

CHAPTER 3

The Different Kinds of Plutonium

This chapter will describe some of the basic properties of plutonium, how it is classified into different grades, the variation in reactor fuel burnup, and how plutonium's properties can vary depending on the initial fuel enrichment and burnup of the reactor fuel that produces the plutonium. The focus will be on the spontaneous fission neutron production and on the decay heat since these are the two properties that are most often cited in claims that plutonium can be denatured.

Natural uranium consists of two main isotopes, U-235 (0.7%) and U-238 (99.3%). Uranium can be used in two different ways to produce the nuclear material required for nuclear weapons. One can either increase (enrich) the percentage of U-235 to 80% or more or one can irradiate uranium in a nuclear reactor to produce plutonium. It is the neutron capture in U-238 that leads to the production of plutonium by the reaction $U-238 + n = U-239$ (half-life 24 minutes) decays to Np-239 (half-life 2.4 days) decays to Pu-239.

Ideally, one would use pure Pu-239 to produce nuclear weapons, but that is not possible. To create significant quantities of plutonium, it is necessary to leave the uranium in the reactor to allow the concentration of the plutonium to build up. During this time, the Pu-239 is exposed to neutrons. Some of the Pu-239 fissions, but some of the Pu-239 absorbs neutrons, which produces higher isotopes of plutonium. The reactions are $Pu-239 + n = Pu-240 +$

$n = \text{Pu-241} + n = \text{Pu-242}$. As will be shown, at low irradiations the plutonium is mostly Pu-239 with a small percentage of Pu-240. At higher irradiations the percentage of Pu-240 increases and the amounts of Pu-241 and Pu-242 become significant.

An additional plutonium isotope (Pu-238) is produced principally by the irradiation of U-235 in the uranium fuel. Though the U-235 mainly fissions, about one-seventh of the time it absorbs a neutron without fissioning. The reactions are $\text{U-235} + n = \text{U-236} + n = \text{U-237}$ (half-life 6.8 days) decays to $\text{Np-237} + n = \text{Np-238}$ (half-life 2.1 days) decays to Pu-238. Since the concentration of U-235 is low in natural uranium, its irradiation produces small amounts of Pu-238. In light water commercial nuclear power reactors, which use enriched uranium fuel, the build-up of Pu-238 can be much more significant and increases the higher the initial fuel enrichment and the higher the fuel burnup. Additionally, if recycled uranium is used as fuel, the amount of Pu-238 produced will be increased since the fuel will already be contaminated with some U-236.

Some of the characteristics of plutonium isotopes are shown in Table 1.⁴⁵ As can be seen, Pu-241 has a half-life short enough that it undergoes significant decay if it is stored for some years. About 4.7% of the Pu-241 decays away every year. Even 8.7% of Pu-238 decays away every decade. If plutonium is stored for decades (as often happens) the percentage of the various isotopes will change significantly due to these two shorter-lived isotopes.

The even number plutonium isotopes (Pu-238, Pu-240, and Pu-242) have a much higher production of spontaneous fission neutrons than do the odd number ones. The presence of these isotopes greatly increases the neutron background of the plutonium. These neutrons

45. J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security* 4, 1993, p. 115, available from <http://scienceandglobalsecurity.org/archive/sgs04mark.pdf>.

can significantly affect the performance of a nuclear weapon by causing the weapon to predetonate, resulting in a lower, possibly much lower, yield than intended. The discovery that any reactor produced plutonium would necessarily contain significant amounts of Pu-240 led the Manhattan Project to abandon its development of a plutonium gun-type weapon and instead develop implosion nuclear weapons, which are less sensitive to background neutrons.⁴⁶ The high neutron background of reactor-grade plutonium is a major reason often cited as to why this plutonium cannot (or will not) be used to produce nuclear weapons. This issue will be discussed in detail in chapter four.

