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The Myth of "Denatured" Plutonium
Reactor-Grade Plutonium and Nuclear Weapons

Part One:
Introduction, Plutonium Basics, Definitions of Grades of Plutonium, Variation in Fuel Burnup and the Properties of Plutonium Produced in Different Reactor Fuels

Introduction

In 1993, UK Foreign Minister Lady Chalker, attempting to reassure the British House of Lords regarding concerns that British commercial reprocessing activities would lead it to export plutonium to nonnuclear weapon states said that reactor-grade plutonium was "not suitable" for nuclear weapons.[2] However, ten days later the British Foreign Office had to retract this statement, saying that Lady Chalker had been "improvising."

In fact the U.S. had revealed in the 1976 that the plutonium produced by nuclear power reactors, "reactor-grade plutonium," can be used even in the most primitive nuclear weapon design to produce powerful nuclear explosives. From the above incident it is clear that the UK concurs with the U.S. assessment. Indeed, it is known but not widely recognized that both Pakistan and Sweden at one time based their nuclear weapons programs on reactor-grade plutonium.

Yet many in the nuclear industry even today continue to claim, as Lady Chalker did, that reactor-grade plutonium is not suitable for nuclear weapons. Using a term originally used for alcohol, they sometimes say that plutonium can be "denatured." These claims are usually based on two properties of reactor-grade plutonium--its high spontaneous fission neutron rate which could lead a weapon to predetonate, reducing its yield and, for reactor-grade plutonium which is produced by high burnup in light-water reactors (LWRs), its high decay heat which potentially could pose a threat to a weapon's operability.

Remarkably, U.S. administration officials, including President Obama himself, have used some of these mistaken beliefs as a basis for a portion of the July 2015 Iran nuclear deal. The deal contains a provision that restricts Iran's Arak nuclear reactor from producing weapon-grade plutonium in normal operation. The nuclear deal intends for the reactor to produce fuel-grade plutonium instead (for the definition of the different grades of plutonium see below). President Obama, in defending the Iran nuclear deal has claimed that weapon-grade plutonium is *necessary* to produce a nuclear weapon, even though it is well-known that fuel-grade plutonium can be used to produce nuclear weapons—something that even the nuclear industry does not dispute.[3]

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[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] Geoffrey Lean, "DIY Atom Bomb Link to Sellafield," *The Observer*, June 6, 1993, p.3.

[3] For example, he has said: "Because of this deal, Iran will not produce the highly enriched uranium and weapons-grade plutonium that form the raw materials *necessary* for a nuclear bomb."[Emphasis added] "Read President Obama's Remarks on Iran Nuclear Deal," *Time*, July 14, 2015.

Though parts of the U.S. Department of Energy know that the President's statements are false, they have apparently decided to stay silent so as to not contradict the boss.

I was part of the research team led by Albert Wohlstetter that in 1976 forced the U.S. government to publically acknowledge for the first time the nuclear weapon dangers of reactor-grade plutonium. In 1977 the U.S. government went further and revealed that in 1962 it had successfully tested a nuclear weapon using reactor-grade plutonium. The nuclear industry has repeatedly claimed that this 1962 nuclear test used only fuel-grade plutonium not reactor-grade. In 2013 I refuted this claim and demonstrated that the plutonium was indeed reactor-grade.[4]

This paper is the first of a series that will comprehensively examine the nuclear weapon dangers posed by reactor-grade plutonium. This paper 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.

In future papers I will examine a variety of topic related to reactor-grade plutonium including (1) how the problems posed by the increased spontaneous fission neutrons and decay heat of reactor-grade plutonium can be circumvented to produce nuclear weapons; (2) additional issues sometimes cited as preventing the use of reactor-grade plutonium in weapons including its increased penetrating gamma radiation and its increased critical mass; (3) a short history of the concerns regarding reactor-grade plutonium as well as the aspirations of the nuclear industry that make it so keen to claim that reactor-grade plutonium does not pose any dangers; (4) a brief histories of the role reactor-grade plutonium played in the nuclear weapon programs of Pakistan and Sweden; and (5) examine the claim that in the early 1950s the UK tested reactor-grade plutonium and found it unsatisfactory.

Plutonium Basics

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 = Pu-241 + n = 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.

[4] Gregory S. Jones, "What was the Pu-240 Content of the Plutonium Used in the U.S. 1962 Nuclear Test of Reactor-Grade Plutonium?," May 6, 2013, http://www.npolicy.org/article.php?aid=1212&rid=3

An additional plutonium isotope (Pu-238) is produced 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 U-235 + n = U-236 + n = U-237 (half-life 6.8 days) decays to Np-237 + n = 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.[5] 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.

Table 1

Some Characteristics of Plutonium Isotopes

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

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 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 several percent 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.[6] 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 a later paper.

[5] J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4, 1993, p.115.
[6] Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project," December 16, 2015 Link

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 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 a later paper.

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 a mainly 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 U.S. 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 weapon. Further, since the radiation is from Pu-241 decay products and not the Pu-241 itself, by 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 a later paper.

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 the 1970s, 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 U.S. 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.[7] A few comments are in order about these definitions.

