used in-flight insertion where the plutonium core was only inserted into the high explosive assembly after the weapon was in flight, meaning that it occurred only minutes before detonation. Using this method there would be no long-term exposure of the high explosives to the heat (or radiation) of the plutonium core.

Therefore, there are a number of ways that high heat plutonium could be used in simple unboosted implosion designs of the type that early nuclear states might develop in their nuclear weapon program. This observation is confirmed by U.S. statements that Am-241 could be used to produce nuclear weapons.[106] Its heat output is 114 watts per kilogram, significantly higher than that of any plutonium.

In sum, plutonium decay heat, even from plutonium with a high Pu-238 content, is not an impediment to the use of this plutonium in simple unboosted implosion nuclear weapons. By using a reduced plutonium core mass in a levitated weapon design utilizing modern high explosives would allow the use of plutonium with a heat output of 40 watts per kilogram, a higher heat output than that produced even in MOX fuel or fuel using recycled uranium. The use of conductive aluminum bridges through the high explosive is another technique that could raise the acceptable level of plutonium decay heat to as high as 80 watts per kilogram.

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106. David Albright and Kimberly Kramer, "Neptunium 237 and Americium: World Inventories and Proliferation Concerns," June 10, 2005, revised August 22, 2005.

The nuclear weapon potential of plutonium with a heat output of 40 watts per kilogram is largely academic since it appears that the world's entire current 270 metric ton stockpile of separated plutonium has a heat output of less than 20 watts per kilogram and the majority has a heat output of less than 10 watts per kilogram. Plutonium with a heat output of 40 watts per kilogram can be used to produce nuclear weapons using early 1950s U.S. nuclear weapon technology and modern high explosives by simply reducing the mass of plutonium in the weapon core. Such a weapon would require no special cooling. Since the standard operating procedure for nuclear weapons using this level of technology is to keep the plutonium cores separate from the high explosive assembly until minutes before the weapon is detonated, the exposure of the high explosives to the heat and radiation of the plutonium core is minimized. It is time to lay to rest the notion that heat can denature plutonium.

Plutonium Reactor Type and Burnup (MWD/Te)	Pu-238%	Pu-239%	Pu-240%	Pu-241%	Pu-242%	Spontaneous Fission Neutrons (neutrons per gram-seconds)	Decay Heat (watts per kilogram)
Weapon-Grade		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
AGR 18,000	0.6	55.8	32.0	6.3	5.2	395	6.9
LWR 1st Discharge	0.1	77.8	18.1	3.5	0.5	176	3.4
LWR 20,000	0.6	69.8	20.6	6.9	2.2	240	6.4
LWR 33,000	1.3	58.8	25.9	8.7	5.4	361	10.5
LWR 51,000	2.6	54.3	25.8	9.7	7.6	432	17.8
LWR MOX 51,000	3.3	41.3	33.0	10.7	11.6	583	22.0
LWR Recycled U 46.300	6.3	61.5	19.4	8.8	4.0	408	38.1

TABLE 10: Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced in Different Types of Reactors with Different Burnups[107], (Ten Years After Discharge)

107. The table is derived from data in chapter three.