Isotope	Half-Life (Years)	Spontaneous Fission Neutrons (neutrons per gram-seconds)	Decay Heat (watts per kilogram)
Pu-238	87.7	2,600	560
Pu-239	24,100	0.022	1.9
Pu-240	6,560	910	6.8
Pu-241	14.4	0.049	4.2
Pu-242	376,000	1,700	0.1

TABLE 1: Some Characteristics of Plutonium Isotopes

Plutonium isotopes produce a significant amount of heat due to their decay. The plutonium spheres used in the first nuclear weapons were obviously warm to the touch. The isotope Pu-238 produces far more heat than any other reactor produced plutonium

46. Gregory S. Jones, “Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project,” December 16, 2015, available from <http://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1>.

isotope. When its concentration is greater than about 0.5%, its heat becomes dominant in the plutonium. In reactor-grade plutonium produced in a light water commercial nuclear power reactor, the Pu-238 concentration is generally greater than 1% and can, in some cases, reach more than 5%. The heat from this plutonium is another major reason cited as to why such plutonium cannot be used to manufacture nuclear weapons. This issue will be examined in detail in chapter five.

Other reasons sometimes cited as posing difficulties for the use of reactor-grade plutonium in nuclear weapons are its increased penetrating gamma radiation and the increased critical mass. The increased gamma radiation is mainly a result of several of the decay products of Pu-241. The increased radiation is high enough to cause problems for a nuclear weapon program such as that of the United States, where there is a serious effort to minimize worker radiation exposure. However, it is not high enough to cause serious worker health problems in the short term that would prevent the manufacture of nuclear weapons. The gamma radiation from plutonium and its decay products are weak and easily shielded. Further, since the radiation is from Pu-241 decay products and not the Pu-241 itself, simply chemically removing these decay products from the plutonium shortly before it is processed into a core for a nuclear weapon would minimize the radiation exposure.

As to reactor-grade plutonium's increased critical mass, its critical mass is always less than that of highly enriched uranium which is well-known to have been used to produce nuclear weapons. Therefore, the critical mass of the plutonium is not a significant issue. Both the increased radiation and critical mass of reactor-grade plutonium will be discussed in chapter six.

Defining Grades of Plutonium

The quality of plutonium is expressed by referring to different grades of plutonium. Since the predetonation problem associated with the spontaneous fission rate of Pu-240 was discovered in 1944 whereas the issue of the higher decay heat associated with Pu-238 was not raised until 1980, the different plutonium grades are defined in terms of Pu-240 content. It has sometimes been suggested that a new system of plutonium grades be used that takes into account the plutonium's Pu-238 content but thus far this has not been done.

The United States currently defines three grades of plutonium. Weapon-grade plutonium is defined as having a Pu-240 content of less than 7%. Fuel-grade plutonium is defined as having a Pu-240 content of between 7% and less than 19%. Reactor-grade plutonium is defined as having a Pu-240 content of 19% or more.⁴⁷ A few comments are in order about these definitions.

As is shown in the appendix, weapon-grade plutonium has not always been defined in this way. In the mid-1940s, weapon-grade plutonium was only 2% Pu-240. By 1954 weapon-grade plutonium could be as much as 8.8% Pu-240. It was only in 1959 that the current goal of 6% Pu-240 was adopted for U.S. nuclear weapons. Up to 7% Pu-240 was acceptable only because it could be blended down to 6%.

In the 1940s and 50s, the United States produced very little plutonium that was not weapon-grade. Non-weapon-grade plutonium was treated as out-of-spec and a variety of terms were used to describe it, such as “unclassified.” The earliest use of the term reactor-grade

47. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, p. 17, available from <https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf>.

that I have been able to find was 1964.⁴⁸ The earliest use of the term fuel-grade that I have been able to find is 1969.⁴⁹

Though the United States uses these definitions, other countries have their own definitions. The UK defines plutonium which is 8% or less Pu-240 as weapon-grade. Plutonium which is more than 8% Pu-240 is reactor-grade.⁵⁰ The U.S.-Russian 2000 Plutonium Management and Disposition Agreement defines weapon-grade plutonium as having a Pu-240 content of no more than about 9.1% (a Pu-240 to Pu-239 ratio of no more than 0.1).

It should be remembered that the build-up of the higher plutonium isotopes is a continuous process as the irradiation proceeds and the division into various grades is somewhat arbitrary. There is nothing wrong with this. After all, we talk of people being young, middle-aged, or elderly even though aging is a continuous process. But one should not overemphasize the importance of different grades of plutonium. The properties of fuel-grade plutonium, which is 18% Pu-240 and reactor-grade plutonium, which is 20% Pu-240, are rather similar.

