"Benefiting from his decades-long research and analysis of publicly available, non-classified information, Jones seeks to debunk a long-standing myth that reactor-grade plutonium cannot be used for nuclear weapons".

– Olli Heinonen, former Deputy Director-General for Safeguards at the International Atomic Energy Agency

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Gregory S. Jones

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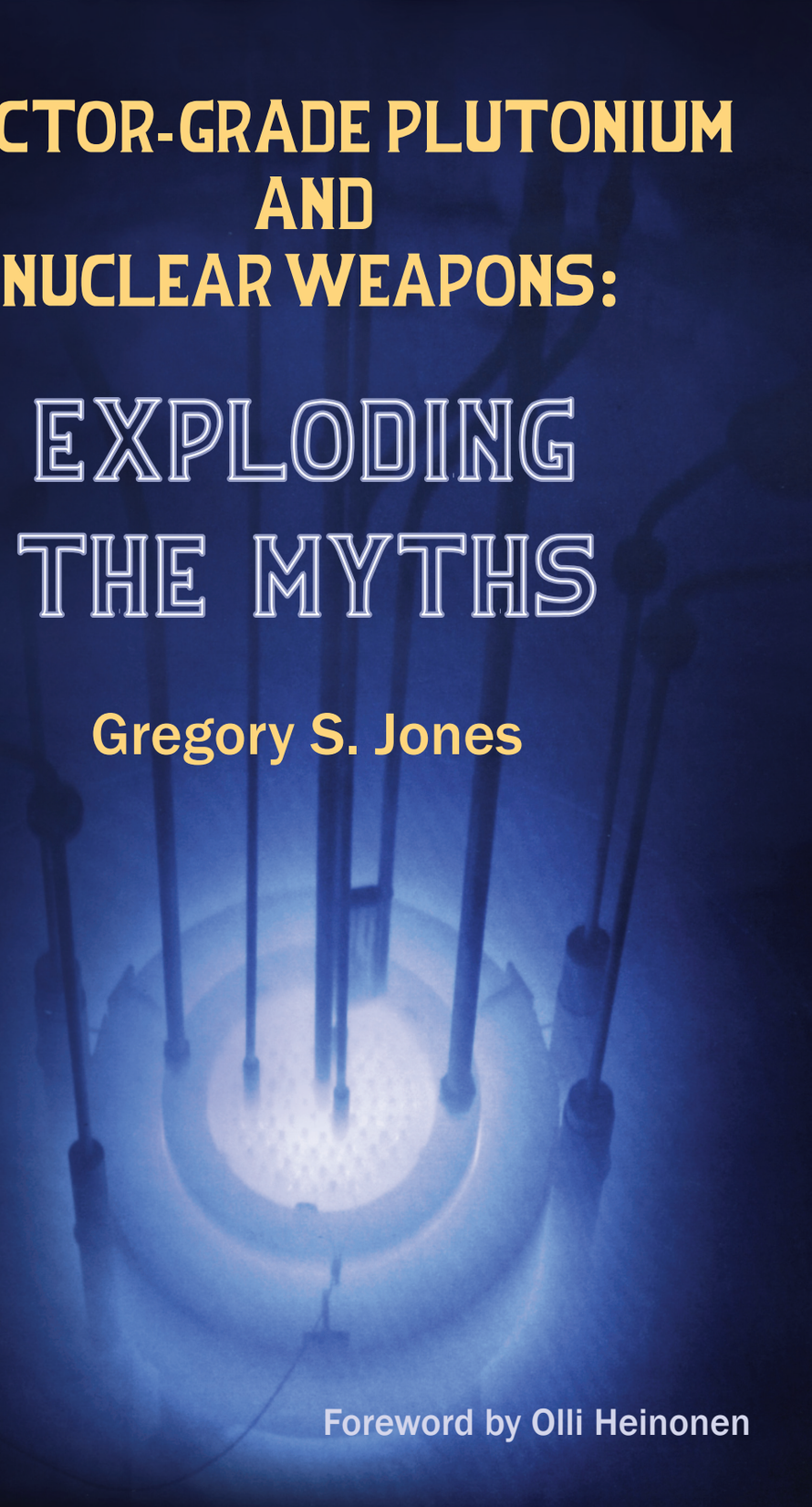

Foreword by Olli Heinonen

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By

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Foreword

Harold S. Green, a former CEO of International Telephone & Telegraph (ITT), put it well when he said "We must not be hampered by yesterday's myths in concentrating (on) today's needs." In this book, benefiting from his decades-long research and analysis of publicly available, non-classified information, Jones seeks to debunk a long-standing myth that reactor-grade plutonium cannot be used—with certain limitations—for nuclear weapons.

This report provides a timely re-think for a number of reasons. Should nuclear developments in Northeast Asia or in the Middle East go in a wrong direction, we may come to witness a new type of nuclear race, based on existing large stocks of spent fuel containing plutonium which can be used in a fairly short time for nuclear weapons, if national security circumstances so warrant. Current states with nuclear weapons have traditionally produced their stocks using dedicated plutonium production reactors and used plutonium with more than 93% isotope plutonium-239, weapon-grade plutonium. Plutonium, that has more than 7% isotope plutonium-240, or reactor-grade plutonium, is not deemed suitable for nuclear weapons due to heating or nuclear pre-detonation possibilities caused by the plutonium-240.

Jones persuasively argues that today's weapon material potential can no longer be viewed as a stark distinction between having usable weapon-grade plutonium or un-usable reactor-grade plutonium. Rather, faced with a lack of weapons grade material, states bent on seeking nuclear weapons that already possess reactor-grade plutonium may view its choices differently.

According to the latest IAEA Nuclear Technology Review, there are 447 operational nuclear power reactors in 30 countries, and another 60 reactors are in construction—many of them in regions with political turmoil and long-term instability. The World Nuclear Association estimated that at the end of 2014 the global stock of spent fuel was 371,000 tonnes of heavy metal (t HM). This spent fuel contains the order of 400 tons of plutonium. The stocks of spent fuel have been estimated to increase about 12,000 tHM annually. In addition, there is highly enriched uranium and already separated plutonium in military and civilian fissile material stocks. The International Panel on Fissile Material estimated in January 2017 that the global stocks were 1,340 tons of highly enriched uranium, 230 tons of military plutonium, and 290 tons of separated plutonium in civilian custody.[1] It can be assumed that most of the latter is reactor-grade plutonium. This stock is sufficient, using the IAEA definition for a significant quantity, for the manufacture of 36,000 nuclear weapons. In addition, plutonium accumulated currently as spent fuel has a calculated potential for at least another 55,000 nuclear devices.

Jones points to the disquieting fact that there is a way to design a reactor-grade plutonium nuclear device that would have a yield of 5 kilotons that could technically mitigate the physical constraints otherwise caused by some of the plutonium isotopes. Such a device may not cause a Hiroshima like devastation to an adversary, but is certainly sufficient to cause tremendous damage—and for that reason—also has a lower threshold in use.

If such a hedging option is selected by a state that has spent fuel or separated plutonium under safeguards, is the IAEA equipped to monitor spent fuel and provide timely warning to states with the current safeguards agreement in force?

1. International Panel on Fissile Material, "Fissile Material Stocks," accessed on February 13, 2018, available from http://fissilematerials.org/.

On the first question, the good news is that IAEA safeguards do not differentiate plutonium based on its isotopic composition. Since the dawn of IAEA safeguards, the IAEA Board of Governors has used as a definition for nuclear material as any source and/or special fissionable material as defined in Article XX of the Statute. Accordingly, any plutonium that has plutonium-239 is subject to safeguards.

At the same time, the IAEA reviews at regular intervals its inspection parameters including definitions. There have been suggestions in the past to split plutonium to weapon grade and reactor-grade plutonium. Advocates for such the split have argued that reactor-grade plutonium is not suitable for nuclear weapons, and that the IAEA spends unnecessary resources to safeguard plutonium that is not a proliferation risk. However, based on consultations with nuclear weapons states, the IAEA Secretariat has not seen it prudent to do so. In other words, the IAEA and its Board of Governors have tacitly acknowledged that reactor grade plutonium can be used to manufacture a nuclear weapon.

But there are also civilian plutonium and spent fuel stocks in states with nuclear weapons that are not monitored by the IAEA. The amount of spent fuel in storage subject to the IAEA safeguards was estimated to have reached 273,000 t HM by the end of 2016 and it is increasing at a rate of 7,000 tons/year. In other words, every year, an additional 70 tons of plutonium is accumulated in newly produced spent fuel. This means that two-thirds of the global spent fuel stocks are covered by the IAEA verification system. Out of 270 tons of civilian plutonium in 2015, only 98.6 tons of plutonium were subject to the IAEA verification.

Most of the plutonium exists today in states that have nuclear weapons, which—at this stage—have sufficient amounts of weapon grade material stocked for their arsenals. If and when nuclear disarmament proceeds, tapping reactor grade plutonium may become attractive. Thus it is important in future disarmament agreements, such as the Fissile Material Cut-off Treaty (FMCT), to include all plutonium

regardless of its origin subject to the treaties to be negotiated.

As to the second question of whether the IAEA verification regime is fit to provide sufficient early warning should a state decide to divert plutonium from existing stock for nuclear weapons, there are two basic scenarios. One is for a state to have a declared program to extract plutonium for future use in a nuclear program to recycle it as fuel. With the current verification regime, reasonable assurances can be provided by the IAEA. The loophole here is that under the Non-Proliferation Treaty (NPT), a state can withdraw from the NPT using the supreme interest provision and use existing materials to produce nuclear weapons. This is what North Korea has done, and Jones proposes that the NPT Parties close this loophole.

Can a state produce nuclear weapons without the IAEA detecting it? Since the verification of spent fuel is a relatively straight forward process, such a development is not likely to go without detection. However, a state's breakout time can be reduced by conducting preliminary studies on plutonium metallurgy with small quantities of plutonium, as North Korea has likely done. North Korea has been able to go from its withdrawal from the NPT to conducting its first nuclear test in three years. Jones further correctly points out that plutonium extraction for the first few nuclear weapons can be carried out under less sophisticated reprocessing installations, which would, in turn, reduce break-out time and possibilities of detection, particularly in an isolated country. While the IAEA can detect with a high probability abrupt diversion of a significant amount of spent fuel from the stocks subject to safeguards, the Achilles heel is still in discovering a clandestine nuclear installation. As in the cases of the Al Kibar reactor in Syria or the Fordow enrichment plant in Iran, the international community had to rely to a great extent on intelligence information from member states, which have their own limitations.

In sum, reactor-grade plutonium poses a proliferation risk, and stocks of civilian separated plutonium and plutonium in spent fuel

should all be subject to international monitoring. It is also essential that the future arms control treaties like the FMCT subject all plutonium regardless of its isotopic composition to Treaty provisions. This book provides the necessary technical justification and considerations to make the case.

Olli Heinonen

Preface

The threat that non-nuclear weapon states could acquire nuclear weapons using commercial reactor-grade plutonium has been a focus of my work for almost my entire 44 year career. Though the United States first revealed the nuclear weapon potential of reactor-grade plutonium in 1976 and various other experts have repeatedly reinforced this point, a segment of the nuclear power industry determined to use plutonium as reactor fuel despite its highly uneconomical nature has continued to deny this fact. Over the past year, I published a series of papers on my website, http://www.proliferationmatters.com, which addressed the arguments from this segment of the nuclear industry. These papers demonstrate that reactor-grade plutonium can be used to produce nuclear weapons that would have a predetonation probability no higher than that of weapons using weapon-grade plutonium. The weapons using reactor-grade plutonium would be the exact same size and weight as weapons that used weapon-grade plutonium and they would require no special cooling. By coating the plutonium core with a thin layer of uranium, the gamma radiation would be significantly less than that of an unshielded weapon-grade plutonium core. For this book, I have put my series of papers together into a unified whole. I have added an introduction, chapters one and nine, refined and sharpened some of my analysis, and corrected some minor errors. Where there are differences between this book and my previous papers, the book should be taken as authoritative.

This book focuses on the production of nuclear weapons by nations not terrorists. Whether or not terrorists can produce nuclear weap-

ons is highly uncertain and not very dependent on the type of plutonium that they might attempt to use.

I am indebted to Henry Sokolski, the executive director of the Nonproliferation Policy Education Center, for not only facilitating the publication of this book but providing many useful comments on prior drafts.

I owe a special debt to my wife, Elsa, not only for her love and support through our many years of marriage but also for her careful reading and editing of this work.

This book 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 and a faculty member of the Pardee RAND Graduate School, this paper is not related to any RAND project or the Pardee RAND Graduate School and therefore these organizations should not be mentioned in relation to this book. I can be reached at *GregJones@proliferationmatters.com.*

Gregory S. Jones

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.[1] However, ten days later the British Foreign Office had to retract this statement, saying that Lady Chalker had been "improvising."

In fact, the United States had revealed in 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 and India may be using reactor-grade plutonium in some of its nuclear weapons today.

Yet many in the nuclear industry 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 spon-

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

taneous fission neutron production 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 could potentially pose a threat to a weapon's operability.

There are generally two variants of the view that reactor-grade plutonium is denatured. In the first view, reactor-grade plutonium is truly denatured and it is impossible for simple fission nuclear weapons to be manufactured from it. This view is usually applied to reactor-grade plutonium that is produced in LWRs and is attributed to the high heat of this plutonium. For example, Gunter Kessler, a retired nuclear scientist from the Karlsruhe Nuclear Research Center in Germany, has published a lengthy book on this subject. He says, "Limits were worked out above which the share of Pu-238 isotopes [sic] in plutonium renders the use in nuclear explosives technically impossible (proliferation proof)."[2]

In the second view, the proponents will admit that some sort of simple fission nuclear explosive can be produced from reactor-grade plutonium. However, in this view, this is only a technicality as the plutonium is seen as being de facto denatured. Due to the predetonation probability resulting from the high Pu-240 content, such weapons are often seen as "unreliable and unpredictable" as well as somehow being "hazardous" to the bomb makers.[3] Therefore, no country would actually use reactor-grade plutonium to produce a nuclear arsenal.

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2. G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles: Safeguards and Non-Proliferation*, KIT Scientific Publishing, 2011, preface, page unnumbered but page ten of the PDF file, available from https://www.ksp.kit.edu/9783866446144.

3. World Nuclear Association, "Plutonium," updated March 2017, available from http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx.

Sometimes the threat from the plutonium's radiation or the need to cool its core is mentioned as well. For example, Japan's Council for Nuclear Fuel Cycle has said, "If you are lavish of time and money, you will probably be able to build 'devices' that induce nuclear explosions even with reactor-grade plutonium; however, such devices will likely to be bulky ones equipped with secure radiation protection and cooling devices that are rarely found in general nuclear weapons."[4]

A related argument is the claim that no country has ever used reactor-grade plutonium to produce a nuclear explosion. Since the U.S. use of reactor-grade plutonium in a 1962 nuclear test contradicts this argument, many have incorrectly claimed that this test did not actually use reactor-grade plutonium.

Remarkably, officials in the prior U.S. administration, 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 Joint Comprehensive Plan of Action). 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 chapter three). 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.[5] Though parts of the U.S. Department

4. "No More Innocent Logic "Plutonium Equals to Nuclear Weapons,"" *Plutonium*, Spring 2016, no. 84, p. 2.

5. 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.

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 at Pan Heuristics led by Albert Wohlstetter that in 1976 forced the U.S. government to publicly 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. In 2013, I refuted the nuclear industry's claim that this test did not use reactor-grade.[6]

Certainly if one has the choice to produce nuclear weapons using either weapon-grade plutonium or reactor-grade plutonium, one would always choose weapon-grade plutonium. However, in countries such as Japan where plutonium is recycled as power reactor fuel, there is ready access to reactor-grade plutonium either in separated form or as unirradiated MOX fuel from which the plutonium can be easily separated. Weapon-grade plutonium may not be so easily available. Then the choice is not between reactor-grade plutonium and weapon-grade plutonium but rather between reactor-grade plutonium and no nuclear weapons at all. At one time in their nuclear weapon programs, both Sweden and Pakistan made this latter choice though for various reasons neither country would eventually produce nuclear weapons from reactor-grade plutonium. India may be using reactor-grade plutonium in its nuclear weapons program today.

Further, though some have argued that countries would never use an inferior nuclear material in nuclear weapons, it should be remembered that weapon-grade plutonium is an inferior nuclear material

6. 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, available from http://nuclearpolicy101.org/wp-content/uploads/2013/05/Reactor-grade-plutonium.pdf. See also chapter eight.

when compared to pure Pu-239. However, it is not easy to produce large quantities of this latter material and countries have found a way to make do with weapon-grade plutonium. Tens of thousands of nuclear weapons have been produced from this "inferior" nuclear material. Similarly, as will be shown in this book, it is possible to make do with reactor-grade plutonium and produce powerful nuclear weapons with a predetonation probability no higher than that of weapons manufactured using weapon-grade plutonium.

One reason why the nuclear weapons potential of reactor-grade plutonium has not been fully appreciated is that discussions focus only on nuclear weapons of the Nagasaki design. But this is completely unrealistic. No country today would use such a design as its first nuclear weapon. It is well known that the performance of unboosted fission weapons can be significantly improved by using levitation, i.e. putting an air gap into the weapon to increase the efficiency of the implosion weapon. As will be seen in chapter four, such technology can improve the assembly speed by up to a factor of three. The United States used such weapons in the early 1950's and even over 50 years ago, France and China used such weapons in their first nuclear tests.

In this book, I will show that reliable nuclear weapons can be manufactured using reactor-grade plutonium. Using early 1950s U.S. unboosted levitated fission weapon technology and modern high explosives, nuclear weapons can be manufactured with a predetonation probability no higher than that of weapon-grade plutonium by using the simple expedient of reducing the amount of plutonium used in the weapon. These weapons would be exactly the same size and weight as weapons using weapon-grade plutonium. The yield of such weapons would be about 5 kilotons and their lethal area about 40% of that of nominal 20 kiloton weapons.

Reducing the amount of plutonium in the weapon also makes the higher heat output of reactor-grade plutonium produced in LWRs

manageable as does the fact that the plutonium core can be kept separate from the weapon until shortly before use. The core would require no special cooling. Coating the plutonium core with just one half centimeter of uranium reduces the gamma radiation to significantly less than that from an unshielded weapon-grade plutonium core. Boosting technology, which is becoming more widely available, allows reactor-grade plutonium to be used in nuclear weapons to produce the same yield as weapon-grade plutonium without any risk of predetonation.

Chapter one looks at the issue of how the much easier access to reactor-grade plutonium provided by commercial nuclear power might lead a country to prefer to use this material to produce nuclear weapons. Chapter two provides a short history of reactor-grade plutonium and shows that the nuclear industry's desire to recycle plutonium has led it to downplay the dangers of reactor-grade plutonium. Chapter three provides some of the basic properties of plutonium, how it is classified into different grades, and how plutonium's properties can vary depending on the initial enrichment and burnup of the reactor fuel that produces the plutonium. Chapter four discusses how the spontaneous fission of plutonium can affect the probability of a weapon predetonating and shows that the predetonation probability of a weapon using reactor-grade plutonium can be made equal to that of a weapon using weapon-grade plutonium. Chapter five discusses how the decay heat of reactor-grade plutonium might affect the functioning of a nuclear weapon and shows that reactor-grade plutonium produced by high burnup in current LWRs, by MOX fuel or recycled uranium, can be effectively used in fission weapons using the U.S. early 1950s level of technology including a levitated design and modern high explosives. Chapter six discusses the additional radiation from reactor-grade plutonium and shows that this weak radiation is easily shielded against. The chapter also looks at the critical mass of reactor-grade plutonium and shows that it is always significantly less than that of highly enriched uranium

(HEU). Chapter seven examines the role that reactor-grade plutonium played in the nuclear weapon programs of Sweden and Pakistan and may be currently playing the nuclear weapon program of India. Chapter eight shows that the 1962 U.S. nuclear test of reactor-grade plutonium used plutonium that was 20% to 23% Pu-240. It also shows that the British 1953 Totem test series did not use non-weapon-grade plutonium and therefore these tests provide no information on the usability of such plutonium in nuclear weapons. Chapter nine summarizes my conclusions. The appendix provides a history of the Pu-240 content of U.S. weapon-grade plutonium and provides key information on the Pu-240 content of the plutonium that the U.S. used to manufacture unboosted fission nuclear weapons in the late 1940s and early 1950s.