As I have written, weapon-grade plutonium has not always been defined in this way.[8] 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

[7] *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, p.17.
[8] Gregory S. Jones, "The History of the Pu 240 Content of U.S. Weapon-Grade Plutonium," May 4, 2016, Link

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 U.S. 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 that I have been able to find was 1964.[9] The earliest use of the term fuel-grade that I have been able to find is 1969.[10]

Though the U.S. 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.[11] 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 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 type of reactor and the fuel's initial enrichment. However over forty years ago I found that power reactors can discharge spent fuel with far less than the expected full burnup.[12] 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.

The U.S. Department of Energy has published the initial fuel enrichment and fuel burnup of all pressurized water reactor (PWR) fuel discharged in the U.S. between 1975 and 2002, which constitutes a total of 70,128 fuel elements.[13] 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 5% 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.

[9] R. L. Dickeman, "Outline: N-Reactor Capability Report," HW-83877 RD, September 1, 1964.
[10] "Douglas United Nuclear, Monthly Report," DUN-5611, May 1969, p.BN-1.
[11] "Plutonium and Aldermaston-An Historical Account," UK Ministry of Defense, 2000.
[12] 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.
[13] C.V. Parks, *et.al.*, "Annual Progress Report—Data and Analysis for Spent Nuclear Fuel Transport and Storage in Burnup Credit Casks," Oak Ridge National Laboratory, November 29, 2005.

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.[14] 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.

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.[15] The country could cite safety 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 241which 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.

[14] C. Zalog and N. Baraitaru, "Fission Product Inventory in CANDU Fuel," *Pressurized Heavy Water Reactor Fuel: Inteegrity, 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.

[15] Gregory S. Jones, "Iran's Bushehr Nuclear Power Reactor: A Potential Source of Plutonium for Nuclear Weapons," March 24, 2016, Link

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 neptunium is over sixty times larger than that of HEU.[16] 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.

Table 2

Spontaneous Fission Neutrons and Decay Heat of HEU, Neptunium and Americium

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

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 U.S. 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.[17]

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 U.S. 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 U.S. 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.

[16] 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.
[17] David Albright and Kimberly Kramer, "Neptunium 237 and Americium: World Inventories and Proliferation Concerns, June 10, 2005, revised August 22, 2005.

Table 3

Spontaneous Fission Neutrons and Decay Heat of Weapon-Grade Plutonium

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 4 gives the characteristics for plutonium that is produced in natural uranium fueled power reactors.[18] For full burnup fuel from a heavy water CANDU reactor, I used a burnup of 7,060 MWD/Te which is the average achieved at the Romanian CANDU 6 reactor at Cernavoda.[19] However, at this reactor 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 used 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 much of the UK's massive plutonium stockpile (over 90 metric tons) was produced in this type of reactor.

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.

[18] For CANDU reactors see: M.S. Milgram & K.N. Sly, "Tables of the Isotopic Composition of Transuranium Elements Produced in Canadian D_2O Moderated Reactors," Atomic Energy of Canada Limited, AECL-5904, Chalk River Nuclear Laboratories, Chalk River, Ontario, August 1977. For MAGNOX see: World Nuclear Association—Plutonium Link

[19] C. Zalog and N. Baraitaru, "Fission Product Inventory in CANDU Fuel," *Pressurized Heavy Water Reactor Fuel: Inteegrity, 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.

Table 4

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

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 7,060	0.07	69.0	26.5	3.1	1.3	265	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 5 presents the characteristics of plutonium produced in Pressurized Water Reactors (PWRs).[20] 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 1975 to 2002 that had an initial enrichment of 3.2%, 5% of it reached burnups of 20,000 MWD/Te or less.[21]

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 equilibrium fuel enrichment is 3.6% but its first core discharge in early 2014 had an enrichment of just 1.6% As I have written

[20] The first two 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 third table entry is from an Origen 2 run. 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, Link

[21] C.V. Parks, *et.al.*, Annual Progress Report—Data and Analysis for Spent Nuclear Fuel Transport and Storage in Burnup Credit Casks," Oak Ridge National Laboratory, November 29, 2005.

elsewhere, the Iranians recently published data on the plutonium produced in this first discharge fuel.[22]

Table 5

Spontaneous Fission Neutrons and Decay Heat of Plutonium Produced in PWRs (Ten Years After Discharge)

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)
3.2% 33,000	1.3	58.8	25.9	8.7	5.4	361	10.5
4.3% 51,000	2.6	54.3	25.8	9.7	7.6	432	17.8
3.2% 20.000	0.6	66.9	19.8	10.7	2.1	232	6.4
1.6% 1st Discharge	0.1	77.8	18.1	3.5	0.5	176	3.4
3.6% One Cycle	0.2	85.4	11.9	2.3	0.2	117	3.6

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.[23]

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, 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.

[22] Gregory S. Jones, "Iran's Bushehr Nuclear Power Reactor: A Potential Source of Plutonium for Nuclear Weapons," March 24, 2016, Link
[23] *Ibid.*

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 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 6 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.[24] 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.

Table 6

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

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

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

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.[25] 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 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. As a result almost none of the plutonium, which has characteristics similar to that shown in Table 6, exists in separated form.

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 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. Yet as will be discussed in later papers, even this plutonium can be used to produce nuclear weapons.

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