Reactor Fuel Burnup Can Vary Substantially

Discussions of the characteristics of plutonium produced in different types of power reactors often implicitly assume that all of the fuel produced by a reactor will have the full burnup expected given the

48. R. L. Dickeman, "Outline: N-Reactor Capability Report," HW-83877 RD, September 1, 1964.

49. "Douglas United Nuclear, Monthly Report," DUN-5611, May 1969, p. BN-1.

50. "Plutonium and Aldermaston-An Historical Account," UK Ministry of Defense, 2000.

type of reactor and the fuel's initial enrichment. However, over 40 years ago, I found that power reactors can discharge spent fuel with far less than the expected full burnup.⁵¹ An examination of more recent data shows that there continues to be substantial variation in fuel burnup, with a significant fraction of the fuel achieving a burnup less than full burnup.

A compilation of the initial fuel enrichment and achieved fuel burnup for U.S. pressurized water reactors (PWRs) and boiling water reactors (BWRs) fuel assemblies between 1968 and June 30, 2013, is shown in Figure 1.⁵² This data shows wide variation in the burnup achieved for fuel with the same initial enrichment. For example, though fuel with an initial enrichment of 3.2% has a full burnup of about 33,000 MWD/Te (megawatt-days per metric ton), roughly 2% of the PWR fuel achieved a burnup of 20,000 MWD/Te or less. As will be discussed in the next section, the first discharge from a PWR regularly contains fuel with significantly less than the standard full burnup.

Figure 1 also shows that as fuel burnups have increased, the scatter in fuel burnup has become unidirectional. Significant amounts of fuel achieve less than the design burnup but very little achieves more than the design burnup. Further, though some discussions of denatured plutonium refer to fuel with burnups of 60,000 MWD/Te, 72,000 MWD/Te or even 100,000 MWD/Te, one can see that very little fuel has achieved a burnup of greater than 54,000 MWD/Te. Further, as long as facility licenses restrict fuel initial enrich-

51. This work was written up in Albert Wohlstetter, "Spreading the Bomb Without Quite Breaking the Rules," *Foreign Policy*, no. 25, Winter 1976-1977, p. 158, available from <http://www.npolicy.org/userfiles/file/Nuclear%20Heuristics-Spreading%20the%20Bomb%20without%20Quite%20Breaking%20the%20Rules.pdf>.

52. Based on GC-859 database. John Scaglione and Kaushik Banerjee, Oak Ridge National Laboratory. Figure used with permission.

ment to no more than 5.0%, fuel burnups will not be greater than about 58,000 MWD/Te.

Romania has published the burnup of the fuel discharged during about eight years of operation (approximately 40,000 fuel bundles) of its natural uranium fueled, heavy water moderated CANDU 6 reactor at Cernavoda.⁵³ Though the average fuel achieved a burnup of 7,060 MWD/Te, over 5% of the fuel had a burnup of 4,300 MWD/Te or less.

Though these examples involved normal variation produced by reactor operation, it has implications for efforts by countries to deliberately produce low burnup fuel. It is sometimes said that any such effort in an LWR would be readily detected, with the implication that steps would be taken to stop it. However, the large variation in normal fuel burnup creates significant background noise that would make a deliberate effort more difficult to detect.

53. C. Zalog and N. Baraitaru, "Fission Product Inventory in CANDU Fuel," *Pressurized Heavy Water Reactor Fuel: Integrity, Performance and Advanced Concepts*, Proceeding of the Technical Meetings Held in Bucharest, September 2012, and in Mumbai, 8-11 April 2013, IAEA-TECDOC-CD-1751, International Atomic Energy Agency, Vienna, 2014, pp. 24-27.