Chapter 1

Why Countries Might Choose Reactor-Grade Plutonium for Their First Weapon

Weapon-grade plutonium is preferred to reactor-grade plutonium for the production of nuclear weapons. It has a relatively low spontaneous fission neutron output, low heat output, and will produce less gamma radiation. All things being equal, a country will always choose to use weapon-grade plutonium instead of reactor-grade plutonium.

But today all things are not equal. In particular, any country looking to become a nuclear weapon state will find it much harder to obtain weapon-grade plutonium than reactor-grade plutonium. The greater ease of access to reactor-grade plutonium is what makes the question of whether reactor-grade plutonium can be used to produce nuclear weapons of great importance.

In the 1940s and 1950s, there was little plutonium anywhere in the world, and the United States, the Soviet Union, the UK, and France built graphite moderated, natural uranium fueled plutonium production reactors to produce weapon-grade plutonium for nuclear weapons. These countries would have found it difficult to produce reactor-grade plutonium even if they had wanted to. Indeed, the first U.S. attempt to produce significant quantities of reactor-grade plutonium in the late 1950s failed (see chapter eight). In the 1960s, China built its own graphite moderated, natural uranium fueled plutonium production reactor and France was happy enough to sell a heavy

water moderated, natural uranium fueled plutonium production reactor to Israel.

Today the situation is quite different. A decade ago, Syria attempted to build a plutonium production reactor, but it was bombed and destroyed by Israel. Countries have attempted to disguise their plutonium production reactors by calling them research reactors. Indeed in the 1950s and 1960s, Canada was naïve enough to sell two heavy water moderated, natural uranium fueled "research reactors" to India and Taiwan. Both reactors became the linchpins of the nuclear weapon programs in these two countries.

However, when China attempted the sale of such a research reactor to Algeria in the 1980s, concerns were raised and the reactor was converted to enriched uranium fuel so as to significantly reduce (but did not eliminate) its production of plutonium. When Iran made its first attempt to acquire a plutonium production reactor in the early 1990s by purchasing a heavy water moderated, natural uranium fueled "research" reactor from India, international pressure forced India to drop the sale. More recently Iran attempted to build such a plutonium production reactor at Arak but as part of the negotiated Joint Comprehensive Plan of Action, the original reactor vessel was destroyed and any follow-on reactor must use enriched uranium fuel to significantly reduce its plutonium production.

In contrast, a number of different vendors from countries as diverse as South Korea, Russia, France, and Canada are willing to build nuclear power reactors in any country willing to pay for them. As of today, there are over 400 operating nuclear power reactors worldwide, which have generated a stockpile of about 2,400 metric tons of plutonium.[7] Most of this plutonium is likely reactor-grade but some of it is no doubt fuel-grade. A small amount may even

7. David Albright et al., "Civil Plutonium Stocks Worldwide, End of 2014," *Institute for Science and International Security*, November 16, 2015.

be weapon-grade. In contrast to Iran's plutonium production reactor at Arak, the Joint Comprehensive Plan of Action barely mentions Iran's nuclear power reactor at Bushehr even though the reactor produces about 240 kilograms of plutonium every year.

Over 2,100 metric tons of the world's plutonium stockpile are contained in highly radioactive spent fuel. Analysis that I participated in at Pan Heuristics over forty years ago indicated that as long as a country does not possess a reprocessing plant, this plutonium is relatively safe from being diverted to the production of nuclear weapons given the time and difficulty in extracting the plutonium from the spent fuel.[8] We estimated that it could take many months for a country to reliably produce sufficient plutonium for multiple nuclear weapons. However, 40 years ago scientists at Oak Ridge National Laboratory raised concerns that the extraction process might not be that difficult.[9] Indeed, it is possible that with the diffusion of solvent extraction technology now used in the processing of uranium ores, the extraction of plutonium from spent fuel is less of a barrier than it was forty years ago. However, even if the Oak Ridge analysis were correct, it would not make reactor-grade plutonium safe. Rather it would raise questions about the wisdom of having nuclear power reactors in any non-nuclear weapon state.

Of greater concern is the 270 metric tons of plutonium that has already been separated from spent fuel. The bulk of this material

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8. Albert Wohlstetter, Thomas A. Brown, Gregory Jones, David McGarvey, Henry Rowen, Vincent Taylor, and Roberta Wohlstetter, "Moving Towards Life in a Nuclear Armed Crowd?" ACDA/PAB-263, Pan Heuristics, December 4, 1975, Revised April 22, 1976, available from http://www.npolicy.org/article_file/Moving_Toward_Life_in_a_Nuclear_Armed_Crowd_(1975).pdf. This analysis was updated in: Albert Wohlstetter, Thomas A. Brown, Gregory Jones, David McGarvey, Henry Rowen, Vincent Taylor, and Roberta Wohlstetter, *Swords from Plowshares,* Chicago: The University of Chicago Press, 1979.

9. D. E. Ferguson, "Simple, Quick Processing Plant," Oak Ridge National Laboratory, August 30, 1977.

is in the nuclear weapons states of the UK, France, and Russia but significant quantities are held in a half a dozen non-nuclear weapons states of which Japan has the largest stockpile. 37 metric tons of Japan's stockpile are being held in the UK and France and 9.8 metric tons are in Japan itself. About 2.7 metric tons of the stockpile in Japan is held as either a pure plutonium nitrate solution or as pure plutonium dioxide.[10] Either form could be converted into a metal core for a nuclear weapon in only days or weeks.[11]

Most of the rest of the 9.8 metric ton stockpile is in the form of a mixture of plutonium and uranium oxides (MOX), either in powder form, in the process to produce MOX fuel, or in the unirradiated MOX fuel. Extracting the plutonium from the MOX powder or unirradiated fuel would not be difficult and could probably be performed using lab scale equipment since the plutonium in these forms is not highly radioactive and would not need to be handled remotely.[12] Further, the plutonium is seven to fifty times as concentrated as it is in spent LWR fuel. The time required to extract the

10. "The Status Report of Plutonium Management in Japan-2016," Office of Atomic Energy Policy, Cabinet Office [Japan], August 1, 2017, available from http://www.aec.go.jp/jicst/NC/about/kettei/170801_e.pdf.

11. Albert Wohlstetter, Thomas A. Brown, Gregory Jones, David McGarvey, Henry Rowen, Vincent Taylor, and Roberta Wohlstetter, *Swords from Plowshares*, Chicago: The University of Chicago Press, 1979.

12. This would include MOX powder which has aged for decades and has accumulated a significant quantity of americium. MOX fabrication plants limit worker radiation exposure from americium to just 0.5 rem. However, the U.S. limit for worker radiation exposure is 5 rem (chapter 6). Therefore though aged MOX powder might contain more americium than is allowed in a MOX fabrication plant, one could easily extract the plutonium from the MOX powder without exceeding the 5 rem limit. See, K. Fukuda et. al., "MOX Fuel Use as a Back-End Option: Trends, Main Issues and Impacts on Fuel Cycle Management," IAEA-SM-358/I, 1999. In the case of Japan this operation could be carried out in the plutonium purification section of the Tokai reprocessing plant.

plutonium and convert it into a metal core for a nuclear weapon is again only days to weeks.

What then would be Japan's options if it wanted plutonium for nuclear weapons? If it wanted to build a plutonium production reactor to produce weapon-grade plutonium, it would either have to acquire at least 20 metric tons of heavy water or hundreds of metric tons of nuclear-grade graphite. Neither task would be easy. Then the reactor would have to be constructed, a process that could take years and cost at a minimum hundreds of millions of dollars. The reactor would then have to operate for at least a year to produce enough plutonium for several nuclear weapons. The spent fuel would then have to cool for a number of months before the plutonium could be extracted in a reprocessing plant. If this operation was to be strictly a military one, a reprocessing plant would also need to be constructed concurrently with the construction and operation of the plutonium production reactor and would cost hundreds of millions of dollars as well. This whole process could take three to five years and probably cost at least one billion dollars. During this time, Japan would face enormous pressure from not only its enemies but also its allies to halt this process. Japan would also need to worry that an adversary might preemptively strike the reactor before the plutonium could be produced.

In contrast, if Japan was willing to settle for reactor-grade plutonium, it could simply seize the plutonium nitrate or dioxide and convert it into metallic weapon cores in a matter of days or weeks. It could probably use existing plutonium facilities to carry out this operation but if not it could build new "plutonium research" facilities in advance. The cost might only be tens of millions of dollars. The production of the nuclear cores could be carried out in such a short time that there would be little danger that an enemy could strike before the diversion of plutonium was detected.

Which option a country chooses depends strongly on the viability of using reactor-grade plutonium to produce nuclear weapons. If reac-

tor-grade plutonium is truly denatured or very difficult or dangerous to use then a country would have no option but to go the plutonium production reactor route to produce weapon-grade plutonium or to give up its nuclear weapon ambitions entirely. However, as this book shows, simply by using a smaller plutonium mass as the weapon core, a country can use early 1950s U.S. technology and modern high explosives to produce nuclear weapons that are the same size and weight and have the same predetonation probability as weapons using weapon-grade plutonium. The smaller plutonium mass would keep its heat output within the limits required to ensure that the weapon's high-explosives are safe. The weapon would require no special cooling. By coating the core with just one half a centimeter of uranium, the gamma radiation would be well below that of an unshielded weapon-grade plutonium core. The destructive area of such a weapon would be 40% of that of a weapon using weapon-grade plutonium. Given the long time, significant expense and major risk associated with acquiring weapon-grade plutonium, a country might well decide to use reactor-grade plutonium instead.

Clearly, the possession of a reprocessing plant by a non-nuclear weapon state is a problem since it gives easy access to plutonium in the form of plutonium nitrate or plutonium dioxide. This plutonium can be quickly converted into a nuclear weapon core. The Pan Heuristic's analysis that I participated in recommended the obvious solution to ban the use of such plants in non-nuclear weapon states. This analysis led to a major change in U.S. policy under the Carter administration ending plutonium reprocessing in the United States and attempting to end it in other countries as well.

Further, the Pan Heuristic's analysis showed that even if reprocessing plants were banned from non-nuclear weapon states, if these states continued to use plutonium containing MOX fuel (produced perhaps in international fuel cycle centers), the problem would still remain. A single reactor reload of fresh MOX fuel can contain over

seven hundred kilograms of plutonium, which is enough for over one hundred nuclear weapons. This fuel is not highly radioactive and a country could use simple hands-on procedures to quickly separate the plutonium from this fuel.

Only if both reprocessing plants and plutonium containing fuels are banned from non-nuclear weapon states can these countries be prevented from having easy access to the plutonium needed for nuclear weapons. However, at the moment, Japan is moving ahead with plans to open a large reprocessing plant which would produce eight metric tons of plutonium each year. In addition, the Joint Comprehensive Plan of Action allows Iran to reprocess after the deal expires in 13 years.

Note that the proponents of the view that plutonium is either denatured or too difficult to use in a practical nuclear weapon strongly oppose either of these steps. Indeed it is the possibility that concerns over the use of reactor-grade plutonium in nuclear weapons might lead to restrictions on the use of plutonium as a nuclear reactor fuel that drives these proponents to promote their erroneous views regarding reactor-grade plutonium. But their arguments are self-defeating. The more that their false narrative is accepted, the more accessible reactor-grade plutonium will be in non-nuclear weapon states and the more likely that such a country would choose to use reactor-grade plutonium to produce nuclear weapons.

The fact that five established nuclear powers chose to use weapon-grade plutonium instead of reactor-grade plutonium is a product of the circumstances of the time when they were developing nuclear weapons and not a universal law. In these countries at those times, weapon-grade plutonium was more easily produced than was reactor-grade plutonium. For a country today where reactor-grade plutonium is easily and quickly obtainable and weapon-grade plutonium is time-consuming, costly and perhaps even dangerous to produce, using reactor-grade plutonium to produce nuclear weapons would be the obvious choice.

Chapter 2

A Short History of Reactor-Grade Plutonium and Why the Nuclear Industry Is Wrong to Downplay Its Dangers

This chapter will provide a short history of views regarding the nuclear weapon dangers of reactor-grade plutonium. The chapter will also discuss how the nuclear industry's desire to recycle plutonium has led it to downplay the threat that non-nuclear weapon states could use reactor-grade plutonium to produce nuclear weapons.

Short History of Reactor-Grade Plutonium

The detonation of a nuclear weapon requires the generation of a supercritical mass of fissile material. There are two ways to produce this supercritical mass. One is the gun method, where one subcritical mass of fissile material is fired as an artillery projectile into another subcritical mass of fissile material, producing the necessary supercritical mass and nuclear explosion. The other is the implosion method, where a subcritical mass of fissile material is surrounded by high explosives. These explosives are detonated simultaneously, compressing the fissile material. The reduced surface area of the compressed fissile material causes it to become supercritical.

From the beginning of the Manhattan Project it was recognized that of the two methods, implosion was the superior one as it would permit more efficient use of fissile material in nuclear weapons. However, in 1943 no one knew how to make this method work and Los Alamos decided to focus the main effort of research on the gun method which involved the use of well-developed conventional artillery technology.

There is one problem with the gun method. It produces a supercritical mass relatively slowly compared to the implosion method. If a stray neutron were to start a chain reaction too early, the weapon would predetonate and produce less (perhaps far less) than its design yield. The main source of neutrons was expected to be the result of the reaction of alpha particles (produced by the decay of U-235 or Pu-239) with light element impurities in the fissile material. For U-235 this was not much of a problem. With a 700 million year half-life, it produces alpha particles at a relatively low rate—resulting in a similarly low rate of neutron production.

For the plutonium gun weapon, this problem was more serious. Pu-239 has a 24,000 year half-life and produces alpha particles at a 30,000 times higher rate than does U-235. To deal with this problem Los Alamos planned to build a special high velocity gun and at the same time to rigorously purify the plutonium so as to greatly reduce the amount of light element impurities. It was hoped that these two measures would be enough to make a plutonium gun nuclear weapon feasible.

In 1943, very little plutonium had actually been produced. Indeed, plans to build large plutonium processing facilities at Hanford were based on less than one milligram of plutonium that had been produced in the Berkeley cyclotron. This plutonium was almost pure Pu-239.

The only way to produce large quantities of plutonium was to build nuclear reactors. In the fall of 1943, the experimental X-10 reactor started operation and by the spring of 1944, it had produced tens of grams of plutonium. Tests on this material showed that reactor produced plutonium would inevitably contain significant amounts of Pu-240. Further tests showed that this Pu-240 would produce large numbers of neutrons through spontaneous fission.[13] The number of neutrons so produced would greatly exceed the number produced by alpha particle reactions with light element impurities. As a result, in July 1944, it was necessary to abandon the development of the plutonium gun weapon.

In August 1944, Los Alamos was reorganized to attack the problem of creating the implosion weapons needed to utilize plutonium. By February 1945, less than seven months later, a design for such a weapon had been selected.[14] It would take until July 1945 before this design could be converted into an actual weapon. It was successfully tested at Alamogordo on July 16, 1945, and successfully used in combat on August 9, 1945.

After the war, this episode formed the basis for the view that plutonium could be denatured, i.e. "make the material unusable by any methods we now know for effective atomic explosives unless steps are taken to remove the denaturants."[15] The 1946 Acheson-Lilienthal Report is one of the more prominent studies to suggest denaturing plutonium as a means of making nuclear electric power available to many countries without providing the means for these

13. Pu-239 also undergoes spontaneous fission but the spontaneous fission rate of Pu-240 is 40,000 times higher.

14. Richard G. Hewlett and Oscar E. Anderson Jr., *A History of the United States Atomic Energy Commission, Volume I, 1939/1946*, The New World, WASH 1214, U.S. Atomic Energy Commission, 1972, p. 318.

15. "The Acheson-Lilienthal Report on the International Control of Atomic Energy," Washington, D.C., March 16, 1946.

countries to produce nuclear weapons. This report did not reveal what the denaturant might be but it did state that to remove the denaturant would require "complex installations," "a large effort," and "scientific and engineering skill of an appreciable order."

It was only with the release of the Manhattan Project history in 1961 that the problem with Pu-240 was officially made public.[16] Indeed, the history is divided into two parts, before and after Los Alamos was reorganized to deal with the Pu-240 problem. This revelation made clear that it was the predetonation of a nuclear weapon caused by spontaneous fission neutrons that formed the basis for the belief that plutonium could be denatured.

The 1950s and 1960s were a very lax time for nonproliferation. The United States exported large quantities of highly enriched uranium to a wide variety of countries even though there was no pretense that this material could be denatured. The United States also declassified and released large amounts of data on the PUREX reprocessing process, which is an effective means of extracting plutonium from spent fuel. The Chinese would later say that this release of information was a significant aid to their nuclear weapon program. India with the aid of a U.S. company would quickly build its own reprocessing plant and by 1965 had produced plutonium metal.[17]

Also in the 1950s and 1960s, Los Alamos apparently performed an analysis of the true effect of high plutonium spontaneous fission neutron production on the performance of a simple fission nuclear

16. David Hawkins, "Manhattan District History, Project Y, The Los Alamos Project, Volume I. Inception Until August 1945," LAMS-2532 (Vol. I), Los Alamos Scientific Laboratory, Los Alamos, New Mexico, written 1946, released December 1, 1961.

17. Shri N. Srinivasan, "Fuel Reprocessing-The Initial Years," IANCAS Bulletin, July 1998, p. 4, available from http://www.igcar.gov.in/rpg/articles/N%20Srinivasan%20on%20Reprocessing.pdf.

weapon, i.e. can plutonium really be denatured? This included a 1962 nuclear test to help confirm the U.S. capability to predict the performance of nuclear weapons. The specific results of this analysis remain classified but in 1970 J. Carson Mark, the Director of the Theoretical Division at Los Alamos, hinted at the results:

> I would like to warn people concerned with such problems that the old notion that reactor-grade plutonium is incapable of producing nuclear explosions-or that plutonium could easily be rendered harmless by the addition of modest amounts of plutonium-240, or "denatured" as the phrase used to go-that these notions have been dangerously exaggerated.[18]

In the early 1970s, the ability to separate plutonium from spent nuclear power reactor fuel threatened to become widespread. In 1971, Japan purchased a reprocessing plant from France, which would start operation in 1981. In 1974, France agreed to sell Pakistan a reprocessing plant. It is now known that this purchase was part of Pakistan's nuclear weapon program. In 1975, West Germany concluded a nuclear deal with Brazil which included the sale of a reprocessing plant. In the meantime, India's 1974 "peaceful nuclear explosion" had significantly raised concerns about the dangers of separated plutonium.

Yet if plutonium could really be denatured, how dangerous were these sales? Mark had hinted that they were dangerous but otherwise the United States did not comment presumably because it considered the information classified. For example, the Manhattan Project history did not state the Pu-240 percentage that constituted weapon-grade plutonium.

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18. J. Carson Mark, "Nuclear Weapon Technology," in B.T. Feld, T. Greenwood, G.W. Ratjens, and S. Weinberg (Eds.), *Impact of New Technologies on the Arms Race*, Cambridge: MIT Press, 1971.

The Germans defended their Brazil deal by claiming that weapon-grade plutonium could contain no more than 2% Pu-240. The appendix contains a history of the Pu-240 content of U.S. weapon-grade plutonium. While the Pu-240 content of U.S. weapon-grade plutonium was just 2% between 1945 and 1949, it was increased to 3.8% in 1949, increased again to 5.5% in 1951 and was as high as almost 9% by 1954, though operational problems prevented the United States from producing plutonium with a Pu-240 content greater than 7.5%. It was only in 1959 that the current Pu-240 content of 6% was set for U.S. weapon-grade plutonium. Even though it was not officially known what the yield of a predonating nuclear weapon would be, the Germans among others claimed that they would not be effective nuclear weapons.