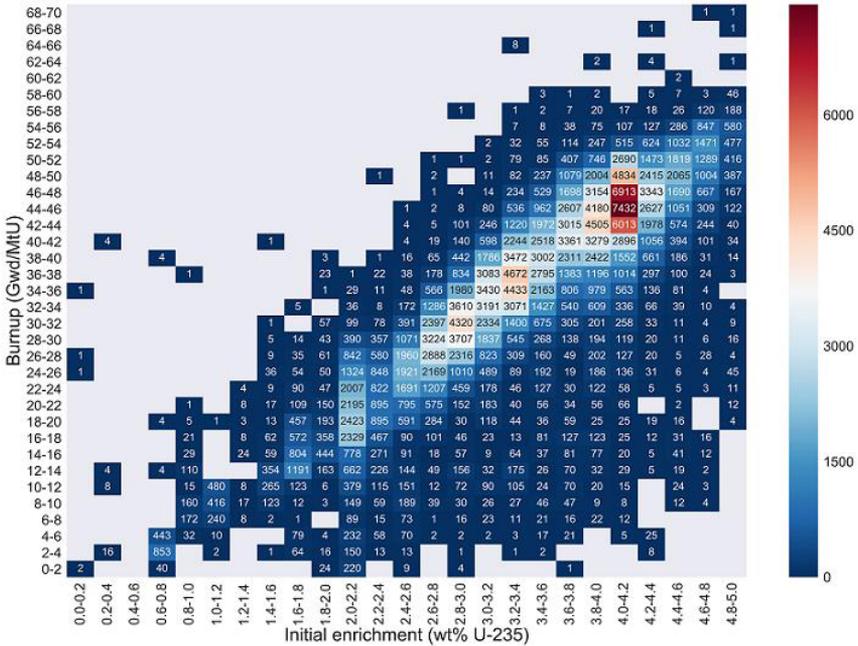


FIGURE 1: Initial Fuel Enrichment and Final Fuel Burnup 244,918 U.S. PWR and BWR Assemblies, 1968 to June 30, 2013, (Number of Fuel Assemblies)

In late 2012, Iran abruptly discharged all of the fuel from its Bushehr PWR. After some months the fuel was reinserted, but the reason for this discharge was never explained. As I have written elsewhere, Iran (or any country with a LWR) has the option of producing near weapon-grade plutonium by simply discharging the fuel in the outermost part of the reactor core after just one irradiation cycle instead of the normal three.⁵⁴ The country could cite safety

54. 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>.

concerns as the reason for the early discharge. Since countries such as Iran plan to produce their own reactor fuel, it would not be hard for them to deliberately introduce flaws into the fuel that they produce so that early discharge would be required.

It is sometimes said that to use a power reactor in this manner would be uneconomical but there is no prohibition against operating a nuclear power reactor in an uneconomical fashion. After all, it is universally acknowledged that the use of plutonium containing fuels in LWRs (mixed oxide fuel, MOX) is uneconomic but the practice continues in countries such as France and Japan. Therefore, even if the International Atomic Energy Agency (IAEA) were to detect the production of low burnup fuel at a nuclear power reactor, it would have no basis for taking any action to prevent it.

Characteristics of Plutonium Produced in Different Reactor Fuels

The spontaneous fission neutron output and the decay heat of plutonium can vary considerably depending on the starting enrichment and the burnup of the fuel that produces it. These factors are generally determined by the type of reactor that produces the plutonium. This section will present the characteristics of different types of plutonium.

Table 2 gives the characteristics of highly enriched uranium (HEU), neptunium, and americium 241 which can also be used to produce nuclear weapons. From the point of view of spontaneous fission neutrons and decay heat, HEU is the best nuclear material for manufacturing nuclear weapons.

Pure neptunium might produce spontaneous fission neutrons at a rate even lower than that of HEU but neptunium is likely to have plutonium impurities. Using reported values for a six kilogram neptunium metal sphere, the spontaneous fission neutron output from neptuni-

um is over 60 times larger than that of HEU.⁵⁵ As we will see, this value is far less than that of any grade of plutonium but is over three times larger than that of pure Pu-239. Therefore, it is doubtful that neptunium could be used in gun-type nuclear weapons though it could be easily used in implosion type weapons. Due to its shorter half-life, neptunium's decay heat is about 100 times that of HEU, though again this is far less than any grade of plutonium.

The spontaneous fission neutron production of Am-241 is significantly higher than that of either HEU or neptunium, but it is less than that of any grade of plutonium. Americium's decay heat is very large, larger than that of any grade of plutonium. Therefore, the fact that the United States has said that americium can be used to produce nuclear weapons immediately throws doubt on the claim that plutonium with high heat decay cannot be used in nuclear weapons.⁵⁶

Material	Spontaneous Fission Neutrons (neutrons per gram-seconds)	Decay Heat (watts per kilogram)
94% enriched HEU	1.1×10^{-3}	2.7×10^{-4}
Np with Pu impurities	6.9×10^{-2}	2.9×10^{-2}
Am-241	1.2	114

TABLE 2: Spontaneous Fission Neutrons and Decay Heat of HEU, Neptunium, and Americium

55. Rene G. Sanchez, et. al., "Criticality of a ^{237}Np Sphere," Proc. 7th Int. Conf. on Nuclear Criticality Safety, ICNC 2003, Tokai-Mura, Japan, October 20-24, 2004.

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

Table 3 gives the characteristics for three different types of weapon-grade plutonium. Plutonium that is only 2.0% Pu-240 was used by the United States for nuclear weapons in the mid-to-late 1940s. Plutonium that is 6.0% Pu-240 is the standard weapon-grade plutonium that is currently used by the United States. Plutonium that is 9.0% Pu-240 represents a high value that has sometimes been suggested as being weapon-grade and is higher than the current U.S. definition of weapon-grade plutonium.

The spontaneous fission neutron output from these three different types of plutonium is directly proportional to their Pu-240 content. Even plutonium with just 2.0% Pu-240 has a spontaneous fission neutron output that is nearly 1,000 times that of pure Pu-239. The decay heat production increases only slightly as the Pu-240 content increases. For all three types of plutonium the concentrations of Pu-238 and Pu-242 are not given since they are less than 0.1 percent.

Pu-239%	Pu-240%	Pu-241%	Spontaneous Fission Neutrons (neutrons per gram-seconds)	Decay Heat (watts per kilogram)
97.9	2.0	0.1	18	2.0
93.4	6.0	0.6	55	2.2
89.9	9.0	1.1	82	2.4

TABLE 3: Spontaneous Fission Neutrons and Decay Heat of Weapon-Grade Plutonium

Table 4 gives the characteristics for plutonium that is produced in natural uranium fueled power reactors.⁵⁷ The average fuel burnup for CANDU 6 reactors (Canada's standard export model) in Romania and South Korea is about 7,000 MWD/Te.⁵⁸ However, at the Romanian CANDU 6 reactor at Cernavoda about 5.4% of the fuel had a burnup of about 4,300 MWD/Te or less. The characteristics of the plutonium produced by this lower burnup fuel are presented as well. CANDU 6 reactors are used in China, South Korea, Argentina, and Romania.

For gas-cooled graphite moderated power reactors which were once common in the UK and France and also employed in Italy, Spain, and Japan, I use the characteristics of the plutonium produced by British MAGNOX reactors. Full burnup was about 5,000 MWD/Te and low burnup, which was common when these reactors first started operation, was 3,000 MWD/Te. There are no longer any gas-cooled graphite moderated power reactors using natural uranium fuel in operation but these reactors produced large quantities of plutonium. In particular, roughly 75 metric tons of the UK's massive plutonium stockpile (about 106 metric tons) was produced in this type of reactor.

57. For CANDU reactors see: M.S. Milgram & K.N. Sly, "Tables of the Isotopic Composition of Transuranium Elements Produced in Canadian D₂O Moderated Reactors," *Atomic Energy of Canada Limited*, AECL-5904, Chalk River Nuclear Laboratories, Chalk River, Ontario, August 1977. For MAGNOX see: "NDA Plutonium Options," *Nuclear Decommissioning Authority*, UK, 2008.

58. C. Zalog and N. Baraitaru, "Fission Product Inventory in CANDU Fuel," *Pressurized Heavy Water Reactor Fuel: Integrity, Performance and Advanced Concepts*, Proceeding of the Technical Meetings Held in Bucharest, 24-27 September 2012, and in Mumbai, 8-11 April 2013, IAEA-TECDOC-CD-1751, International Atomic Energy Agency, Vienna, 2014 and Dong-Keun Cho et al., "Current Status and Characterization of CANDU Spent Fuel for Geological Disposal System Design," *Journal of the Korean Radioactive Waste Society* 6, no. 2, June 2008.