In September 1976, a research team at Pan Heuristics led by Albert Wohlstetter[19] discovered two declassified memos from 1945 that revealed the predetonation characteristics of the Nagasaki nuclear weapon.[20] In particular, there is a lower limit on the yield of any predetonating weapon, which is referred to as the fizzle yield. This is the yield that would be produced if a stray neutron started the chain reaction just as the weapon became critical. One of these memos stated that for the Nagasaki weapon the minimum yield would be about one kiloton. Since the lethal area of a one kiloton nuclear weapon is about 30% of that of the 16 kiloton weapon that devastated Hiroshima, this yield can hardly be considered insignificant.

When the Energy Research and Development Agency (ERDA—the predecessor to the current Department of Energy) found out that

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

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

Wohlstetter was going to publish the predetonation probabilities and yields of the Nagasaki weapon, its first impulse was to attempt to reclassify the information. When this was not possible, ERDA decided to preempt Wohlstetter. In mid-November 1976 Robert Selden of the Lawrence Livermore National Laboratory and J. Carson Mark gave a series of briefings explaining that reactor-grade plutonium can be used to produce nuclear weapons. The final slide of Selden's briefing said:

> All plutonium isotopes can be used directly in nuclear explosives. The concept of "denatured" plutonium (Pu which is not suitable for nuclear explosives) is fallacious. A high content of the Pu-240 isotope is a complication, but not a preventative.[21]

In July 1977 the Department of Energy revealed that in 1962 it had successfully tested a nuclear weapon using reactor-grade plutonium. In 1994 the Department of Energy released additional information regarding this test. Part of this information said:

> The test confirmed that reactor-grade plutonium could be used to make a nuclear explosive…The United States maintains an extensive nuclear test data base and predictive capabilities. This information, combined with the results of this low yield test, reveals that weapons can be constructed with reactor-grade plutonium.[22]

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21. Robert W. Selden, "Reactor Plutonium and Nuclear Explosives," November 1976.

22. "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-Grade Plutonium," available from https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc29.html.

The release of this information helped to increase pressure on West Germany and France and their sales of reprocessing plants to Brazil and Pakistan were never completed. Yet many in the nuclear industry refused to accept the full dangers of reactor-grade plutonium. As Japan's stockpile of plutonium continued to grow, Tokio Kanoh, director of Tokyo Electric Power said, "The general consensus seems to be that civil plutonium *can* make a bomb but it would be difficult to do and inefficient—like building a plane with iron."[23] [Emphasis in original]

In 1980, there was a significant development. Instead of proposing that the spontaneous fission neutrons from Pu-240 could denature plutonium by causing a nuclear weapon to predetonate, an article in the journal *Nuclear Technology* suggested that Pu-238 could be used to denature plutonium by its heat.[24] The Pu-238 content of reactor-grade plutonium could be intentionally increased by spiking fuel with neptunium. It was not realized at the time that neptunium itself could be used to produce nuclear weapons. Though various schemes have been suggested over the years to increase the Pu-238 content of plutonium, none has ever been implemented.

In 1990, J. Carson Mark, now working for the Nuclear Control Institute, used the declassified 1945 memos published by Wohlstetter to quantify the yield distribution for a weapon of the Trinity/Nagasaki design given various levels of spontaneous fission neutron production in the plutonium.[25] Mark expanded on this work in 1993 and

23. "Pu—an element of concern in Japan," *Nuclear Engineering International*, July 1993.

24. P. Wydler et al., "A Uranium-Plutonium-Neptunium Fuel Cycle to Produce Isotopically Denatured Plutonium," *Nuclear Technology* 49, no. 1, June 1980.

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

added a discussion of the problem of the plutonium's heat output.[26] Mark considered this problem easily solved by using an aluminum "thermal bridge."

In 1994, the National Academy of Sciences published a book written by experts such as Richard Garwin, Michael May, Wolfgang Paknofsky, and John Holdren, which contained a discussion of reactor-grade plutonium.[27] This work reaffirmed that the yield of the Nagasaki weapon even with reactor-grade plutonium would be at least "on the order of one or a few kilotons." It refers to classified work that suggested that "With a more sophisticated design [than Nagasaki], weapons could be built with reactor-grade plutonium that would be assured of having higher yields." It also stated that another way of dealing with the higher heat of reactor-grade plutonium would be "delaying assembly of the device until a few minutes before it is to be used."

In 2004, former U.S. nuclear weapon designer Harmon Hubbard expanded Mark's 1993 analysis of the yield distribution of Nagasaki weapons using reactor-grade plutonium.[28] He calibrated Mark's analysis by providing the actual neutron output of the Nagasaki plutonium and extended the analysis to weapons that had superior performance compared to that of the Nagasaki weapon. This work showed that even when a weapon predetonates, there is a significant probability that the yield will be considerably higher than just

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

27. *Management and Disposition of Excess Weapons Plutonium*, Committee on International Security and Arms Control, National Academy of Sciences, 1994, pp. 32-33.

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

the fizzle yield and that higher yields could be expected from superior weapon technology.

Though the work of Mark, the National Academy of Sciences, and Hubbard would seem to have settled the matter of the weapon usability of reactor-grade plutonium, many in the nuclear industry continued to believe otherwise. In 2002, Bruno Pellaud, former deputy director general of the International Atomic Energy Agency (IAEA), claimed that reactor-grade plutonium with high Pu-240 content was so benign that IAEA safeguards on such material should be relaxed.[29] He falsely claimed that the Pu-240 content of the U.S. 1962 test was only 12%. In 2013, I showed that the Pu-240 content was actually in the range of 20% to 23%.[30]

Pellaud also made a common argument that while one could produce some sort of nuclear explosion from reactor-grade plutonium, this is just a technicality. The difficulties of actually using reactor-grade plutonium are so great that no country would ever do so. The IAEA, in fact, has not changed the way in which it safeguards reactor-grade plutonium.

In 2011 Gunter Kessler published a book which contains several chapters on reactor-grade plutonium.[31] Kessler claims that reactor-grade plutonium produced in light water reactors contains sufficient Pu-238 to prevent its use in what Kessler calls "hypothetical nuclear explosive devices." Kessler's analysis is restricted to just Nagasaki type weapons with very large plutonium cores and he does not

29. Bruno Pellaud, "Proliferation aspects of plutonium recycling," *Journal of the Institute of Nuclear Material Management*, Fall 2002.

30. 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, available from http://www.npolicy.org/article.php?aid=1212&rid=3.

31. G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles*, KIT Scientific Publishing, 2011.

discuss more advanced but still quite primitive weapons that the United States deployed in the late 1940s which used levitation and in-flight insertion. Kessler also greatly exaggerates the predetonation probability of reactor-grade plutonium even in a Nagasaki type weapon.

These arguments have become quite common and are repeated by the World Nuclear Association and sources such as Wikipedia. The persistence of these arguments has led me to undertake the writing of this book. In later chapters, I will discuss in further detail the issues raised by Pellaud, Kessler, and others.

Note that the problem of the predetonation of nuclear weapons applies only to unboosted nuclear weapons, which are typically the type of weapon that a country first develops. Later in nuclear weapon development programs, countries develop boosted nuclear weapons.[32] Boosted nuclear weapons use hollow cores of nuclear material. Just before detonation a tritium/deuterium gas mixture is inserted into this hollow space. The detonation of the weapon causes a fusion reaction. The energy output from this fusion reaction is small but by releasing large numbers of high energy neutrons, the reaction significantly increases the efficiency of the fission reactions in the weapon. Further, as the British have pointed out, boosted fission weapons are "immune" to predetonation.[33] Boosted weapons would produce the same yield whether they were manufactured from weapon-grade plutonium or reactor-grade plutonium. This issue is discussed further in chapter four.

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32. Gregory S. Jones, "The Role of Boosting in Nuclear Weapons Programs," July 25, 2017, available from http://nebula.wsimg.com/ccbc92a7e380925d944880521d489ea5?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1.

33. Lorna Arnold, *Britain and the H-Bomb*, UK Ministry of Defense, Palgrave, 2001.

Plutonium Recycle: Why Does the Nuclear Industry Downplay the Dangers of Reactor-Grade Plutonium?

Given extensive authoritative expert analysis as well as official statements by both the U.S. and UK governments regarding the dangers of reactor-grade plutonium, one might wonder why so many in the nuclear industry are so keen to downplay its dangers. The answer is that the nuclear industry has been obsessed with the concept of reprocessing the spent fuel of nuclear power reactors to recover plutonium which would then be used to create more power reactor fuel, i.e. plutonium recycling. The long-term goal of this plutonium recycling is the development and commercial use of breeder reactors. The nuclear industry has maintained this obsession even though even it admits that plutonium recycling has always been uneconomical and commercial breeder reactor are at least 30 years away, even though they have already been delayed by over 35 years. Some countries such as the United States and UK no longer plan to develop breeder reactors.

During World War II the first nuclear reactors were designed to produce plutonium. It was recognized that if these reactors were modified to increase the temperature of the coolant, then useful amounts of electricity could be generated. The problem was that at the time very little uranium was known to exist in concentrations that could be economically mined. What is worse, nuclear power reactors whose design was derived from plutonium production reactors, as well as the lighter water power reactors which are in widespread use today, obtain their energy from mainly the U-235 in the uranium. But uranium is only 0.7% U-235 (U-238 makes up 99.3%) and with the known uranium resources of the time, nuclear power's contribution to energy production could not be large.

In the early 1950s, the solution to this problem was believed to be the fast breeder reactor. Current light water reactors convert some U-238 into plutonium but these reactors produce less plutonium than they consume U-235. However, reactors can be designed that use plutonium fuel and as they operate, actually convert more U-238 to plutonium than is consumed in the process. These breeder reactors are of a significantly different design than that of current nuclear power reactors and in particular use liquid metallic sodium as the coolant. Since this coolant does not slow the neutrons produced by the reactor's operation, they are known as fast reactors. By "breeding" more plutonium than is consumed, this type of reactor has the potential to utilize a large fraction of the U-238 contained in uranium and potentially increase the amount of energy extracted from uranium by roughly one hundred fold.

Therefore, for most in the nuclear industry it was a given that the spent fuel would need to be reprocessed and the plutonium extracted. However, not all countries believed this to be true, particularly Canada, which operates natural uranium fueled heavy water reactors. The spent fuel from these reactors contains plutonium at a significantly lower concentration than does spent light water reactor fuel and unlike this latter fuel, the residual uranium is not worth recovering. Therefore, the economics of reprocessing and recycling are significantly worse for Canadian heavy water reactors than for light water reactors. As a result, the Canadians, from the beginning of their nuclear power program in the 1960s, planned to dispose of the spent fuel without recovering the plutonium.

The state of nuclear industry thinking regarding reprocessing and plutonium recycling can be found in an introductory lecture included in a course on reprocessing in Norway in 1967.[34]

34. B. Gaudernack, "Introductory Lecture," *Kjeller Report: Reprocessing of Fuel from Present and Future Power Reactors*, Advanced Course Organized by the Netherlands'-Norway Reactor School, Institutt for Atomenergi, Kjeller, Nor-

> Some years ago an argument was often heard (notably, and repeatedly, from certain Canadian quarters) stating that reprocessing and recycling of power reactor fuels actually was unnecessary and uneconomic. Naturally, all this arguing in favour of the "throw-away cycle" was a bit worrying for people who had engaged themselves in the reprocessing field. Would it be better, perhaps, to look around for a new job? The latest developments have convinced us, however, that there is no need for worrying. A large proportion of the power reactors to come will use fuel requiring reprocessing. And of course, in the case of the fast breeder (or any other breeder reactor) the success of the concept will depend entirely upon a satisfactory fuel cycle, including a successful reprocessing step.

It is clear that almost all nuclear power reactor fuel was expected to be reprocessed and the plutonium recovered. The Canadian view that such reprocessing was unnecessary was seen as almost heretical. This lecture also illustrates the conflict-of-interest of many nuclear experts, as their jobs depended on reprocessing going forward.

But the driving factor behind these plans for reprocessing and the breeder reactor was the belief that supplies of uranium were not very large. However, the only reason that world reserves of uranium were so low in the 1940s and early 1950s is that no one had tried very hard to look for uranium since before the nuclear age there was no need to. In the 1950s, the United States used a price incentive program and provided technical information to spur uranium exploration in the United States and large amounts of uranium were discovered

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way, September 1967, pp. 2-3.

in the Western United States.[35] That higher uranium prices would lead to an increase in uranium supplies is a lesson that the nuclear industry has repeatedly failed to learn.

Nevertheless, in the 1960s and 70s there was a concern that while there were sufficient uranium resources for the moment, all of the best uranium deposits had already been discovered and that a uranium shortage would occur in the near future. The concern over a uranium shortage was greatly exacerbated by large overestimates in the demand for nuclear generating capacity. In 1974, it was estimated that in 20 years uranium production would have to increase nine fold.[36] It was thought that the breeder reactor would be the long-term solution to this problem. In 1974, the U.S. Atomic Energy Commission estimated that today there would be almost 2,000 gigawatts of breeder reactors in the United States alone.[37]

In reality, though uranium production nearly doubled by the early 1980s, it declined in the 1990s to levels about the same as those in the 1970s, as the demand for nuclear power was far less than forecast. Even today, over 40 years later, uranium production is less than double what it was in 1974. The current total electricity generating capacity in the United States is less than 1,100 gigawatts, of which only about 100 gigawatts are nuclear. The total world nuclear generating capacity is only 348 gigawatts. There are no commercial breeder reactors operating anywhere in the world.

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35. Robert D. Nininger, *Minerals for Atomic Energy*, D. Van Nostrand Company, Inc., 1954.

36. R.D. Nininger, "The World Uranium Supply Challenge—an Appraisal," *Formation of Uranium Ore Deposits, Proceedings of a Symposium*, IAEA, Vienna, 1974.

37. Albert Wohlstetter, Gregory Jones, and Roberta Wohlstetter, "Towards a New Consensus on Nuclear Technology, Volume I, Why the Rules Need Changing," Pan Heuristics, PH-78-04-832-33, July 6, 1979, p. 16, available from http://www.npolicy.org/files/19790706-TowardsANewConsensus-Vol01.pdf.

New deposits of uranium were discovered in Canada and Australia which are richer than any that were known in the 1970s. The end of the Cold War led to the worldwide marketing of the uranium resources of the former Soviet Union.

The actual development of breeder reactors proved more difficult than hoped and the predicted date for when the first commercial breeder reactor would start operation kept moving further into the future instead of getting closer as time passed. To find a use for the plutonium recovered by reprocessing in the interim it was decided in the middle 1970s to recycle the plutonium into light water reactors. There were several problems with this idea. First, the amount of plutonium produced by a light water reactor is not sufficient to provide all of the fuel for the reactor, i.e. it is not a breeder reactor. Second, the control rods of a light water reactor were designed for uranium fuel and are insufficient for a full core of plutonium fuel. Third, unlike a breeder reactor where all of the plutonium isotopes are fissionable, in a light water reactor only two of the five plutonium isotopes can be readily fissioned, Pu-239 and Pu-241. Therefore it will take more plutonium than U-235 to make proper fuel. Fourth, when the plutonium is recycled repeatedly, more and more of the Pu-239 and Pu-241 will be burned out, so that after a number of recycles, the plutonium will become unusable.

To deal with these problems the plan was to use a self-generating plutonium recycle. The plutonium recovered from a light water reactor would be mixed with natural uranium and manufactured into fuel. Since both the plutonium and uranium would be in oxide form, the fuel is called mixed oxide fuel or MOX. This would be sufficient to provide about one-third of the fuel for the reactor with the other two-thirds being uranium fuel. The plutonium recovered from the MOX would be degraded by the burnout of Pu-239 and Pu-241 but it would be mixed together with the plutonium recovered from the uranium fuel in the other part of the reactor. After several

such recycles the plutonium degradation would cease as the burn-out of Pu-239 and Pu-241 in the MOX would be compensated by the Pu-239 and Pu-241 produced in the uranium fuel.

Another reason for promoting reprocessing and plutonium recycling was the claim that it would help reduce the amount of nuclear waste. But the purported reduction in waste produced by reprocessing was simply a matter of definition. The recovered plutonium and uranium would no longer be considered to be waste. Therefore, according to the nuclear industry, the comparison was between spent fuel as waste which contained plutonium, uranium, other actinides, and fission products and reprocessing waste which contained only the other actinides and fission products.

This incomplete analysis ignored the question of what would ultimately happen to the plutonium and what actual waste would be. Plutonium recycling via the self-generating recycle would generate a substantial increase in americium and curium in the waste. The heat generated by these elements would cause the waste to take up more space in a nuclear waste repository than would the unreprocessed spent fuel. Further, the act of reprocessing and fabricating MOX fuel would contaminate many items, which would also have to be disposed of as nuclear waste. Therefore, reprocessing would actually make the problem of nuclear waste worse, not better. The U.S. government presented my analysis of this issue to various foreign representatives in 1977.[38]

The United States abandoned reprocessing of spent power reactor fuel in 1977 but many other countries continued with reprocessing programs. Indeed, a number of countries required by law that spent

38. Albert Wohlstetter, Gregory Jones, and Roberta Wohlstetter, "Towards a New Consensus on Nuclear Technology, Volume I, Why the Rules Need Changing," Pan Heuristics, PH-78-04-832-33, July 6, 1979, Appendix B, available from http://www.npolicy.org/files/19790706-TowardsANewConsensus-Vol01.pdf.

power reactor fuel be reprocessed because of the purported nuclear waste benefits.

Another important issue was whether reprocessing made economic sense. The nuclear industry had claimed that MOX fuel would be a money saver. However, analysis by Vince Taylor, a researcher at Pan Heuristics, found that the nuclear industry had significantly underestimated the costs of reprocessing and that reprocessing and recycling of plutonium would be uneconomical.[39] Eventually it became apparent that if anything Taylor had underestimated the costs and reprocessing was even more uneconomical than he had estimated. This result was reinforced by the much lower than anticipated uranium demand which resulted in continued low uranium prices.

Further, it turned out that simply converting the plutonium into MOX fuel was very expensive and that even if one treated the cost of reprocessing as a sunk cost, i.e. the separated plutonium was free, MOX fuel was not economical. Due to unfavorable economics, a number of countries rescinded the requirement that spent nuclear power reactor fuel be reprocessed and utilities wherever possible tried to avoid using MOX fuel.

The uneconomical nature of MOX fuel meant there was little demand and as a result stockpiles of separated civil plutonium became quite large—reaching 87 metric tons worldwide by 1992. A concerned International Atomic Energy Agency (IAEA) held a conference in 1993.[40] At this conference, the IAEA predicted that by the year 2000

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39. Albert Wohlstetter, Thomas A. Brown, Gregory Jones, David C. McGarvey, Henry Rowen, Vince Taylor and Robert Wohlstetter, *Swords from Plowshares: The Military Potential of Civilian Nuclear Energy*, Chicago: The University of Chicago Press, 1979, Chapter IV.

40. "Problems concerning the accumulation of separated plutonium," IAEA-TECDOC-765, IAEA, Vienna, 1994, available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/26/009/26009629.pdf.

the plutonium stockpile would have increased to about 160 metric tons and then would slowly decline to 150 metric tons by 2003. A nuclear industry Advisory Group at this conference assumed that all projected reprocessing and MOX plants would be operated on schedule and at full capacity (assumptions that even the IAEA considered "probably optimistic"),[41] and claimed that the civil plutonium stockpile would peak in 1997 at only 120 metric tons and would then sharply decline to only 10 metric tons by 2003. In fact, the worldwide stockpile of separated civil plutonium has continued to grow, reaching 270 metric tons by the end of 2014.[42]

One effect of this large accumulation of separated plutonium is that plutonium recycling in light water reactors using a self-generating recycle has never occurred. Instead, light water reactors are using a de facto "once-thru" MOX cycle where the spent MOX is not reprocessed. It makes no sense to reprocess the spent MOX fuel to recover plutonium partially depleted in Pu-239 and Pu-241 when large quantities of plutonium recovered from uranium fuel with larger percentages of Pu-239 and Pu-241 are available.

The once-thru MOX cycle further undermines claims that reprocessing helps deal with nuclear waste, since the spent MOX is now a waste. As with the self-generating MOX cycle, the once-thru MOX cycle generates increased americium and curium. These elements, plus the plutonium in the MOX spent fuel, generate more heat than does uranium spent fuel and therefore would take up more space in an underground waste repository.[43] France, which uses far more

41. Pierre M. Chantoin and James Finucane, "Plutonium as an energy source: Quantifying the commercial picture," *IAEA Bulletin*, 3/1993, p. 41.

42. "Global Fissile Material Report 2015," Eighth annual report of the International Panel on Fissile Materials, December 21, 2015, available from http://fissilematerials.org/library/gfmr15.pdf.

43. Brian G. Chow and Gregory S. Jones, "Managing Wastes With and Without Reprocessing," P-8035, Santa Monica, California: RAND, 1999, available from

MOX than any other country, has refused to accept that the spent MOX fuel is waste and plans to store it unreprocessed indefinitely. However, since large quantities of separated plutonium recovered from uranium fuel are available, France will never have a reason to reprocess spent MOX fuel and one day France will have to dispose of it.

The current status of plutonium use in the nuclear power reactors has been well analyzed by the International Panel on Fissile Materials.[44] It has found that viable breeder reactors are still many decades away. The recycling of plutonium in current nuclear power reactors remains uneconomical and fewer than 10% of the world's operating power reactors do so. There has been no upward trend in the price of uranium in the last 50 years. Stockpiles of separated plutonium continue to grow.

Given this state of affairs, one must wonder why the nuclear industry continues to deny the nuclear weapon dangers of reactor-grade plutonium. The nuclear industry appears to believe that if it can be shown that reactor-grade plutonium is safe, i.e. is or can be denatured, then there would be no further obstacles to plutonium use in nuclear power reactors. In fact, even if plutonium were perfectly safe from a nuclear weapon point of view, the poor economics of plutonium recycling pose a major barrier to its use. That reactor-grade plutonium can be used to produce powerful nuclear weapons is just one more reason for reprocessing to be discontinued.

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https://www.rand.org/content/dam/rand/pubs/papers/1999/P8035.pdf.

44. Two of their latest reports are: Frank von Hippel and Gordon MacKerron, "Alternatives to MOX: Direct-disposal options for stockpiles of separated plutonium," *International Panel on Fissile Materials*, April 2015, available from http://fissilematerials.org/publications/2015/04/alternatives_to_mox.html and "Plutonium Separation in Nuclear Power Programs: Status, Problems and Prospects of Civilian Reprocessing Around the World," *International Panel of Fissile Materials*, July 2015, available from http://fissilematerials.org/library/rr14.pdf.

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 = 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.

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 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.[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.

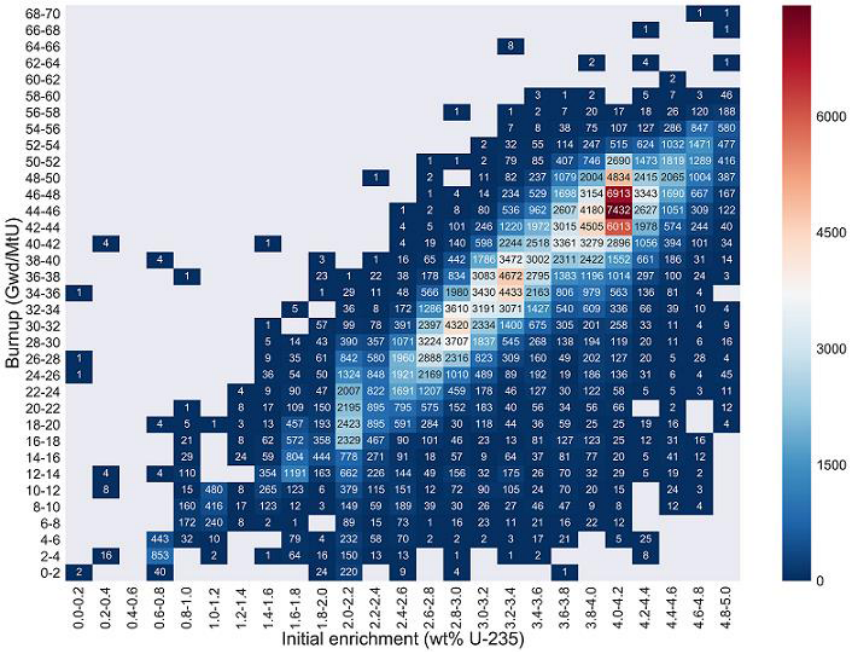

FIGURE 1: Initial Fuel Enrichment and Final Fuel Burnup 244,918 U.S. PWR and BWR Assemblies, 1968 to June 30, 2013, (Number of Fuel Assemblies)

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 237Np 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.

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57. 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: "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: 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 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://nebula.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.

Chapter 4

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

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

Predetonation of Unboosted Nuclear Weapons

The creation of a nuclear explosion requires the production of a supercritical mass of nuclear material (usually either highly enriched uranium or plutonium or both) from a subcritical configu-

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Calculating the Predetonation Probability

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

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

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

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

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

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

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

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

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

74. Neutrons per gram-second.

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

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

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

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

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

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

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

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

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

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

A Technicality?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Boosted Nuclear Weapons Are Immune to Predetonation

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

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

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

Boosted nuclear weapons are immune to predetonation and if boosted nuclear weapons become the norm for early stage nuclear weapon

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

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

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.

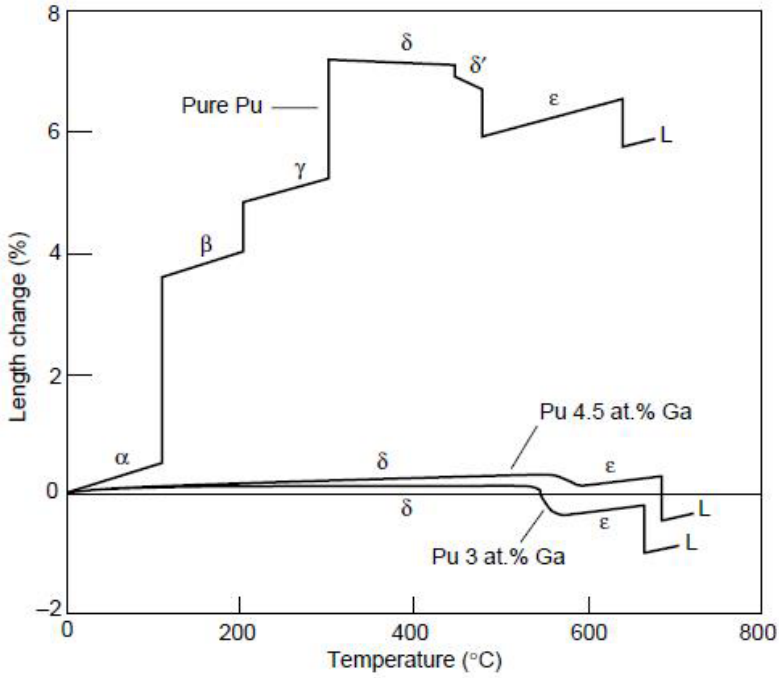

FIGURE 2: The Benefits of a Plutonium-Gallium Alloy

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.

Chapter 6

Radiation and Critical Mass: No Barriers to Reactor-Grade Plutonium Use in Nuclear Weapons

Though predetonation and heat are the two main reasons often cited to support the mistaken notion that plutonium can be denatured, there are two other factors that are sometimes cited as well. These are the increased radiation of reactor-grade plutonium and its increased critical mass. This chapter demonstrates that neither of these factors poses a serious problem for the production of nuclear weapons using reactor-grade plutonium.

Radiation from Plutonium

All of the isotopes of plutonium are radioactive and therefore give off ionizing radiation as they decay. Of the five main isotopes (Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242) that comprise reactor-grade plutonium, four (Pu-238, Pu-239, Pu-240, and Pu-242) decay by emitting an alpha particle. Alpha particles are quite short-ranged and easily blocked by even a piece of paper. Therefore as long as precautions are taken to prevent the plutonium from being inhaled or ingested, the alpha particles pose no radiation hazard. However, after the alpha particle is emitted, the resulting nucleus is sometimes left in an excited state which leads to the emission of gamma

rays or x-rays. These radiations are far more penetrating than are alpha particles and can be a hazard to personnel though all of the x-rays and most the gamma rays from the decay of these plutonium isotopes are generally low energy. Note that the daughter products of these four isotopes (U-234, U-235, U-236, and U-238 respectively) are all long-lived alpha emitters which do not contribute any significant radiation.

The decay of Pu-241 is different. Pu-241 decays by emitting a beta particle with a half-life of 14.4 years. Beta particles are somewhat more penetrating than are alpha particles, but they are still only a hazard if the Pu-241 is ingested, inhaled or comes into direct contact with the skin. The beta decay of Pu-241 does not emit any gamma rays or x-rays. However, Pu-241's decay product, Am-241, with a 433 year half-life, emits significant amounts of low energy gamma radiation during its decay. Furthermore, Pu-241 also rarely (half-life of about 600,000 years) emits alpha particles producing the decay product U-237 which has a half-life of only 6.75 days. The decay of U-237 produces relatively powerful but still low energy gamma rays.

Therefore almost all of the gamma radiation emitted by the decay Pu-241 is from its decay products and not the Pu-241 itself. When plutonium has first been separated from spent fuel, the plutonium is pure and the gamma radiation resulting from the decay of Pu-241 is very low. Quickly the amount of U-237 builds up in the plutonium and in only 6.75 days it is already half its equilibrium value and will reach its equilibrium value in about 50 days.[108] At the same time the Pu-241 is also decaying into Am-241 and due to Am-241's long half-life, its quantity increases steadily for many years. Initially the gamma radiation contribution from U-237 is dominant, but in time

108. The quantity of U-237 will be at equilibrium when the amount of U-237 produced by the decay of Pu-241 equals the amount of U-237 that decays away. The fraction of the equilibrium value attained is dependent on the half-life of U-237 and is found by the formula $1 - e^{-\lambda t}$ where λ is the ln 2 divided by the half-life.

the Am-241 overtakes it. In a situation where there is no shielding, the contribution from Am-241 becomes more important in just three months but in situations where there is significant shielding, it can take years.

Reactor-grade plutonium gives off significantly more gamma radiation than does weapon-grade plutonium due to increased amounts of Pu-241 and Pu-238. At the time of chemical separation, reactor-grade plutonium gives off about four times as much gamma radiation as does weapon-grade plutonium. Over time, as the Pu-241 decay products accumulate, this ratio increases. At 50 days after separation the ratio is about a factor of 12, and one year after separation the ratio is about a factor of 14.[109]

This higher dose is not a significant impediment to using reactor-grade plutonium in nuclear weapons since the dose can be greatly reduced by a combination of shielding and keeping some distance away from the radiation source. Heavy elements used as shielding, such as lead or uranium, are very effective at stopping the low energy gamma radiation from plutonium, Am-241, and U-237.

Keeping some distance away from a radiation source can also be very effective. Simple geometry demonstrates that the intensity of any radiation source declines with the inverse square of the distance from the source. This rule is not restricted to sources of ionizing radiation (gamma rays, x-rays and neutrons) but any source of radiation such as light from a light bulb. From our own experience we know that the light grows dim as we move away from a light

109. For this calculation, weapon-grade plutonium has the composition of 93.4% Pu-239, 6.0% Pu-240, and 0.6% Pu-241. Reactor-grade plutonium has the composition of 2.6 % Pu-238, 54.3% Pu-239, 25.8% Pu-240, 9.7% Pu-241, and 7.6% Pu-242. These calculations used equation 25.6 in H. V. Larson, "Factors in Controlling Personnel Exposure to Radiations from External Sources," *Plutonium Handbook*, Volume II, O. J. Wick ed., United States Atomic Energy Commission, 1967, p. 851.

bulb. The radiation level at the surface of a six kilogram plutonium sphere is reduced by a factor of 500 at one meter away.

The gamma radiation from plutonium spheres used as the cores of nuclear weapons can be very effectively shielded by covering them with just one half a centimeter of natural uranium. This would amount to less than 4 kilograms of uranium and it could function as part of the weapon's tamper. Even for the relatively energetic gamma rays from U-237, the uranium layer would reduce the exposure by a factor of at least 100. Many of the weaker gamma rays from plutonium and Am-241 would be stopped completely. Therefore, by covering a sphere of high burnup plutonium with just one half a centimeter of uranium, the gamma dose would significantly less than the dose from an unshielded sphere of weapon-grade plutonium. Increasing the uranium covering to one centimeter (about 8 kilograms total) would increase the shielding by at least an additional factor of one hundred.

The dose from neutrons produced by spontaneous fission in metallic plutonium is less than that from gamma rays, but neutrons are harder to shield against and in some circumstances can be more important. However, for safety and security reasons, early nuclear powers (such as the United States in the 1940s and 1950s and Pakistan today) keep their cores stored away from the rest of the weapon. The stored cores can be heavily shielded and in peacetime personnel would have no reason to be near them. If the cores are removed from storage for combat use, the amount of time that personnel would have to be within a meter or less from the core would only be a matter of hours and would not result in a serious exposure.

For a 5.8 kilogram sphere of reactor-grade plutonium,[110] the surface dose rate from neutrons would be about 1.2 rad/hr. The addition of 1 centimeter of natural uranium to the plutonium sphere would do

110. 432 spontaneous fission neutrons produced per gram-seconds.

little to reduce this dose rate. However, at 1 meter away from the sphere, the dose rate would only be 2.4 mrad/hr. Even at this close distance, it would take over 2000 hours (about an entire year's worth of standard work weeks) to accumulate the 5 rem that is the U.S. standard for annual worker exposure to radiation.[111] There would be no need for military personnel to be that close to the finished plutonium weapons cores for such a long time.

Processing of the reactor-grade plutonium from plutonium oxide into plutonium metal weapon cores could lead to increased exposure, but it is not clear that the total exposure would be that significant. Countries such as Pakistan, India, and North Korea are only adding about five new nuclear weapons to their arsenals each year. Therefore, the amount of time workers would spend processing the reactor-grade plutonium for this small number of weapons would not be that great. In addition, the greatest exposure would be to workers' hands. The U.S. standard for annual worker radiation exposure to the extremities is 50 rem.

Further, some of the processing of even weapon-grade plutonium (in particular when it is a fluoride) requires remote handling. This raises the issue of what other plutonium handling operations could be handled remotely. When the United States developed its nuclear weapon production capacity in the 1940s and 1950s, there was little choice and most operations had to be performed hands-on. With today's computer controlled machines, it could be possible for a new nuclear power to carry out many more operations remotely, making the increased radiation dose from reactor-grade plutonium largely irrelevant. Processing the reactor-grade plutonium just after it has been chemically separated would be another method for reducing worker radiation exposure.

111. For our purposes, the radiation units rad and rem are equivalent.

Another far cruder alternative would be for the worker exposure levels to be higher than what the United States would consider acceptable. For example, in the first few years of the Soviet nuclear weapons program, workers were exposed to an average of 25 to 30 rem per year, which is five to six times the current U.S. standard for maximum worker exposure.[112]

Some have asked that if reactor-grade plutonium can be used to produce nuclear weapons, why has the United States not used it? There are multiple reasons. First, it should be remembered that the U.S. infrastructure to produce weapon-grade plutonium was built in the 1940s and 50s when there was no reactor-grade plutonium. By the mid-1960s, when reactor-grade plutonium first started to become available, U.S. production of weapon-grade plutonium was sharply declining as various plutonium production reactors were being shut down. U.S. production of weapon-grade plutonium ended for the most part by 1971. By that time, the United States had plenty of weapon-grade plutonium and had no need to supplement it with reactor-grade plutonium.

Second, the increased radiation of reactor-grade plutonium is a major impediment to its use in U.S. nuclear weapons. U.S. radiation standards require not only that worker exposure be below specific limits (for example, 5 rem for annual whole body exposure) but also that the ALARA principle be applied. ALARA stands for "As Low As is Reasonably Achievable," which means making every reasonable effort to maintain exposures as far below the dose limits as practical.[113] For the United States to change over to the use of reactor-grade

112. TV Azizova, ES Grigorieva, MV Bannikova, and MB Moseeva, "Circulatory diseases in the cohort of Mayak PA workers occupationally exposed to radiation," *Joint RERF-ICRP Workshop on Health Risk of Radiation and the System of Radiological Protection*, Tokyo, Japan, October 9, 2016 available from http://www.icrp.org/docs/2016tokyo/5%20Azizova.pdf.

113. 10 CFR 20.1003.

plutonium while continuing to use the current weapon manufacturing facilities would result in increased worker radiation exposure, which would be inconsistent with ALARA. U.S. weapon manufacturing facilities would need to be completely rebuilt in order not to increase worker radiation exposure. New nuclear weapon states are not bound by ALARA.

Third, changing from weapon-grade plutonium to reactor-grade plutonium in U.S. nuclear weapons would probably require that the weapon be recertified by conducting nuclear tests. However, the United States has had a nuclear test moratorium since 1992 which would prevent any such recertification. Since the United States has surplus weapon-grade plutonium, this is not an issue. However, for countries without access to weapon-grade plutonium but with access to large quantities of separated reactor-grade plutonium, the latter could be an attractive alternative.

Radiation from other Nuclear Weapon Fissile Materials

Reactor-grade plutonium is not the only fissile material that can be used to produce nuclear weapons that emits significant amounts of gamma radiation. For U-233 the problem of gamma radiation can be substantially worse. U-233 is produced by irradiating thorium in nuclear reactors. The resulting uranium is about 98% U-233 and about 1% each of U-234 and U-238. However, the production of U-233 also produces small quantities of U-232. Initial U.S. efforts to produce U-233 resulted in a U-232 content of over 100 ppm[114] but techniques were developed that resulted in U-233 containing only about 5 to 10 ppm U-232.[115]

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114. C.W. Forsberg, et. al., "Disposition Options for Uranium-233," ORNL/TM-13553. Oak Ridge National Laboratory, June 1, 1999, Table 2.2, p. 12.

115. J. M. Boswell et. al., "Production of ^{233}U with Low ^{232}U Content," *Thorium*

U-232 has a half-life of 68.9 years and alpha decays into thorium 228, which has a half-life of 1.9 years. Th-228 then rapidly undergoes five more decay steps before ending as a stable lead isotope. One of the Th-228 decay products (thallium 208) emits a powerful gamma ray that is difficult to shield against.[116] When U-233 is first separated from thorium, its radiation is low since there is no Th-228. The radiation buildup follows a pattern similar to that of U-237 from Pu-241 except since the half-life of Th-228 is 1.9 years as opposed to 6.75 days for U-237, it occurs much more slowly. U-233 containing just 5 to 10 ppm U-232 can be processed by hand in glove boxes by performing the operations soon after the U-233 is separated from thorium.

Handling fabricated U-233 weapon cores would be more difficult. One year after separation, U-233 containing just 5 ppm of U-232 emits seven times as much gamma radiation as does reactor-grade plutonium.[117] U-233 containing 100 ppm U-232 emits 150 times as much gamma radiation as does reactor-grade plutonium. Even a one centimeter coating of natural uranium would only reduce this radiation by about a factor of two.

Yet even U-233 containing 100 ppm U-232 is usable in a nuclear weapon. "This emission [the gamma ray from thallium 208] produces a radiation field that requires much of the material to be stored inside shielded vaults. The radiation is sufficient to create major handling complications, but is not sufficient to prevent its use as

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Fuel Cycle, Proceedings of Second International Thorium Fuel Cycle Symposium, Gatlinburg, Tennessee, May 3-6, 1966, U.S. Atomic Energy Commission, February 1968, pp. 745-763.

116. P.J. Bereolos et. al., "Strategy for the Future Use and Disposition of Uranium-233: Technical Information," ORNL/TM-13552, April 1998, Figure 2.2, p .5.