As can be seen from Table 4, the spontaneous fission neutrons produced by plutonium from natural uranium fueled reactors can be three to five times greater than 6% Pu-240 weapon-grade plutonium. However, the increase in decay heat is far less, being only about 30% to 60% higher. Even in normal operation some of the plutonium produced by these reactors is fuel-grade and not reactor-grade. Of course, these reactors could be operated to intentionally produce weapon-grade 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)
CANDU 7,000	0.07	69.2	26.4	3.0	1.3	264	3.6
CANDU 4,300	0.03	79.4	18.4	1.7	0.4	175	3.0
MAGNOX 5,000	<0.1	69.9	25.5	3.4	1.2	254	3.6
MAGNOX 3,000	<0.1	80.8	17.1	1.7	0.3	161	2.9

TABLE 4: Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced in Natural Uranium Fueled Power Reactors (Ten Years After Discharge)

Table 5 presents the characteristics of plutonium produced in power reactors that use enriched uranium fuel. The first entry in the table is for the British Advanced Gas-Cooled Reactors (AGR). This reactor uses 2.5% enriched uranium fuel and achieves a burnup of about 18,000 MWD/Te. These reactors only operate in the UK but the Russian RBMK reactors are similar in fuel enrichment and burnup.

The remainder of the entries in the table are for Pressurized Water Reactors (PWRs).⁵⁹ From the 1970s until into the 1990s, the standard burnup was about 33,000 MWD/Te with a starting enrichment of 3.2%. More recently, there has been a trend to use higher enrichments to achieve higher burnups. For example, burnups of 51,000 MWD/Te can be achieved with a starting enrichment of 4.3%. Note that the current nuclear infrastructure will not permit the use of starting enrichments of greater than 5%, which will limit the trend to higher burnups.

As was the case with natural uranium fueled reactors, not all of the fuel reaches full burnup. For example, of the PWR fuel from 1968 to mid-2013 that had an initial enrichment of 3.2%, two percent reached burnups of 20,000 MWD/Te or less.

When PWRs first start operation, they typically use some fuel whose enrichment is significantly less than its equilibrium fuel enrichment. This fuel is irradiated for only one cycle and then discharged. For example, at Iran's Bushehr power reactor, its equi-

59. For the first entry see: "NDA Plutonium Options," Nuclear Decommissioning Authority, UK, 2008. The second and third table entries are from: Brent Dixon & Roald Wigeland, "The Impact of Burnup on the Performance of Alternative Fuel Cycles," GNEP-SYSA-AI-NE-RT-2008-000252, April 28, 2008. The fourth table entry is from an Origen 2 run I performed. The last two entries are from 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>.

librium fuel enrichment is 3.6% but its first core discharge in early 2014 had an enrichment of just 1.6%. As I have written elsewhere, the Iranians recently published data on the plutonium produced in this first discharge fuel.⁶⁰

Even after a LWR has been in operation for some time it would not be hard to produce plutonium that was not reactor-grade. Fresh fuel is placed into the outermost part of the core. After one fuel cycle (typically one year or one-and-one-half years) this fuel is shuffled into the inner part of the core where it remains for two more fuel cycles. However, this fuel could be discharged instead with the country citing some sort of safety concern. Iran has published data on the isotopic composition of this fuel after one fuel cycle.⁶¹

As can be seen from Table 5, the spontaneous fission neutron production of plutonium from full burnup PWR spent fuel can be even higher than that from full burnup natural uranium fuel. For a given starting fuel enrichment, the neutron output is roughly linear with burnup. A more dramatic difference between plutonium produced in PWR fuel and natural uranium fuel is the decay heat, which depends mainly on the Pu-238 content. The trend to higher initial fuel enrichment and higher design burnup has led the plutonium's decay heat to rise substantially. For full burnup PWR fuel the decay heat is roughly four and one half times to eight times that of 6% Pu-240 weapon-grade plutonium.

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

61. Ibid.

Reactor Type, Initial Enrichment 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)
AGR 2.5% 18,000	0.6	55.8	32.0	6.3	5.2	395	6.9
PWR 3.2% 33,000	1.3	58.8	25.9	8.7	5.4	361	10.4
PWR 4.3% 51,000	2.6	54.3	25.8	9.7	7.6	432	17.8
PWR 3.2% 20,000	0.6	69.8	20.6	6.9	2.2	240	6.4
PWR 1.6% 1st Discharge	0.1	77.8	18.1	3.5	0.5	176	3.4
PWR 3.6% One Cycle	0.2	85.4	11.9	2.3	0.2	117	3.6

TABLE 5: Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced in Reactors Using Enriched Uranium Fuel (Ten Years After Discharge)

But the factors that produce this increased plutonium decay heat cut both ways. Decay heat is significantly reduced for PWR fuel that does not achieve full burnup. The plutonium produced from first discharge spent fuel from modern PWRs is not even reactor-

grade but rather fuel-grade. Its decay heat is only about 50% higher than that of 6% Pu-240 weapon-grade plutonium and similar to the plutonium produced in natural uranium fueled reactors. For fuel that is kept in a PWR for only one fuel cycle in the outermost part of the core, the spontaneous fission neutron production is only about twice that of 6.0% Pu-240 weapon-grade plutonium. If the fuel were kept in the reactor for about six months, the plutonium produced would be weapon-grade.

For plutonium produced by AGRs, the spontaneous fission neutron production is similar to that of plutonium produced by full burnup in a PWR but the decay heat is significantly less. It is only about three times that of 6.0% Pu-240 weapon-grade plutonium.

As was discussed above, the half-lives of Pu-238 and Pu-241 are short enough that the composition of the plutonium changes if it is stored for decades. Table 6 shows the characteristics of PWR fuel with an initial enrichment of 3.2% and a full burnup of 33,000 MWD/TE, which was typical for fuel discharged from the 1970s into the 1990s, as it decays for a period of decades. Initially the percentage of Pu-241 declines rapidly, which greatly reduces the radiation from the plutonium. It also causes the percentage of Pu-239, Pu 240, and Pu-242 to increase (since the total of the percentages must always be 100) which results in the spontaneous fission neutron output gradually rising for the first 40 or 50 years. The decay heat steadily declines due to the loss of Pu-241 and Pu-238.

Countries do not report the age of their plutonium, but Japan's large 37 metric ton plutonium stockpile in the UK and France must be 20 to 45 years old since Japan sent this spent fuel to these countries between 1973 and 1998.⁶² When this plutonium becomes 50 years of age, its spontaneous fission neutron output would be 6% larger

62. Y. Nomura and F. Kunugita, "Spent Fuel Management in Japan," IAEA-SM-352/10, 1998.

and its decay heat as 15% smaller than the same plutonium that had decayed for only 10 years.

Time After Discharge	Pu-238%	Pu-239%	Pu-240%	Pu-241%	Pu-242%	Spontaneous Fission Neutrons (neutron per gram-seconds)	Decay Heat (watts per kilogram)
10 years	1.3	58.7	25.9	8.7	5.4	361	10.4
20 years	1.2	60.8	26.8	5.5	5.6	371	10.0
30 years	1.2	62.3	27.3	3.5	5.7	375	9.7
40 years	1.1	63.1	27.8	2.2	5.8	380	9.3
50 years	1.0	63.7	28.0	1.3	5.9	381	8.8
100 years	0.7	64.9	28.3	0.1	6.0	377	7.0
200 years	0.3	65.3	28.3	0	6.1	370	5.0
300 years	0.1	65.6	28.2	0	6.1	364	3.9

TABLE 6: Spontaneous Fission Neutrons and Decay Heat of Plutonium from PWR Spent Fuel, Initial Fuel Enrichment 3.2%, Burnup 33,000 MWD/Te, After Lengthy Storage

For boiling water reactors (BWRs), the properties of the plutonium are similar to that of PWRs for the same initial fuel enrichment and burnup. However, the technical characteristics of BWRs are such that the initial fuel enrichment and burnup are a little less than that of PWRs and therefore the spontaneous fission neutron production and decay heat are also a little less.