117. Jungmin Kang and Frank N. von Hippel, "U-232 and the Proliferation Resistance of U-233 in Spent Fuel," *Science and Global Security* 9, 2001, Table 2, p. 10, available from http://scienceandglobalsecurity.org/archive/sgs09kang.pdf.

a weapons-usable material."[118] Presumably the U-233 would be managed by keeping personnel away from the cores most of the time. The United States and the Soviet Union are each known to have conducted at least one nuclear test using U-233.[119]

Neptunium is now known to be a nuclear material that can also be used as the core of a nuclear weapon. Its gamma ray emissions are significantly less than those from U-233 but are similar to those from reactor-grade plutonium. Neptunium is produced by the irradiation of U-235 and in LWRs is produced at a rate about one-tenth that of plutonium. The main isotope produced by this process is Np-237, which has a half-life of 2.1 million years. It decays into protactinium 233 by emitting an alpha particle. Pa-233 has a 27 day half-life and decays by emitting a beta particle and gamma rays. This process is similar to the production of U-237 by Pu-241 and the gamma rays from Pa-233 have a similar energy to those of U-237.

The half-life of Np-237 is about three and one-half times longer than that of the alpha decay half-life of Pu-241 but neptunium is 100% Np-237 whereas reactor-grade plutonium is only about 10% or less Pu-241. As a result the gamma radiation would be at least three times stronger from neptunium than from U-237 component of reactor-grade plutonium. The four times longer half-life of Pa-233 compared to U-237 means that there would be more time to process the neptunium before the gamma emissions reached their full intensity.

When handling a six kilogram sphere of neptunium to determine its critical mass, it was necessary to coat the neptunium with 0.28 cm of tungsten and 0.39 cm of nickel to reduce the gamma ray contact

118. Dean R. Tousley, Charles W. Forsberg, and Alan M. Krichinsky, "Disposition of Uranium-233," ORNL/CP-95149, October 16, 1997.

119. David Holloway, "Research Note: Soviet Thermonuclear Development," *International Security* 4, no. 3, Winter 1979/80, p. 195.

dose of the sphere to 300 mR/hr.[120] I calculate that even this small amount of shielding was able to reduce the gamma dose by about a factor of eight. Coating the neptunium with a half a centimeter of uranium would reduce the exposure from its gamma rays by a factor of about 200.

That neptunium and especially U-233 can be used to produce nuclear weapons is a clear indication that the increased radiation from reactor-grade plutonium will not prevent its use in a nuclear weapon.

Critical Mass

The critical mass of reactor-grade plutonium is larger than that of weapon-grade plutonium but it was authoritatively shown by Robert W. Selden of Lawrence Livermore Laboratory as long ago as 1976 that the critical mass of reactor-grade plutonium is significantly less than that of highly enriched uranium (HEU) and therefore can be readily used to produce nuclear weapons.[121] However, one still finds statements that do not accurately reflect the relative critical masses of these different types of plutonium. For example it has been claimed that while a nuclear weapon would require only three kilograms of weapon-grade plutonium, using reactor-grade plutonium would require eight kilograms and using plutonium recovered from mixed oxide fuel (MOX—fuel that was initially plutonium and uranium oxides) would require over 20 kilograms.[122] Therefore, it is useful to review this issue.

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120. Rene G. Sanchez, et.al., "Criticality of a ^{237}Np Sphere," Los Alamos National Laboratory, 2003.

121. Robert W. Selden, "Reactor Plutonium and Nuclear Explosives," Lawrence Livermore National Laboratory, November 1976.

122. Bruno Pellaud, "Proliferation aspects of plutonium recycling," *Journal of the Institute of Nuclear Material Management*, Fall 2002, p. 4.

Part of the confusion concerning the critical mass of reactor-grade plutonium is that the isotopes Pu-238, Pu-240, and Pu-242 are not readily fissioned by thermal neutrons. The isotopes Th-232 and U-238 are also not readily fissioned by thermal neutrons and these latter isotopes cannot sustain the fast neutron chain reaction needed to produce a nuclear explosion. It was initially assumed that these three plutonium isotopes could not sustain a fast chain reaction as well and their presence in reactor-grade plutonium would act as neutron poisons. As long ago as 1969, it was known that this was not always the case and that some isotopes that cannot sustain a thermal chain reaction can sustain the fast neutron chain reaction.[123] Selden showed that all three of these even-numbered plutonium isotopes can sustain a fast neutron chain reaction. More modern information has demonstrated that all the isotopes of neptunium, plutonium, americium, and curium, which have half-lives of greater than ten years, can sustain a fast neutron chain reaction. Indeed, of all the long-lived actinide isotopes, only Ac-227, Th-230, Th-232, U-236, and U-238 cannot sustain a fast neutron chain reaction.[124]

The unreflected[125] critical masses of various nuclear materials relevant to the production of nuclear weapons are shown in Table 11.[126] Not all critical masses have been determined by direct mea-

123. S. R. Bierman and E. D. Clayton, "Criticality of Transuranium Actinides-Undermoderated Systems," *American Nuclear Society Transactions* 12, 1969. At that time data was only available for Pu-238 and Cm-244.

124. E. D. Clayton, "Anomalies of Nuclear Criticality, Revision 6," PNNL-19176, Pacific Northwest Laboratory, Richland, Washington, February 2010, pp. 108-112.

125. Bare nuclear material not surrounded by any neutron reflecting substance. Neutron reflectors can substantially reduce the critical mass of some nuclear materials.

126. E. D. Clayton, "Anomalies of Nuclear Criticality, Revision 6," PNNL-19176, Pacific Northwest Laboratory, Richland, Washington, February 2010, pp. 108-112; "Evaluation of nuclear criticality safety data and limits for actinides

surement but are instead based on nuclear calculations. Therefore the estimated critical masses are a range, since different computer codes give different results. As can be seen, Pu-238 and Pu-241 have critical masses very similar to that of Pu-239. Pu-240's critical mass is somewhat larger but still less than that of HEU. Only Pu-242's critical mass is larger than that of HEU but even in plutonium produced in high burnup LWR fuel, this isotope is less than eight percent of the total plutonium and will not result in a great increase in the critical mass. Direct measurement of the critical mass of relatively low-burnup reactor-grade plutonium compared to weapon-grade plutonium shows only a 14% increase. For high-burnup reactor-grade plutonium the critical mass increase would be no more than about 50% which is about half that of HEU. Such material could easily be used to produce nuclear weapons.

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in transport," C4/TMR2001/200-1, Institut de Radioprotection et de Surete Nucleaire; Hemanth Dias, Nigel Tancock and Angela Clayton, "Critical Mass Calculations for ^{241}Am, ^{242m}Am, and ^{243}Am," JAERI-Conf 2003-019; Rene G. Sanchez, et.al., "Criticality of a ^{237}Np Sphere," Los Alamos National Laboratory, 2003; and R. W. Brewer, "242 Pu Critical Mass," LA-UR-99-3509, Los Alamos National Laboratory.

Nuclear Material	Critical Mass (Kilograms)	Directly Measured
Highly Enriched Uranium*	52.4	Yes
Weapon-Grade Plutonium** Delta phase	16.9	Yes
Reactor-Grade Plutonium*** Delta phase	19.3	Yes
Pu-238 Alpha phase	7 to 9	No
Pu-239 Alpha phase	10.0	Yes
Pu-240 Alpha phase	33 to 39	No
Pu-241 Alpha phase	12 to 13	No
Pu-242 Alpha phase	82 to 89	Yes
U-233****	16.2	Yes
Np-237	~ 60	Yes
Am-241	56 to 108	No

TABLE 11: Unreflected Fast Critical Mass of Various Nuclear Materials

*93.7% U-235

**95.2% Pu-239, 4.5% Pu-240 and 0.3% Pu-241

***76.3% Pu-239, 20.2 % Pu-240, 3.1% Pu-241 and 0.4% Pu-242

****98.1% U-233, 1.3% U-234 and 0.6% U-238

The critical mass of U-233 is similar to that of weapon-grade plutonium. The critical mass of neptunium is similar to that of HEU, which explains why this material is now considered capable of being used to produce a nuclear weapon. There is still a significant range of estimates for the critical mass of Am-241 and therefore its usefulness as a nuclear weapon material must be considered somewhat uncertain.

In sum, neither the increased radiation from reactor-grade plutonium nor its increased critical mass prevent this material from being used to produce nuclear weapons. The gamma radiation from the cores of nuclear weapons made from reactor-grade plutonium can be easily shielded using a one half centimeter layer of natural uranium. The neutron radiation is low enough so as to not have a serious effect on military personnel.

The processing of reactor-grade plutonium will not pose serious problems for new nuclear proliferants since these countries are unlikely to handle large amounts of reactor-grade plutonium each year. They also have the option to handle the plutonium remotely using computer controlled equipment, process the plutonium soon after chemical separation, or simply expose their workers to higher amounts of radiation than U.S. standards would allow. That U-233, which can emit high doses of penetrating radiation, has been used to produce nuclear test devices is a clear indication that the increased radiation from reactor-grade plutonium will not pose a serious problem for its use in nuclear weapons. The critical mass of reactor-grade plutonium from high burnup LWR fuel is about half that of HEU and therefore can be readily be used to produce nuclear weapons.

Chapter 7

How Sweden and Pakistan Planned and India May Be Planning to Use Reactor-Grade Plutonium to Make Weapons

As was discussed in chapter three, the preferred isotopic composition of plutonium for nuclear weapons would be pure Pu-239, but it is not feasible to produce large quantities of such plutonium. Instead, countries have been forced to make do with the inferior choice of weapon-grade plutonium that contains at least several percent Pu-240. Yet countries have gone ahead and manufactured tens of thousands of nuclear weapons using this less than optimal nuclear material.

Reactor-grade plutonium is clearly less desirable for the manufacture of nuclear weapons than is weapon-grade plutonium. As was discussed in the introduction, many have used this fact to claim that though reactor-grade plutonium can be used to make a nuclear explosion this is just a technicality. They argue that the difficulties of using reactor-grade plutonium are so great that no country would actually use it to produce nuclear weapons. The historical experience of the five major nuclear weapon states is sometimes cited as confirming this argument since none of them ever considered using reactor-grade plutonium in their nuclear weapons.

But this is rather misleading since none of the five major nuclear weapon states had the option to use reactor-grade plutonium even if

they had wanted to. Attempting to produce reactor-grade plutonium with the low power density, graphite moderated plutonium production reactors that these countries used to produce their first plutonium would have added many years to the plutonium production time. Further, when the United States first attempted to use such a reactor to produce reactor-grade plutonium in the late 1950s, it failed (see chapter eight).

The test case for such a proposition is one where reactor-grade plutonium is much more readily accessible compared to weapon-grade plutonium especially since, as was discussed in prior chapters, the use of reactor-grade plutonium for the manufacture of nuclear weapons is not nearly so difficult as some imagine. In the two historical cases of Sweden and Pakistan where only reactor-grade plutonium was readily available, the countries did not terminate their weapons programs. If reactor-grade plutonium were truly unsuitable for use in nuclear weapons, then countries that had ready access only to reactor-grade plutonium should have given up their attempt to produce nuclear weapons. However, both Sweden and Pakistan were not deterred and were prepared to move ahead using reactor-grade plutonium. That these two countries did not produce nuclear weapons from reactor-grade plutonium had nothing to do with the properties of this material. In the case of Sweden, it wound down its nuclear weapon program before it made any final decision to produce nuclear weapons. In the case of Pakistan, U.S. counteraction led France to cancel the sale of the reprocessing plant that was needed to obtain the reactor-grade plutonium and the theft of centrifuge technology from the Netherlands provided Pakistan with other options.

India has access to weapon-grade plutonium, but the quantities it has produced may be insufficient for the needs of its nuclear arsenal. India has retained the option to use reactor-grade plutonium in its nuclear weapon program by exempting eight of its nuclear power reactors from International Atomic Energy Agency (IAEA) safe-

guards. India may have already exercised this option such that up to half of its nuclear arsenal could be composed of nuclear weapons made with reactor-grade plutonium.

This chapter will not provide comprehensive histories of these countries' nuclear weapons programs but will simply discuss the role reactor-grade plutonium played in them. As far as I am aware, this is the first time that the role of reactor-grade plutonium in the nuclear weapon programs of Sweden and Pakistan has been examined, even though this information has been available for decades.

Sweden's Nuclear Weapon Program

In 1945, Sweden found that it needed to explore and develop a number of new technologies that had been used in World War II if it was to maintain the strong defense vital to ensure its neutrality. Jet aircraft and radar were two such technologies; nuclear weapons were another.

Sweden was also interested in the possibilities of nuclear power, and its nuclear development program focused on both nuclear power and nuclear weapons, though its public statements emphasized the former rather than the latter. Over time, Sweden's military generated a requirement for one hundred simple fission weapons with yields in the low tens of kilotons. Sweden intended to employ the weapons tactically to disrupt a Soviet invasion by striking embarkation ports, invasion forces at sea, or even enemy forces that had landed on Swedish territory.[127]

127. Paul M. Cole, "Sweden without the Bomb: The Conduct of a Nuclear Capable Nation without Nuclear Weapons," Santa Monica, CA: RAND, 1994, available from https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR460.pdf.

Sweden planned to produce plutonium using natural uranium fueled heavy water reactors. Sweden possesses large uranium deposits which had been discovered at the beginning of the twentieth century when there was an interest in mining radium.[128] In the 1950s, Sweden began to develop its resources so as to produce uranium that was unencumbered by foreign restrictions. However, the concentration of uranium in the Swedish ore is only 200 ppm.[129] With the discovery of uranium deposits in the United States with ten times this concentration of uranium, the Swedish deposits were uneconomical.[130] Only 215 metric tons of uranium were produced before production was shut down in 1969.

Sweden hoped to acquire large quantities of heavy water without use restrictions from Norway but ultimately received most of its heavy water from the United States. Sweden realized that the only likely way to acquire large quantities of heavy water without use restrictions would be to produce it itself. Sweden has large hydroelectric resources and could use electrolysis to produce heavy water in a manner similar to Norway. Sweden performed pilot studies but ultimately did not build its own heavy water plant.[131]

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128. Jan Lindholm, "The Ranstad Uranium Mine in Sweden," April 27, 2007, available from http://nonuclear.se/lindholm20070427.html.

129. V. E. McKelvey, "Uranium in the Upper Cambrian Black Shale of Sweden," United States Department of the Interior, Geological Survey, January 1955, available from https://pubs.usgs.gov/tei/0495/report.pdf

130. Even richer deposits were later discovered in Canada and Australia. Although the Swedish deposits may contain up to one million metric tons of uranium, they are no longer counted as conventional uranium resources. "Uranium 2014: Resources, Production and Demand," Nuclear Energy Agency and Organization for Economic Co-operation and Development, 2014, available from https://www.oecd-nea.org/ndd/pubs/2014/7209-uranium-2014.pdf.

131. Thomas Jonter, "Nuclear Weapons Research in Sweden: The Co-operation between Civilian and Military Research, 1947 – 1972," SKI Report 02:18, May 2002, available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/42/022/42022455.pdf.

Sweden would also need to reprocess the spent uranium fuel in order to separate the plutonium. Sweden constructed a plutonium laboratory, which contained a number of glove boxes and performed experiments on small quantities of plutonium acquired from foreign countries. The plutonium laboratory was completed in 1959. This facility had a limited plutonium reprocessing capability. Sweden considered building a large-scale reprocessing plant but ultimately did not.[132]

Sweden's first nuclear reactor, the R1, started operation in 1954. It used French uranium and Norwegian heavy water and was free of any encumbrances on the use of the plutonium produced by the reactor. However, with a power level of 600 kW it could only produce about 100 grams of plutonium per year.

Sweden began to construct its first nuclear power reactor, Agesta, in 1957. Agesta went into commercial operation in 1964.[133] The reactor was an indigenous design which used natural uranium fuel and heavy water as the moderator. It had a thermal power output of 65 MW which was later increased to 80 MW. It used 76 metric tons of heavy water, a significant portion of which came from the United States. Agesta could produce about 15 to 20 kilograms of plutonium per year, which would be enough for about three or four nuclear weapons per year. Agesta's rate of plutonium production was too low to produce a 100 weapon arsenal in a reasonable amount of time and for this reason the focus on plutonium production for nuclear weapons was on the larger follow-on power reactor, Marviken.

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132. Ibid.

133. N. Rydell, P. Blomberg and E. Ericsson, "Experience from the commissioning, the criticality experiments and the power operation of the Agesta nuclear power plant," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy*, Volume 5, Nuclear Reactors-I. Gas-cooled and Water-cooled Reactors, United Nations, New York, 1965.

In 1960, Sweden designed the Marviken power reactor as a scaled-up version of Agesta.[134] With a 400 MW thermal power output it would produce about 110 kilograms of plutonium per year which, would be enough for about 18 to 22 weapons per year. Such a reactor would be able to produce enough plutonium for a 100 weapon arsenal in about five years.

However, the desire to produce a more economical nuclear power reactor led to a major redesign of the Marviken reactor in 1962 and 1963. The reactor had a number of unusual features including an on-line refueling machine located *inside* the reactor's pressure vessel.[135] It would also use enriched uranium, which would have to be imported from the United States. Peaceful use restrictions imposed by the United States would make it difficult to use this reactor for the production of plutonium for nuclear weapons.

In a separate effort, Sweden produced a design for a boiling water reactor which used light (ordinary) water as the coolant. Like all other LWRs, this design used enriched uranium which would have to be imported from the United States. The design was similar to that of General Electric's boiling water reactors. In 1965 the first of these reactors, Oskarshamn 1, was ordered. With a thermal output of 1,375 MW, this reactor was the first full-scale nuclear power reactor in Sweden.

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134. Carl-Erik Wikdahl, "Marvikenreaktorn-ett industripolitiskt utvecklingsprojekt i otakt med tiden," SKI Rapport 2007:18, April 2007, available from https://www.stralsakerhetsmyndigheten.se/contentassets/cc1a3c563fd3457a8787b88f0f42b9e2/200718-marvikenreaktorn---ett-industripolitiskt-utvecklingsprojekt-i-otakt-med-tiden.

135. P. H. Margen, L. Leine and R. Nilson, "The design of the Marviken boiling heavy-water reactor with nuclear superheat," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy*, Volume 6, Nuclear Reactors-II. Fast Reactors and Advanced Concepts, United Nations, New York, 1965.

Sweden planned to produce weapon-grade plutonium for its nuclear weapons. A 1963 study considered using either plutonium that was 2.0% Pu-240 or plutonium that was 3.5% Pu-240.[136] However with the rise of LWRs in the Swedish nuclear power program, there was an interest in what could be achieved using reactor-grade plutonium. In November 1965, Torsten Magnusson, who was head of the Swedish nuclear weapon design effort, addressed this issue at a conference on nuclear weapon cores. He said:

> It is important in this situation to keep one's eyes on what could be done from a military technical viewpoint, through the use of ordinary reactor plutonium.
>
> A certain amount of energy could obviously be obtained from reactor plutonium (Pu 238) [sic] simply by making a plutonium lump, compressing it and letting whatever happens happen. The initiation itself cannot be controlled.
>
> We have studied the energies which could be achieved by using reactor-grade plutonium in this manner. The limit for what might be possible to extract is likely to be in the region of 1 kiloton. That is to say, in taking a lump of reactor plutonium and compressing it, it seems likely, no matter how big this lump is made, that you cannot get significantly more than 1 kiloton.

136. Thomas Jonter, "Nuclear Weapons Research in Sweden: The Co-operation between Civilian and Military Research, 1947 – 1972," SKI Report 02:18, May 2002, available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/42/022/42022455.pdf.

> If a strong reflector is laid on top of the material, this will have a tamping effect. In that situation, a few kilotons could be achieved.
>
> *But in either case, in the 1-kiloton range a probable possibility appears to exist for making nuclear cores with reactor plutonium as weapon material.*
>
> *We wanted to show this example, above all, because of the conceivable opportunities that are hidden here.*[137] [Emphasis added]

It is clear that the man in charge of the Swedish nuclear weapon design effort did not consider the use of reactor-grade plutonium a show-stopper. It was realized that building a dedicated plutonium production reactor to produce weapon-grade plutonium was the preferred option, but Sweden did not take this step any more than it built its own heavy water production or reprocessing facilities. Ultimately, the weapons usability of reactor-grade plutonium turned out to be irrelevant since by the time Oskarshamn 1 started operation in 1972, Sweden had already signed the Non Proliferation Treaty in 1968 and ratified it in 1970. Curiously, Sweden conducted plutonium explosive compression tests into 1972. Due to uncertainties about the workability of some of its unique features and having been leap-frogged by Oskarshamn 1, Marviken was completed but never put into operation. Agesta was shut down in 1972 as being uneconomic.