Table 7 shows the characteristics of plutonium that is produced by reprocessing and recycling LWR-produced plutonium and uranium back into LWRs. The plutonium that is recovered from spent fuel can be mixed with depleted uranium to produce new fuel for an LWR. Since this fuel is a mixture of plutonium and uranium oxides, it is known as mixed oxide fuel (MOX). Due to the fact that only the Pu-239 and Pu-241 readily fission in an LWR this fuel must be 10% plutonium to produce a burnup of 51,000 MWD/Te.⁶³ The plutonium that is produced in this MOX fuel has about ten times the spontaneous fission neutron production and decay heat as that of 6% Pu-240 weapon-grade plutonium.

63. G. Youinou, & S. Bays, "A Neutronic Analysis of TRU Recycling in PWRs Loaded with MOX-UE Fuel (MOX with U-235 Enriched Support)," AFCI-SY-SA-TRAN-SS-RT-2009-000055, Idaho National Laboratory, U.S. Department of Energy, May 2009, p. 40.

Fuel 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)
10% Pu MOX 51,000	3.3	41.3	33.0	10.7	11.6	583	22.0
Reenriched U (2.62% U-236) 46,300	6.3	61.5	19.4	8.8	4.0	408	38.1

TABLE 7: Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced by Recycling, (Ten Years After Discharge)

The uranium that is recovered from reprocessed LWR spent fuel can be reenriched and used to fuel a LWR. This uranium is contaminated by U-236 and its concentration is further increased by the reenrichment. Using an extreme case where the reenriched uranium is 5.0% U-235, it could contain as much as 2.42% U-236.⁶⁴ Plutonium produced by such reenriched uranium would not have a spontaneous fission neutron production any higher than that of high burnup PWR fuel using uranium that did not contain any U-236. However, due to the large amount of Pu-238 produced, the decay heat is about double that of ordinary high burnup PWR fuel and about seventeen times that of 6% Pu-240 weapon-grade plutonium.

It should be noted that while both MOX fuel and fuel using reenriched uranium are being used to a limited extent in countries such

64. Kosaku Fukuda, et. al., "Feasibility of Reprocessed Uranium in LWR Fuel Cycle for Protected Plutonium Production," *Journal of Nuclear Science and Technology* 45, no. 10, October 2008.

as France, very little of the spent fuel produced is being reprocessed. The undesirable characteristics of the plutonium produced from such fuel from the point of view of nuclear weapons production are also undesirable characteristics from the point of view of reusing this plutonium as reactor fuel. Indeed it has been reported that on those rare occasions when such fuel is reprocessed, it must be mixed with enriched uranium spent fuel in order to dilute the recovered plutonium.⁶⁵ As a result, it is likely that none of the plutonium, which has characteristics similar to that shown in Table 6, exists in separated form. Given the abundance of plutonium that has already been separated from uranium spent fuel, it is not likely that much of this very hot plutonium will be separated in the future either even though proponents of the concept of denatured plutonium often tout its supposed “proliferation-resistant” characteristics.

Various schemes have been proposed to produce plutonium with large concentrations of Pu-238 by adding either neptunium or americium to the fresh uranium fuel. However, due to the unfavorable economics of such schemes, no such plutonium exists, nor is it likely to.

In sum, the spontaneous fission neutron production and decay heat of even weapon-grade plutonium is far higher than that of HEU, yet plutonium can still be used to produce nuclear weapons. The plutonium produced in natural uranium fueled power reactors has a significantly higher spontaneous fission neutron production than does weapon-grade plutonium but its decay heat is only 30% to 60% higher. Plutonium produced in full burnup PWRs has both significantly higher spontaneous fission neutron production and decay heat compared to weapon-grade plutonium. Both natural uranium fueled reactors and PWRs routinely discharge fuel at less than full burnup

65. Mary Byrd Davis, “The La Hague Reprocessing Plant: Basic Facts, Infrastructure, Contracts and Products,” *EcoPerspectives*, Lexington, KY., October 2009.

which reduces both the spontaneous fission neutron production and the decay heat of the plutonium in such fuel. The plutonium produced by the irradiation of MOX fuel and reenriched uranium fuel has the highest spontaneous fission neutron production and/or the highest decay heat. Very little if any of this plutonium exists in separated form, yet even if it did, as will be discussed in later chapters, it can be used to produce nuclear weapons.