Even before Oskarshamn 1 had been completed, Sweden began ordering additional LWRs and by the mid-1970s, 12 reactors were on order, under construction or in operation. A committee (the Aka

137. Christer Larsson, "The History of a Swedish Atomic Bomb 1945-1972," Ny Teknik, no. 17, April 25, 1985, translation from U.S Foreign Broadcast Information Service.

committee) was formed to address the issue of nuclear waste. In its 1976 report, the committee recommended that the spent fuel from these reactors be reprocessed and that Sweden build its own reprocessing plant.[138] To avoid the obvious nuclear weapon implications of this decision, the committee claimed that the plutonium produced by Swedish LWRs was denatured:

> The plutonium which is produced in Swedish power reactors contains as much as 25 to 30% of plutonium-240. Such plutonium can only be utilized in weak and probably unreliable nuclear charges of highly questionable military value.[139]

This episode shows that, whether by ignorance or design, countries that are aware of the dangers of reactor-grade plutonium can still perpetuate the myth of denatured plutonium. At any rate, Sweden never built its own reprocessing plant and now prefers that spent LWR fuel be directly disposed of without reprocessing.

The bottom line is that the Swedish nuclear weapon effort planned to produce weapon-grade plutonium using natural uranium fueled heavy water reactors. However, when it became clear that such reactors would not be feasible under the constraints of the Swedish nuclear power program and that the emphasis had shifted to LWRs producing reactor-grade plutonium, the Swedish nuclear weapon design effort did not end. Rather, the Swedish program correctly calculated that nuclear weapons with yields in the low kilotons could still be produced. Sweden's head of its nuclear weapon design effort considered using reactor-grade plutonium for the cores of nuclear weapons "a probable possibility."

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

139. Ibid., p. 43.

Pakistan's Nuclear Weapon Program

In early 1972, in the aftermath of its defeat in the 1971 Indo-Pakistan War that led to Bangladesh's independence, Pakistan embarked on a nuclear weapon program. Like all countries developing nuclear weapons, the main requirement for such an effort was to acquire the nuclear material needed for the weapons, and Pakistan initially appears to have chosen plutonium. A key step in the Pakistani program was to negotiate with France for a large-scale reprocessing plant. Pakistan signed the initial contract with France in March 1973 and the final contract on October 18, 1974.

A question that is seldom asked in the accounts of Pakistan's nuclear weapon program is what spent fuel was Pakistan planning to reprocess in this plant? Since at that time Pakistan had only one source of spent fuel, the KANUPP nuclear power plant, the obvious answer is that Pakistan planned to violate safeguards, reprocess the spent fuel from this reactor, and use the resulting reactor-grade plutonium to produce nuclear weapons. However, this obvious conclusion is often either ignored or met with denial.

For example, Feroz Hassan Khan, the former director of Pakistan's nuclear Strategic Plans Division, has cited various Pakistani sources who claim that Pakistan would never have violated safeguards on KANUPP to produce nuclear weapons but would have only used indigenous facilities.[140] But what were Pakistan's options? A 1978 U.S. intelligence study correctly outlined the three possibilities.[141]

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140. Feroz Hassan Khan, *Eating Grass: The Making of the Pakistani Bomb*, New Delhi: Foundation Books, 2013, pp. 192-194.

141. "Proliferation Group Quarterly Report, January-March 1978," Lawrence Livermore Laboratory, June 1978, formerly TOP SECRET, unclassified with redactions.

First, Pakistan could build its own plutonium production reactor. However, there is no evidence that Pakistan either planned to or had the capability to build its own plutonium production reactor in the 1970s. Pakistan did eventually build such a reactor but it did not start operation until 1998. It is a heavy water moderated plutonium production reactor that required Pakistan to first build a heavy water production plant. Khan claims that Pakistan built the heavy water production plant without foreign design assistance, but given the great difficulties both Canada and India first experienced setting up their own heavy water production plants, Khan's assertion is implausible.[142] Indeed, an unanswered question regarding Pakistan's nuclear weapon program is the source of the foreign assistance for this facility.

Second, Pakistan could produce its own fuel bundles for KANUPP and from this fuel acquire plutonium free from safeguards. In the early years of the reactor's operation, this was not possible as Pakistan could not manufacture fuel for KANUPP. Instead, Canada was supplying all of the reactor's fuel. However, it was only for this reason that there were safeguards at the reactor. This is to say the reactor was not under IAEA safeguards, only the Canadian fuel was. Therefore, if Pakistan could produce fuel for KANUPP, it would not be under safeguards.

Due to Canada's cutoff of nuclear assistance to Pakistan at the end of 1976, Pakistan was actually forced to follow this path and manufacture its own fuel bundles for KANUPP. But this experience demonstrates that this path was not a feasible method for Pakistan to acquire weapon-grade plutonium. It was not until 1980 that Pakistan was able to produce a small quantity of reactor fuel and the rate of fuel production was low during the first half of the 1980s. It

142. Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-Up," *Foreign Policy,* Fall 1986, available from https://www.jstor.org/stable/pdf/1148695.pdf?refreqid=excelsior:af9fae3c3f40b3f5f58696980147342f.

was not until 1986 that the rate of fuel production allowed the reactor to start operating at a capacity factor of higher than 20% and not until 1990 that the last of the Canadian provided fuel was removed from the reactor.[143] Further, this fuel was used in a manner to achieve high burnup so as to conserve the limited supply. Thus even if this had been Pakistan's plan, it would have still only acquired reactor-grade plutonium. The production of weapon-grade plutonium would have required the manufacture of roughly five times as much fuel, something clearly beyond Pakistan's capability. As it is, even with Pakistani fuel, the reactor has continued under IAEA safeguards.

Third, Pakistan could violate safeguards and use the plutonium contained in the KANUPP spent fuel. This is clearly the only option that could have provided Pakistan with plutonium for nuclear weapons before the 1990s. The burnup of the KANUPP spent fuel has been published and one can calculate that the plutonium was mostly reactor-grade with a small amount of fuel-grade.

The KANUPP nuclear power plant is a CANDU type reactor with a design thermal output of 457 MW. Its design total electricity production is 137 MW. Subtracting the 12 MW required to operate the reactor, its design net electrical output is 125 MW. The plant started commercial operation on December 7, 1972, and began to be refueled on June 14, 1973. By the end of 1973 it had discharged 2.75 metric tons of uranium in spent fuel, which had an average burnup of 4,600 megawatt-days per metric ton (MWD/Te).[144] The spent fuel would have contained about eight kilograms of plutonium with a

143. Muhammad Salim, Iqbal Ahmed, and Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP," available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/000/30000477.pdf.

144. R. J. Graham and J. E. S. Stevens, "Experience with CANDU Reactors Outside of Canada, KANUPP, Karachi, Pakistan, RAPP, Rajasthan, India," CNA-74-203, available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/06/160/6160925.pdf.

Pu-240 content of about 18%. This would have been fuel-grade plutonium, almost reactor-grade.

U.S. intelligence incorrectly estimated that KANUPP could produce 60 to 120 kilograms of plutonium per year. However, this estimate failed to take account of KANUPP's low capacity factor. Despite being a one-third scaled down version of the CANDU prototype (Douglas Point), KANUPP produced more electricity than could be absorbed by the small Pakistani grid, especially at night and on weekends. As a result, the reactor was forced to operate at a reduced capacity and KANUPP actually produced about 40 kilograms of plutonium per year in its early years.

Between the beginning of 1974 and April 1977, when Pakistan began to take steps to conserve reactor fuel, the average fuel burnup was 6,561 MWD/Te.[145] For the years 1974 through 1976, KANUPP would have discharged a total of roughly 120 kilograms of plutonium and its Pu-240 content would have been about 23%, making it reactor-grade.

But could Pakistan have run the reactor so as to produce weapon-grade plutonium? The answer is no. As described above, Canada was providing the fuel for the reactor and would have noticed the five-fold increase in fuel consumption that would have attended the production of weapon-grade plutonium. Canada would have cut off the supply of fresh fuel. From the operation of KANUPP after Canada did cut off the fuel supply in December 1976, it appears that the reactor had about a one year supply of fuel on hand, which was about 11.5 metric tons. If Pakistan would have used this fuel to produce weapon-grade plutonium, it would have only been able to produce about 12

145. Muhammad Salim, Iqbal Ahmed, and Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP," available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/000/30000477.pdf.

kilograms of plutonium.[146] This would have been enough for only two or three weapons, hardly enough for Pakistan to be able to face a possible Indian nuclear arsenal. In contrast, the roughly 120 kilograms of reactor-grade plutonium accumulated at the reactor to the end of 1976 would be enough for about 20 nuclear weapons.

Khan has incorrectly claimed that it was the cutoff of Canadian fuel in 1976 that led KANUPP to produce low burnup spent fuel (what Khan calls "slow burned"). Actually, the opposite is true. When the reactor first started operation, the reactor operated with a flux flattened central zone in order to produce the design power output. In 1977, to conserve fuel and increase burnup, the flux in the central zone was allowed to peak. While the reactor operated in this fashion, the average spent fuel burnup increased to almost 8,000 MWD/Te and the resulting plutonium would have contained 26% Pu-240.[147] The price for this increased burnup was to lower the reactor electrical output from 137 MW to 105 MW. From 1986 to 1990 as the supply of Pakistani produced fuel began to increase, some flattening was restored and the power level increased to 112 MW. It was later increased to 120 MW but is now limited to less than 100 MW due to the deterioration of the reactor, which is scheduled to be permanently shut down in 2019.

Due to pressure from the United States, France began to delay the sale of the reprocessing plant and eventually cancelled it in 1978, though Pakistan may have acquired some important technical information in the process. At the same time, Pakistan began to develop centrifuge enrichment using technology stolen from the Netherlands. By the late 1980s, Pakistan had produced its first nuclear weapon

146. Fuel burnup 1,300 MWD/Te, 5.9% Pu-240.

147. Muhammad Salim, Iqbal Ahmed, and Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP," available from http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/000/30000477.pdf.

using highly enriched uranium. As was discussed above, in 1998, Pakistan's first plutonium production reactor went into operation. By about 2000, Pakistan would have produced and separated its first plutonium for nuclear weapons.

None of this should be allowed to obscure the main point. If Pakistan had acquired a reprocessing plant from France, Pakistan was fully prepared to violate the safeguards on the KANUPP spent fuel and use the plutonium from this reactor to produce nuclear weapons. This plutonium would have been reactor-grade with a Pu-240 content of about 23%.

India's Nuclear Weapon Program

Unlike both Sweden and Pakistan, for whom the option of using reactor-grade plutonium in nuclear weapons has likely long passed, India has taken steps to ensure that it currently has the option of using reactor-grade plutonium in its nuclear weapons. Further, there is some possibility that India has already deployed nuclear weapons which use reactor-grade plutonium.

As part of the 2006 India-U.S. nuclear deal, India pledged to place its "civilian" nuclear facilities under IAEA safeguards. India exempted eight nuclear power reactors from the list of civilian facilities. This is somewhat surprising since India already had two natural uranium fueled, heavy water moderated, plutonium production reactors (CIRUS and Dhruva, which are termed "research reactors"). However, this 2006 exchange between science journalist Pallava Bagla and Anil Kakodkar, chairman of India's Atomic Energy Commission is illuminating:

> Bagla: Is your strategic need for plutonium not met by CIRUS and Dhruva? Do you need additional capacity from civilian reactors?
>
> Kakodkar: "Yes, very clearly. Not from civilian reactors, but from power reactors."[148]

This statement characterizes these eight power reactors as military and not civilian. At first glance, it is not clear why India has taken this step since using nominal production figures, I will illustrate that CIRUS and Dhruva should have produced more than enough weapon-grade plutonium for India's nuclear weapon program.

CIRUS was provided to India by Canada and was a copy of Canada's NRX reactor. As part of the 1958 paper describing CIRUS, the Canadians pointed out that one of the four purposes of the NRX reactor was "the production of plutonium."[149]

CIRUS had a nominal thermal power output of 40 MW and began sustained operation in the early 1960s. By 1965, India had already produced plutonium metal using material derived from this reactor[150] and it also provided the plutonium for India's 1974 "peaceful nuclear explosive." The reactor was shut down for refurbishing between 1997

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148. "India ratifies an additional protocol and will safeguard two more nuclear power reactors," *International Panel of Fissile Materials Blog*, July 1, 2014, available from http://fissilematerials.org/blog/2014/07/india_ratifies_an_additio.html.

149. R. D. Sage, D. D. Stewart, H. B. Prasad, and H. N. Sethna, "Canada-India Reactor," *Papers Presented by Canada-India to the Second International Conference on the Peaceful Uses of Atomic Energy*, Geneva, Switzerland, September 1-13, 1958, P-1704. It is a measure of the lax thinking of the time that Canada saw no nuclear weapon dangers in providing CIRUS to India.

150. Shri N. Srinivasan, "Fuel Reprocessing-The Initial Years," IANCAS Bulletin, July 1998, available from http://www.igcar.gov.in/rpg/articles/N%20Srinivasan%20on%20Reprocessing.pdf.

and 2002 and, as part of the terms of the 2006 India-U.S. nuclear deal, the reactor was permanently shut down at the end of 2010.

Dhruva has a nominal thermal power output of 100 MW. It was constructed by India and began sustained operation in 1988. It is still in operation today.

Using nominal numbers for reactor operating time and plutonium production, Dhruva should produce about 20 kilograms of weapon-grade plutonium per year and CIRUS about 8 kilograms.[151] Assuming Dhruva has operated for 27 years[152] and CIRUS operated 42 years over its lifetime, this would result in a total production of 876 kilograms of separated weapon-grade plutonium. Assuming that 131 kilograms has been consumed by nuclear testing and other operations[153], a net total weapon-grade plutonium stockpile of 745 kilograms would remain. Assuming 5 kilograms of plutonium per weapon, this stockpile would be sufficient to produce 149 nuclear weapons, more than enough given the nominal estimates of 120 to 130 nuclear weapons in India's arsenal.[154]

However, for many years there have been indications that these two reactors' capacity factors were not nearly as high as the nomi-

151. Assuming 250 days of operation per year (68.4% capacity factor), 0.8 kilograms of plutonium produced per 1,000 MWDs of operation, and plutonium 6% Pu-240.

152. 1988 through 2015, assuming that the more recent fuel discharges have not yet been reprocessed.

153. Zia Mian, A. H. Nayyar, R. Rajaraman, and M. V. Ramana, "Fissile Materials in South Asia and the Implications of the U.S.-India Nuclear Deal," *Science and Global Security* 14, 2006, p. 123, available from https://www.princeton.edu/sgs/publications/articles/Fissile-Materials-South_Asia-SGS-2006.pdf.

154. Hans M. Kristensen and Robert S. Norris, "Indian Nuclear Forces, 2017," *Bulletin of the Atomic Scientists* 73, no. 4, 2017, available from http://www.tandfonline.com/doi/pdf/10.1080/00963402.2017.1337998?needAccess=true.

nal calculations assume. Buried in a number of India's Department of Atomic Energy's Annual Reports are the quantities of fresh fuel provided to these reactors. If Dhruva were to operate at the 68.4% capacity factor that I assumed, then the reactor would require about 20.8 metric tons of fresh fuel per year.[155] However, for the four years for which data was provided (Annual Reports for the years 2004-2005, 2006-2007, 2009-2010, and 2011-2012) only an average of 9.4 metric tons of fresh fuel was provided each year. This implies a capacity factor of 31 percent, which would mean that Dhruva would only produce about 9 kilograms of plutonium per year instead of 20.

India recently confirmed Dhruva's poor performance.[156] For almost all of its operating life it never had a sustained power level of more than 50 to 60 MW. The 53 percent capacity factor that the reactor achieved in 2014 was its highest ever.[157]

Similar data for CIRUS reveals a capacity factor of about 40 percent and an annual plutonium production rate of 4.7 kilograms. Using these revised annual plutonium production rates for these two reactors results in a total gross plutonium production of 440 kilograms and a net plutonium production of 309 kilograms. This amount of plutonium is only sufficient for about 62 nuclear weapons. It is possible that India's nuclear weapon arsenal is significantly smaller than is generally assumed but if it is not then India has manufactured up to half of its nuclear arsenal using plutonium produced in its unsafeguarded nuclear power reactors.

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155. Assuming a fuel burnup of 1,200 MWD/Te to produce plutonium with a Pu-240 content of 6%.

156. "Operation of Dhruva Reactor at Rated Power of 100 Mw on Sustained Basis," *BARC Newsletter*, March-April 2016, available from http://www.barc.gov.in/publications/nl/2016/2016030401.pdf.

157. The performance of the Dhruva reactor has continued to improve. In 2015 its capacity factor was 62% and in 2016 it was 61%. Therefore for these two years Dhruva has been producing about 18 kilograms of plutonium per year.

Could these unsafeguarded power reactors have produced large amounts of weapon-grade plutonium? The answer is no.

India's nuclear power reactors use a two-zone burnup configuration.[158] The inner 78 fuel channels have a target exit burnup of 10,000 MWD/Te and the outer 228 fuel channels have a target burnup of 5,500 MWD/Te. This produces an average burnup of about 6,650 MWD/Te and plutonium that is about 24% Pu-240. Even the 5,500 MWD/Te fuel has a Pu-240 content of about 20%.

It would have been difficult for India to produce large amounts of weapon-grade plutonium in its unsafeguarded nuclear power reactors. Until recently, India had a shortage of uranium and the production of weapon-grade plutonium requires about five times as much fuel as compared to the normal operation of the reactor.

Separating the weapon-grade plutonium would also pose a problem. The Trombay reprocessing plant where India produces all of its weapon-grade plutonium cannot process the uranium oxide fuel used in India's nuclear power reactors. Reprocessing the oxide fuel in one of India's plants which handle power reactor spent fuel would result in the plutonium being comingled with reactor-grade plutonium, unless the reprocessing plant were first shutdown and completely flushed out.

It has been proposed that India plans to use the reactor-grade plutonium from these eight unsafeguarded power reactors to fuel its Prototype Fast Breeder Reactor (PFBR).[159] In the process of this

158. S. S. Bajaj and A. R. Gore, "The Indian PHWR," Nuclear Engineering and Design, 2006, available from http://www.sciencedirect.com/science/article/pii/S0029549306000707.

159. Alexander Glaser and M. V. Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security* 15, 2007, available from http://scienceandglobalsecurity.org/archive/

reactor's operation, some of the reactor-grade plutonium would be converted into weapon-grade plutonium. While this is a possibility, it was more plausible ten years ago when this idea was first proposed and the PFBR was due to start operation in 2010. The start date of the PFBR has repeatedly slipped and is now scheduled for mid-2018. Meanwhile, India needs to try to match Pakistan's growing nuclear arsenal now.

Therefore, there is a distinct possibility that India has produced up to half its nuclear arsenal using reactor-grade plutonium. At the very least, the low plutonium production from Dhruva and CIRUS makes it clear as to why India has preserved the option of using reactor-grade plutonium in nuclear weapons by exempting eight of its nuclear power reactors from IAEA safeguards.

In sum, when faced with the option of either shutting down their nuclear weapon programs or using reactor-grade plutonium, both Sweden and Pakistan chose to use reactor-grade plutonium. Sweden's head of its nuclear weapon design effort considered using reactor-grade plutonium for the cores of nuclear weapons "a probable possibility." Pakistan's only source of spent fuel to be processed in the reprocessing plant that it attempted to purchase from France in mid-1970s was its KANUPP power reactor. Published burnup figures show that the plutonium produce by KANUPP was reactor-grade. Pakistan did not have sufficient fuel for KANUPP to produce large quantities of weapon-grade plutonium. That neither country eventually produced nuclear weapons from reactor-grade plutonium should not be allowed to obscure these facts.

India has access to weapon-grade plutonium but the poor performance of its two plutonium production reactors has resulted in a plutonium stockpile that is significantly smaller than is generally assumed. This explains why India has retained the option of using

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reactor-grade plutonium in its nuclear arsenal by declaring eight of its nuclear power reactors to be military and not civilian. India's nuclear arsenal may be significantly smaller than is generally assumed, but if it is not, then India has already used reactor-grade plutonium to produce up to half of its nuclear stockpile.

Chapter 8

Did the U.S. and the British Test Reactor-Grade Plutonium in Nuclear Weapons?

Several nuclear tests regarding the usability of reactor-grade plutonium in nuclear weapons have generated controversy. In 1977, the United States revealed that in 1962 it had successfully tested a weapon with reactor-grade plutonium. While this would seem to definitely settle the issue of the usability of reactor-grade plutonium in nuclear weapons, instead it has been heavily disputed. Advocates of the viewpoint that reactor-grade plutonium is denatured have claimed that the plutonium used in the 1962 test could not have been reactor-grade but only fuel-grade, with a Pu-240 content perhaps as low as 12%. Both the United States and UK have confirmed that the plutonium for this test originated in the UK but a number of sources have falsely claimed that the British were not producing any reactor-grade plutonium in 1962. In fact, the plutonium in the 1962 U.S. test was 20% to 23% Pu-240 and was produced in British plutonium production reactors. I published this information in 2013 but it continues to be ignored.[160]

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160. 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, available from http://nuclearpolicy101.org/wp-content/uploads/2013/05/Reactor-grade-plutonium.pdf.

In 1953, the British conducted two nuclear tests in the Totem test series. One of the purposes of these tests was to examine the effect of increasing the percentage of Pu-240 in the plutonium used in British nuclear weapons. This has led to the claim that the British tested high Pu-240 plutonium in at least one of these tests. Further, it has been claimed that since the British did not use high Pu-240 plutonium in their weapons, they must have found the test results "unsatisfactory," thereby providing an illustration of the unsuitability of reactor-grade plutonium in nuclear weapons. However, calculations of the burnup that could have been achieved by 1953 in the British Windscale plutonium production reactors show that the plutonium available for the Totem nuclear tests could have been no more than mid-range weapon-grade material, not reactor-grade. As a result, the Totem tests provide no information on the suitability of non-weapon-grade plutonium for nuclear weapons.

1962 U.S. Test of Reactor-Grade Plutonium

In 1977, the United States declassified the fact that in 1962 it had successfully tested a nuclear weapon using reactor-grade plutonium. In 1994, additional information about this test was released.[161] Though on the face of it this test would seem to definitively settle the issue about whether reactor-grade plutonium can be used in nuclear weapons, ironically the specifics related to this nuclear test have generated some of the most controversy.

Only a few facts about this successful nuclear test have been released. Its yield was less than 20 kilotons, it was detonated underground at the Nevada Test Site and the plutonium used in the test

161. "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-Grade Plutonium," U.S. Department of Energy, available from https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc29.html.

was provided to the United States by the United Kingdom under the 1958 United States/United Kingdom Mutual Defense Agreement.

The test was specifically conducted to "obtain nuclear design information concerning the feasibility of using reactor-grade plutonium as the nuclear explosive material."[162] The Department of Energy (DOE) statement goes on to say, "The United States maintains an extensive nuclear test data base and predictive capabilities. This information, combined with the results of this low yield test, reveals that weapons can be constructed with reactor-grade plutonium." This last statement is very important and is almost always ignored in discussions about this test. It says that U.S. statements about the utility of reactor-grade plutonium for the production of nuclear weapons are not based only on this test but rather its entire nuclear test database and the predictive capabilities that have resulted. Therefore the United States need not have conducted nuclear tests with plutonium of all possible concentrations of Pu-240 to know that nuclear weapons can be manufactured from such material.

The United States has not revealed which test in 1962 was the test that used reactor-grade plutonium. The United States conducted the most nuclear tests in 1962 of any year—96.[163] Even if one selects only those tests where the yield is described as being less than 20 kilotons, was conducted underground in Nevada, and was weapons related, one finds that there are 36 such tests, the earliest was January 30 and the latest was December 14.

The United States has not revealed the exact Pu-240 content of the reactor-grade plutonium used in this test. Further, the DOE statement

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162. All quotations in this paragraph are from Ibid.

163. *United States Nuclear Tests*, July 1945 through September 1992, DOE/NV—209-REV 15, U.S. Department of Energy, Nevada Operations Office, December 2000, available from https://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/doe%20nv%202000e.pdf.

about this test points out that in 1962 any plutonium with Pu-240 content higher than 7% would have been considered reactor-grade and that the current definitions of plutonium grades used by the DOE and in particular that of fuel-grade plutonium (Pu-240 between 7% and 19%) did not come into use until the 1970s.[164] Having pointed this fact out, the DOE statement then fails to say which of these two definitions of reactor-grade plutonium it is using when describing this test. This fact has allowed many to claim that the plutonium used in this test was fuel-grade rather than reactor-grade.

In 1996, Alexander DeVolpi, writing in the Physics and Society Newsletter, suggested that there is "government deception" regarding the withheld data on the 1962 test.[165] Based on a personal communication from "R.V. Hesketh," he asserts that British sources claim that the plutonium used in the test could not have been what is now defined as reactor-grade but rather was fuel-grade. Puzzlingly he then says that the plutonium might have been reactor-grade (less than 81% fissile) but near the boundary with fuel-grade plutonium. He also suggests that the plutonium might not have been produced in the UK but rather might have been produced in Canada or even in the United States and then transferred to the UK and then back to the United States to hide the material's origins.

At about the same time, John Carlson et al. from the Australian Safeguards and Non-Proliferation Office (ASNO) suggested that the plutonium used in this test was "what would now be termed

164. The United States currently defines weapon-grade plutonium as having a Pu-240 content of less than 7%. It defines fuel-grade plutonium as having a Pu-240 content of between 7% and less than 19% and defines reactor-grade plutonium as having a Pu-240 content of 19% or more. See, *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.

165. A. Devolpi, "A Coverup of Nuclear Test Information?" *Physics and Society newsletter* 25, no. 4, October 1996.

'fuel-grade,' probably closer to the weapons-grade end of the fuel-grade range."[166] Similar such statements have been made in other ASNO documents. In 2006, ASNO published a diagram which showed that it had revised its views somewhat as it now shows the plutonium having a likely Pu-240 content of between 14% and 18% i.e. near the reactor-grade end of the fuel-grade range.[167] Also in the 1990s, a French government publication claimed that the plutonium used in this test was likely derived from low-burnup fuel and had properties not very different than that of weapon-grade plutonium.[168]

In 2002, Bruno Pellaud, the former Deputy Director General of the International Atomic Energy Agency, stated that the DOE announcement was misleading and that the plutonium used in this test was fuel-grade with a Pu-240 content of only 12%.[169] Pellaud's reference for this important assertion is a private communication from an unnamed source. He also cites Albright et al. as saying that the plutonium could not have been produced at the UK's Calder Hall and Chapelcross military plutonium production reactors since the burnup was too low.[170]

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166. John Carlson, John Bardsley, Victor Bragin, and John Hill, "Plutonium Isotopics—Nonproliferation and Safeguards Issues," Australian Safeguards Office, IAEA-SM-351/64.

167. "Reactor-Grade Plutonium: Use in Weapon Tests," ASNO Information Sheet, December 2006 (revised August 2008).

168. "l'energie nucleaire en 110 questions," Sous la direction de Dominique Maillard Directeur général de l'Energie et des Matières Premières, p. 156.

169. Bruno Pellaud, "Proliferation aspects of plutonium recycling," *Journal of the Institute of Nuclear Material Management*, Fall, 2002, p. 3.

170. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI, Oxford University Press, 1997, pp. 61-62.

Looking at Albright et al.'s statements in more detail, they claim that the U.S. announcement had caused a "lively private debate" between the British and U.S. governments since, as was stated in the last paragraph, it is claimed that Calder Hall and Chapelcross reactors were not producing reactor-grade plutonium. They then go on to contradict this statement by saying that in fact the British Defense Minister had confirmed the U.S. statement to the House of Commons. Despite having official statements from both the British and U.S. governments that the plutonium had originated in the UK, Albright et al. say that the source of the plutonium used in the 1962 test has not been identified and that it is unclear whether the material was produced in the United States or the UK. Though they claim that the source of the plutonium is highly uncertain, they say "it [the plutonium] was definitely fuel- rather than reactor-grade."

Also, though Albright et al. focus on British plutonium production "before 1962," as was noted above, the test might well have occurred in late 1962 (5 of the 36 possible tests referred to above, occurred in December).[171] Therefore, the fuel could have still been in British reactors as late as mid-1962 and there would have still been time for the plutonium to be provided to the United States.[172]

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171. Forrest notes that the Tendrac nuclear test on December 7, 1962 is listed as being a joint US-UK test and suggested that this may be the date of the test. See, Eric Forrest, "Assessing the Proliferation Risk of Reactor Grade Plutonium, Massachusetts Institute of Technology, Fall 2010 p. 7 and United States Nuclear Tests, July 1945 through September 1992, DOE/NV—209-REV 15, U.S. Department of Energy, Nevada Operations Office, December 2000, p. 27.

172. At this time, the British cooled their spent fuel for 100 days before reprocessing. See: J.M. Kay, C.G. James, K. Saddington, and C.J. Turner, "Chemical processes," *The Journal of British Nuclear Energy Conference* 4, no. 2, April 1959, p. 136. If, for example, fuel was discharged on June 30, 1962, then there would be more than enough time (60 days) for the separated plutonium to be transported to the United States and fabricated for a test on December 7.

Statements that the plutonium in the 1962 test was fuel-grade are becoming quite common. For a number of years, the World Nuclear Association stated that the plutonium used in this test contained about 85% Pu-239.[173] This would imply a Pu-240 content of about 13% to 14%. Such statements are now finding their way to sources such as Wikipedia.

Now, why is it so important what the exact Pu-240 content of the plutonium was? Would it make that much difference if the Pu-240 content was 15% as opposed to 20% or 25%? As was discussed above, the purpose of this test was to validate U.S. calculations on the utility of plutonium with a relatively high Pu-240 content. There is no reason why this objective could not be achieved using plutonium with a Pu-240 content of just 15%.

Many of those who assert that the plutonium in the 1962 test was fuel-grade rather than reactor-grade plutonium also then make the statement that in all of the years of nuclear testing no country has ever used reactor-grade plutonium in a nuclear explosive. Such a statement sounds impressive but really is just empty rhetoric. After all, as far as is known, no country has ever used either neptunium or U-235 produced by laser enrichment for a nuclear weapon. Yet the weapons usability of these materials is determined solely by their nuclear and physical properties, not by whether anyone has used them before now. No one doubts that such materials could be used to manufacture nuclear weapons.

At any rate, as we will see, the Pu-240 content of the 1962 nuclear test was in the range of 20% to 23%, i.e. truly reactor-grade. It is quite implausible that it was as low as 12% to 14%.

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173. "Plutonium," World Nuclear Association, updated March 2017 but the WNA has had the identical statement on its website since at least 2009, available from http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx.

At first glance, it does seem odd that the United States would use plutonium obtained from the UK. After all, in the second half of the 1950s, the United States had eight plutonium production reactors in operation at Hanford in Washington State. If the United States wanted plutonium with a high Pu-240, content why would the United States not just make it itself? The answer is that the United States tried but failed.

In October 1957, Hanford received a request from the U.S. Atomic Energy Commission to produce 11 kilograms of plutonium with a Pu-240 content of 20%.[174] This was the first time that Hanford had been asked to produce plutonium with a high Pu-240 content, and fulfilling this request was not a straightforward matter. If Hanford were to irradiate natural uranium to meet this request, it would require Hanford to subject the natural uranium fuel to a burn-up of around 3,800 MWD/Te. As Hanford had not ever irradiated natural uranium to burn-ups of higher than about 1,200 to 1,400 MWD/Te (Pu-240 content of 9% to 10%), this would require burn-ups of roughly triple what had ever been done before.

A constant concern for the reactor operators at Hanford was the rupture of the metallic uranium fuel elements. A rupture would expose the hot metallic uranium to the water coolant, leading it to oxidize and swell, which would block the fuel channel. This could cut off the flow of coolant to the fuel elements in the same fuel channel which in the worst case would lead those elements to overheat, catch fire, and set the entire reactor ablaze. Therefore, there were systems that detected the release of radioactivity when a rupture occurred. The reactor would then have to be shut down

174. "Feature Report: Depleted Uranium Irradiations in the Single-Pass Reactors to Produce High Pu-240 Plutonium," *Monthly Report, September 1968*, DUN-4452, Douglas United Nuclear, Inc., Richland, Washington, October 16, 1968. Note that U.S.AEC operations were compartmented so that for most of its history Hanford was never told why it was requested to produce any particular reactor product including this batch of plutonium.

immediately and the ruptured fuel element removed. In some cases, the fuel element would already be sufficiently swollen so that great force would be needed to remove it from the reactor. Sometimes this effort would damage the aluminum tube in which the fuel and water coolant were contained so badly that the tube would have to be replaced. Or the swollen ruptured fuel element could rupture the fuel channel leading large amounts of water to spill into the reactor. The reactor's graphite would then need to be dried before the reactor could be restarted. Fuel ruptures were a major cause of lost reactor operating time and thereby lost plutonium production. The chance that a fuel element would rupture increased the higher the fuel burn-up.

In order to try to avoid these problems, Hanford decided to use depleted uranium with a U-235 content of only 0.15% instead of the natural concentration of 0.71%. The use of this depleted uranium would lessen the number of fissions that occurred in the fuel and, it was hoped, decrease the chance that the fuel would rupture. Hanford estimated that it would require the irradiation of about 65 to 70 "tubes" (reactor fuel channels) worth of depleted uranium fuel elements to produce the required amount of 20% Pu-240 plutonium.[175] To provide a margin for error, Hanford used 84 tubes of depleted uranium which if totally successful would have produced about 14 kilograms of plutonium with a Pu-240 content of 20%.

On seven different dates during March, April, and May of 1958 these depleted uranium fuel elements were loaded into the C reactor.[176] It was anticipated that it would take irradiations of about 12

175. There were 36 fuel elements in each tube. Only the central 26 were depleted uranium, the other 10 were natural uranium. This arrangement "centered" the depleted elements in the region with higher neutron flux.

176. W.A. Blanton, "I & E Depleted Uranium Fuel Element Ruptures Experienced Under PT-IP-132-AC," HW-58281, General Electric, Hanford Atomic Products Operation, Richland, Washington, December 1, 1958, Appendix II.

to 14 months to produce the required plutonium. However, in September 1958 there was the first fuel rupture in this batch of fuel. This rupture was fuel that had been loaded only six months earlier. In October, there were four more ruptures and five more in November. In addition, there was evidence that swelling in other fuel elements was making it difficult to move them in the fuel channel. All elements in channels containing either ruptured or swollen fuel elements were removed.

By this time, nearly half of the initial fuel elements had been discharged. Hanford manufactured eight additional tubes of depleted uranium fuel elements using what was hoped would be an improved method. These new fuel elements were charged into the C reactor in November 1958. There was an additional rupture in the original depleted fuel in December and two more in January which were only two days apart. As a result, all of the rest of the original depleted uranium fuel was discharged.

Irradiation of the new depleted fuel elements continued, but in September 1959 one of these elements ruptured and all of this fuel was discharged as well.[177] It was determined that the improvement in these newer fuel elements was marginal at best. Nearly two years after the initial request, Hanford had to admit defeat. The United States had entered into a nuclear test moratorium at the end of October 1958 and there was no need for Hanford to continue its efforts. It would not be until 1964 that Hanford would once more try to produce high Pu-240 plutonium. However, this effort did result in the production of about 10 kilograms of plutonium with a Pu-240 content of 15%.[178]

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177. R.E. Hall, "Irradiation Summary Report PT-IP-231-A, Irradiation of Depleted Uranium to High Exposure," HW-62232, October 7, 1959.

178. The initial estimate for the plutonium produced in the 84 tubes was the 9 kilograms with a Pu-240 content of 14%. The additional 8 tubes would have produced roughly one additional kilogram. Later analysis showed that the plu-

The effect of this failure was almost immediate. Hanford had been expecting to receive from Oak Ridge a shipment of 1.2 kilograms of plutonium with a Pu-240 content of 20%.[179] This plutonium was to be used in the Physics Constants Test Reactor. However, Hanford was informed that it would not be receiving this material because "The Division of Military Applications" had exercised "a prior claim" on this material.[180] Work at Hanford had to be suspended, illustrating just how rare plutonium with a high Pu-240 content was in 1959.

In September 1961, the Soviet Union suddenly ended the nuclear test moratorium and the United States raced to conduct a number of nuclear tests. There was no time for Hanford to make another attempt to produce high Pu-240 plutonium and therefore the United States approached the British for help. But how did the British happen to have reactor-grade plutonium? The UK had eight virtually identical plutonium production reactors, four at Calder Hall and four at Chapelcross which were being operated by the United Kingdom Atomic Energy Authority (U.K.A.E.A.). Like the U.S. reactors at Hanford, these eight reactors used graphite as a moderator but unlike the U.S. reactors the British ones were designed to produce electricity as well. There is no British source that states what the burn-up of the fuel from these reactors was during the 1950s and early 1960s but apparently the fuel was only irradiated for about

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tonium had a Pu-240 content of 15%. *Monthly Record Report*, *Irradiation Processing Department, January, 1959*, HW-59041, February 20, 1959 and "Feature Report: Depleted Uranium Irradiations in the Single-Pass Reactors to Produce High Pu-240 Plutonium," *Monthly Report, September 1968*, DUN-4452, Douglas United Nuclear, Inc., Richland Washington, October 16, 1968.

179. This material was apparently produced in the Material Testing Reactor, a high power research reactor.

180. *Hanford Laboratories Operation Monthly Activities Report, November, 1959*, HW-62899, General Electric, Hanford Atomic Products Operation, Richland, Washington, December 15, 1959, p. B-12.

one year.[181] It is easy to calculate that this irradiation period would produce burnups of no more than 1,000 MWD/Te, which would result in plutonium being produced with a Pu-240 content of 8% or less, i.e. British weapons grade plutonium.[182] Since it is known that the primary mission of these reactors during this time was the production of weapons grade plutonium, this is hardly surprising.

The British were also building a series of reactors to be operated by the civilian Central Electricity Generating Board (CEGB). These reactors were scaled up versions of Calder Hall and Chapelcross reactors but their mission was to produce electricity, which for economic reasons meant that they would try to achieve the highest fuel burn-up possible. When these reactors started operation it was thought that the fuel could reach an average burn-up of 3,000 MWD/Te (Pu-240 content of about 17%) and hoped that it might be able to reach 5,000 MWD/Te (Pu-240 content of about 25%—this hope would be fulfilled). However, the first two of these reactors (Berkeley 1 and Bradwell 1) only started operation in the summer of 1962. Since it would take about one year for these reactors to produce plutonium with a Pu-240 content of more than 8%, these reactors were obviously not the source of the plutonium for the 1962 test. At first glance then, neither the plutonium production reactors nor the civil power reactors could have been the source of the plutonium for the 1962 test.

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181. John Cockcroft, "British Experience in the Technical Development of Nuclear Power Reactors," DPR/INF/261, United Kingdom Atomic Energy Authority, May 1961, p. 2.

182. The irradiation for one year at the average neutron flux would produce a burnup of about 500 MWD/Te which would have a Pu-240 content of about 4.5%. The maximum burnup would be about 1,000 MWD/Te. The British define weapons grade plutonium as having a Pu-240 content of 8% or less. Any plutonium with a Pu-240 content greater than this is defined as reactor grade. See, "Plutonium and Aldermaston-An Historical Account," available from http://fissilematerials.org/library/mod00.pdf. Note the British use the term "weapons grade" as opposed to the American "weapon-grade."

The solution to this seeming puzzle is that though the Calder Hall and Chapelcross reactors' primary mission was to produce weapons grade plutonium, it was not their only mission. In particular, with the advent of the CEGB power reactors there was a need to test the fuel that would be used in these reactors to see if they could attain the relatively high burn-up needed to make these reactors economic. What better place to test such fuel than in the Calder Hall and Chapelcross reactors, which were essentially identical in design in the new CEGB reactors. This was especially so since the U.K.A.E.A. which operated these reactors would be providing the fuel for the CEGB reactors.

Hardy et al., writing in the latter part of 1962, indicated that as part of the high burnup testing program at the Calder Hall and Chapelcross reactors, average channel burnups of over 3,000 MWD/Te had been achieved.[183] This burnup level would mean that the central fuel elements would have obtained a burnup of about 4,500 MWD/Te and it was reported that the highest burnup obtained by any fuel element was 4,650 MWD/Te. The Calder Hall and Chapelcross reactors used six fuel elements per fuel channel. By segregating the central two fuel elements from the fuel channels, one could obtain plutonium with a Pu-240 content of 23%. One could double the amount of plutonium obtained if the four central fuel elements were processed together. The resultant plutonium would blend to a Pu-240 content of about 20%. Stewart has published mean and peak fuel burnups obtained in various of the high burnup fuel channels in the Calder Hall and Chapelcross reactors as of August 1963.[184] Interpolating the

183. Hardy H.K., Bishop J.F.W., Pickman D.O., and Eldred V.W., "The development of uranium-magnox fuel elements for an average irradiation life of 3000 MWD/te," *Journal of the British Nuclear Energy Society* 2, January 1963, p. 40. Though the article was published at the beginning of 1963, the data had to have been from the latter part of 1962.

184. J.C.C. Stewart, "Development and Manufacture of Magnox Fuel," Proceeding of the Institution of Mechanical Engineers, Vol. 178, Part 1, No. 9, 1963-1964, p. 238.

data back to mid-1962 confirms Hardy's paper's burnup levels and also shows that there were a sufficient number of high burnup fuel channels so that kilogram quantities of plutonium with a Pu-240 content of 20% to 23% would have been available in mid-1962. Now it is clear why the United States approached the UK for help.

None of this directly indicates the Pu-240 content of the plutonium in the U.S. 1962 test. However, in 1993, J. Carson Mark, who was head of the Los Alamos Theoretical Division from 1947 to 1972, said that the 1962 test used plutonium with the highest Pu-240 content available.[185] Since the United States had already produced plutonium with a Pu-240 content of 15%, claims by Pellaud, Carlson et al. and the World Nuclear Association that the plutonium had only a Pu-240 content of 12% or 14% are obviously not true.

Further, the Pu-240 content must have been significantly higher than 15%, otherwise there would have been no reason to have approached the British. As we have seen, the highest available Pu-240 content from the British was in the range of 20% to 23%. Given what Mark has said about using the highest Pu-240 content available, the 20% to 23% range represents what was used in the 1962 test. This conclusion is supported by the observation that the original requirement for Hanford had been a Pu-240 content of 20%. Also recall that in November 1959 Hanford did not receive 1.2 kilograms of plutonium with a Pu-240 content of 20% because The Division of Military Applications had exercised a prior claim on the plutonium. So despite numerous statements to the contrary, it appears that the plutonium in the 1962 test was reactor-grade after all even by the current definition requiring such material to have a Pu-240 content of at least 19% and was in the range of 20% to 23% Pu-240.

185. Geoffrey Lean, "DIY Atom Bomb Link to Sellafield," *The Observer*, (London), June 6, 1993, p. 3.

No doubt there will be some who will argue that even if the 1962 test did use plutonium with a Pu-240 content of 20% or 23% that plutonium discharges from current reactors have a significantly higher Pu-240 content (the equivalent of over 30%) and that such material has never be tested in a nuclear weapon. While such a statement would be true, it ignores the point discussed above that is worth repeating: "The United States maintains an extensive nuclear test data base and predictive capabilities. This information, combined with the results of this low yield test, reveals that weapons can be constructed with reactor-grade plutonium." U.S. statements about the utility of reactor-grade plutonium for the production of nuclear weapons are not based only on the 1962 nuclear test but, rather, its entire nuclear test database and the predictive capabilities that have resulted. Therefore, the United States need not have conducted nuclear tests with plutonium of all possible concentrations of Pu-240 to know that nuclear weapons can be manufactured from such material.

I originally published this information about the Pu-240 content of the plutonium used in the 1962 U.S. nuclear test in 2013, but false claims continue to be made. In 2015, Alex DeVolpi repeated his claim that the plutonium was not reactor-grade and the World Nuclear Association still incorrectly states that the plutonium was 85% Pu-239 which would imply a Pu-240 content of only 13% or 14%. It is time for these false statements to come to an end.

British Totem Test Series

In October 1952, the British tested their first nuclear device, codenamed Hurricane. The device had a yield of 25 kilotons. In October 1953, the British tested two additional nuclear devices in the Totem test series. One purpose of these tests was to examine the effect of

increasing the percentage of Pu-240 in the plutonium that the British were producing for nuclear weapons.

There are conflicting reports about the percentage of Pu-240 in the plutonium used in this test series. On the one hand, many have jumped to the conclusion that these tests involved plutonium with a Pu-240 content significantly higher than the 8% that the British define as weapon-grade.[186] Alex DeVolpi, a leading proponent of the notion of denatured plutonium, has gone a step further. He has claimed that since the British used non-weapon-grade plutonium in these tests but used weapon-grade plutonium in their weapons, they must have found something about the non-weapon-grade plutonium unsatisfactory.[187]

On the other hand, Friends of the Earth Australia has pointed out that fallout measurements indicate the plutonium used in the Totem test series was weapon-grade.[188] However, this conclusion has been generally ignored. I will show that Friends of the Earth Australia is correct and indeed, the maximum Pu-240 content that the British Windscale plutonium production reactors could have produced in time for the Totem tests was only about 4.4%. Therefore these tests provide no information about the suitability of reactor-grade plutonium in nuclear weapons.

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186. For example, John Walker, who is generally well-informed on the British nuclear weapon program has said: "…we do know that the British tested devices with high Plutonium 240 content during the Totem trials in 1953." John R. Walker, *British Nuclear Weapons and the Test Ban 1954-1973*, Ashgate, 2010, p. 96.

187. Alex DeVolpi, "A Coverup of Nuclear Test Information?" *Physics and Society Newsletter* 25, no. 4, October 1996. DeVolpi has repeated this claim more recently: Alexander DeVolpi, "Demilitarizing Weapon-Grade Plutonium: Part II," *APS Physics Newletter*, July 2015.

188. Jim Green, "Can 'reactor grade' plutonium be used in nuclear weapons?" *Friends of the Earth Australia*, September 10, 2007.

The two British Windscale plutonium production reactors were air-cooled and used aluminum clad natural uranium fuel. Each of the two reactors was apparently intended to each have a thermal power output of about 115 MW.[189] However, given the limited technical information available to the British, errors were made in the reactor design. After the first subcritical testing of Windscale 1 in August 1950, it was apparent that the reactors would not be able to operate at their design power. To try to improve the reactor's performance the British were required to remove all of the fuel (180 metric tons) from Windscale 1 and then shave a 1/16 of an inch off of the fuel cooling fins to reduce the amount of aluminum in the reactor.[190] Windscale 1 went "on power" on December 22, 1950, at the power level of 1 MW. The reactor's power was progressively increased from January 1951 to April 1951 when it reached the maximum that the design could sustain—76 MW.[191]

The British Butex reprocessing plant (B204) first processed Windscale spent fuel on February 25, 1952. Given that the fuel had to be cooled for at least 90 days before reprocessing, the fuel could only have been irradiated for about seven months at full power. This would produce an average fuel burnup of about 80 Megawatt Days

189. Unlike the later British Calder Hall and Chapelcross plutonium production reactors, these reactors did not produce electricity. The information on the Windscale reactors and their operation are from the official British history: Margaret Gowing assisted by Lorna Arnold, *Independence and Deterrence, Britain and Atomic Energy, 1945-1952*, Volume 2 Policy Execution, New York: St. Martin's Press, 1974.

190. This was 70,000 fuel elements. The process took three weeks.

191. Later each of the two Windscale reactors was able to achieve a power level of 180 MW by supplementing the natural uranium fuel with fuel enriched to 0.92%. In October 1957 the Windscale 1 reactor caught fire and suffered major damage. Both reactors were permanently shut down. Significant radioactivity was released, making this the worst nuclear accident up to that time.

per Metric Ton (MWD/Te).[192] Assuming that the fuel came from the central part of the reactor where the neutron flux is highest and that the reactor's flux was unflattened, similar to the French G1 plutonium production reactor,[193] then the burnup would have been almost twice this value—150 MWD/Te. At this burnup the plutonium's Pu-240 content would have been a little more than 1%.

The full amount of the plutonium for the Hurricane nuclear test had to be separated by August 1, 1952, so that three nuclear cores of various sizes could be produced. Given the time required for the fuel to cool and to process all of the spent fuel, the maximum time that the fuel could have resided in the reactor was about one year.

This would produce an average burnup of about 130 MWD/Te and a central fuel burnup 250 MWD/Te. The Pu-240 content of the average fuel would be about 1% and that of the central fuel about 2%. Since three nuclear cores would require on the order of 15 kilograms of plutonium and that up to that point the reactor would have only produced about 22 kilograms of plutonium in total, more than just the central reactor fuel would have needed to be reprocessed to meet the August 1 deadline. A reasonable inference is that the British intended to produce plutonium with a Pu-240 content of 2% just as the United States did between fall of 1945 and the beginning of 1949 but the British were forced to irradiate the fuel to a lower burnup than intended to meet the deadline. The plutonium for Hurricane would have had a Pu-240 content somewhere between about 1% and 2%.

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192. (76 MW/180 Mt) x 183 days of operation equals 77 MWD/Te which I rounded to 80 MWD/Te. The life-time capacity factor for the two Windscale reactors was 86%.

193. J. Horowitz and J. Bussac, "Thermal Flux Flattening and Increase of Reactor Output," Commissariat a l'Energie Atomique, Rapport CEA No. 1106, 1959.

One purpose of the Totem tests was to examine the effect of increasing the percentage of Pu-240 in the plutonium used in British nuclear weapons. The British were driven to consider increasing the percentage of Pu-240 by their plans to build two additional plutonium production reactors, Calder Hall A1 and A2. The power level of these two reactors would be about double that of the two Windscale reactors. While this would triple the rate of plutonium production, it would also triple the required uranium, fuel fabrication, and fuel reprocessing. Increasing the fuel burnup would decrease these requirements. For example, in 1949, the United States increased its fuel burnup from 200 MWD/ton[194] to 400 MWD/ton. This increased the Pu-240 content of U.S. plutonium from about 2% to 3.8% but it halved the required amount of uranium while producing almost the same amount of plutonium.[195]

The two Totem tests occurred in October 1953, about one year after the Hurricane test. The plutonium for these tests had to have come from either the Windscale 1 reactor or the Windscale 2 reactor. If Windscale 1 produced the plutonium for these tests, the fuel could have at most been in the reactor for two years. The central fuel burnup would have been twice what it had been in 1952, i.e. about 500 MWD/Te. The maximum Pu-240 content of the plutonium would have been about 4.2%.

The Windscale 2 reactor reached full power in October 1951, about six months after Windscale 1. It managed to achieve a higher power level—about 105 MW. If this reactor provided the plutonium for the Totem tests, its fuel could have been exposed at full power for about one and one half years. This would have produced a central fuel burnup of about 520 MWD/Te, which is slightly higher than the fuel

194. These are 2,000 pound tons.

195. "Technical Report to the General Advisory Committee," HW-13292, General Electric Co., Hanford Works, May 10, 1949.

from Windscale 1. The maximum Pu-240 content of the plutonium would have been no more than about 4.4%.

Therefore, the plutonium used in the Totem tests could have contained no more than about 4.4% Pu-240. This is significantly higher than what would have been used in the Hurricane test but is still weapon-grade. As a result, the Totem tests provided no information on the suitability of non-weapon-grade plutonium in nuclear weapons.

Nor were the British likely to have been disappointed by the results of the two Totem tests, as DeVolpi claims. The British considered the most likely yield of the Totem 1 test to be about 5 kilotons and that of the Totem 2 test 2-3 kilotons.[196] The actual test yields were 10 kilotons and 8 kilotons respectively—hardly disappointing.

196. Lorna Arnold, *A Very Special Relationship: British Atomic Weapon Trials in Australia*, Her Majesty's Stationery Office, London, 1987.

Chapter 9

Conclusions

All things being equal, weapon-grade plutonium is preferred over reactor-grade plutonium for the production of nuclear weapons. However, today, unlike the 1940s and 1950s, all things are not equal. A non-nuclear weapon state would find it difficult to build a plutonium production reactor without being subjected to enormous international pressure and, as Syria found out in 2007, the reactor could be bombed before it even began operation. In contrast, nuclear power reactors are readily available and, as part of the continuing legacy of the myth of denatured plutonium, half a dozen non-nuclear weapon states have large quantities of separated plutonium. Japan currently has several metric tons of plutonium in the form of pure plutonium nitrate solution or pure plutonium dioxide. In 13 years, after the Comprehensive Joint Plan of Action expires, Iran will be permitted to reprocess spent fuel to obtain pure plutonium nitrate.

For countries today, the choice is not between weapon-grade plutonium and reactor-grade plutonium for nuclear weapons but rather between reactor-grade plutonium and no nuclear weapons at all. In the past, both Sweden and Pakistan at one time based their nuclear weapon programs on reactor-grade plutonium when weapon-grade plutonium was unavailable. That neither country would eventually produce reactor-grade based nuclear weapons does not change these facts. In the case of Pakistan, its failure to produce nuclear weapons using reactor-grade plutonium had nothing to do with the properties of such weapons. Rather, the United States recognized the dangers

of reactor-grade plutonium and applied pressure to France to block the sale of the reprocessing plant needed to produce separated reactor-grade plutonium. Today, India may have deployed nuclear weapons using reactor-grade plutonium.

It has been claimed that nuclear weapons manufactured using reactor-grade plutonium would be "unreliable," "unpredictable," "bulky," and "hazardous to bomb makers." None of this is true. The *entire* 270 metric ton current world stockpile of separated plutonium can be used to produce nuclear weapons by simply using a reduced amount of plutonium that is only 60% of a critical mass and coating the core with a half a centimeter of uranium. Employing early 1950s U.S. unboosted implosion technology and modern high explosives, these weapons would have the same predetonation probability as that of the same type of weapon using weapon-grade plutonium and a near critical core. The weapons would be the same exact size and weight as ones using weapon-grade plutonium, and they would require no special cooling. The gamma radiation from the core would be significantly less than that of an unshielded weapon-grade plutonium core. The only difference would be that while the weapon-grade plutonium weapon would produce a yield of 20 kilotons, the reactor-grade plutonium weapon would produce a yield of only 5 kilotons, though its destructive area would still be about 40% that of the 20 kiloton weapon. Further, boosting technology appears to be becoming more readily available to early nuclear weapon states. Boosted weapons produce the same yield regardless of whether weapon-grade or reactor-grade plutonium is used.

Many claims about so-called denatured plutonium relate to reactor-grade plutonium produced by spiking reactor fuel with either neptunium or americium. However, this spiking has not been done nor is it likely to ever be done since this would greatly increase the costs and technical difficulty of using plutonium as nuclear reactor

fuel. Even then, the plutonium could be used to produce nuclear weapons though in this case some special effort would be needed to cool the core by expanding the size of the core to improve heat dissipation and using thermal bridges to conduct the heat away from the core.

The obvious solution to the nuclear weapon dangers posed by reactor-grade plutonium is to deny non-nuclear weapons states easy access to this material by banning all reprocessing and plutonium recycling, including unirradiated MOX fuel, from such countries. This was the conclusion of the analysis that I participated in at Pan Heuristics over 40 years ago. Our conclusion led to the Carter Administration to end commercial reprocessing in the United States and to try to prevent it in non-nuclear weapon states as well. The intervening years have only reinforced the wisdom of this recommendation. In the 1970s, those in the nuclear industry objected that such a policy would retard the growth of nuclear power which they believed was destined to be a major if not the main source of electricity generation. The nuclear industry expected that uranium resources would be insufficient to support such a large nuclear industry and only plutonium fuel in breeder reactors could power the large number of reactors that they expected.

Today there are no commercial breeder reactors and none are in sight. Nuclear power did not grow to become anywhere as important as was predicted and uranium resources have proven to be no constraint on nuclear power. The use of plutonium based reactor fuels is universally acknowledged to be uneconomic. Nuclear energy faces stiff competition from natural gas and renewable energy sources.

Though plutonium reprocessing in nuclear weapon states poses little proliferation risk, it is clearly uneconomic and unnecessary given the 270 metric ton stockpile of separated plutonium that already exists. Reprocessing should be ended in these countries as well to prevent this unnecessary plutonium stockpile from growing even larger.

Appendix

How Much Pu-240 Has the U.S. Used in Nuclear Weapons: A History

Introduction and Summary

Ideally plutonium used in nuclear weapons would contain only the isotope Pu-239. However, the United States discovered in 1944 that plutonium produced in nuclear reactors must contain at least a small percentage of the isotope Pu-240. The relatively high spontaneous fission rate of Pu-240 causes this isotope to release neutrons which can cause unboosted nuclear weapons to have a significant probability of predetonating, i.e. starting the nuclear reaction prematurely, resulting in a lower than designed nuclear yield. Therefore, limits were placed on the percentage of Pu-240 in the plutonium used in early U.S. nuclear weapons so as to ensure a reasonable probability of achieving the design yield. Plutonium that the United States uses in its nuclear weapons is termed "weapon-grade."

As is discussed in chapter three, currently the United States defines weapon-grade plutonium as having a Pu-240 content of less than 7% and U.S. nuclear weapons use plutonium with a Pu-240 content of about 6%. Given that all U.S. nuclear weapons are now boosted, this limit on Pu-240 content has nothing to do with the probability of predetonation, but rather with other properties of the plutonium, such as radiation output. But this was not always the case. The

United States did not deploy boosted fission weapons until 1957 and continued to stockpile unboosted nuclear weapons well into the 1960s.[197]

The declassification of documents related to the operation of the plutonium production reactors at Hanford allows the construction of an approximate history of the Pu-240 content of U.S. weapon-grade plutonium. In the 1940s the limit on the permissible Pu-240 content was fairly low due to the relatively slow assembly time associated with early implosion fission weapons. As implosion technology improved, the Pu-240 limit increased.

The Nagasaki weapon used plutonium that was only 1.0% Pu-240.[198] Soon after the Nagasaki weapon was employed, the limit was increased to 2.0% Pu-240. In 1949 the limit was increased to 3.8% and in March 1951 to 5.5%. This high limit is an indication that, even in 1951, unboosted implosion fission technology had been significantly improved over that used in the Nagasaki weapon. Indeed in the 1950s, U.S. implosion fission weapons employed a technique known as levitation, which is the use of an air gap between the weapon's fissile core and the tamper. This air space allows the implosion wave to increase in speed and compress the nuclear core more rapidly.

In 1954, the Pu-240 limit for much of the weapon-grade plutonium being produced was 8.8%. However, Hanford never produced weapon-grade plutonium with a Pu-240 percentage this high since operating problems at Hanford, not the neutron output of the pluto-

197. N. Stetson et al., *Savannah River Production Reactor History*, CIV-685-2A, September 1963.

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

nium, determined the Pu-240 content of the plutonium. Due to the fuel rupture problem, Hanford was only able to produce plutonium that was 7.5% Pu-240 in 1955. This was lowered to 6.8% in 1956 and in 1957 and 1958 further lowered to 4.7% Pu-240.

At about the same time (1954-1956), Hanford had a program to produce low burnup plutonium with a Pu-240 content of 2.0% which was later raised to 2.5%. This involved the C reactor and part of the capacity of the other reactors. About half the plutonium produced at Hanford during these years was low burnup. Presumably this low Pu-240 plutonium was intended for the primaries of the unboosted thermonuclear weapons in use at this time.

With the advent of tubular fuel elements in 1959, the limit was increased to 6.0%, and it soon became frozen at this level. It is interesting to speculate what might have been the result if Hanford had been able to produce plutonium that was 8.8% Pu-240 in the mid-1950s. Perhaps this Pu-240 percentage would have become the standard and all U.S. weapon-grade plutonium today would have a Pu-240 content of 8.8%.[199] Table 12 gives a breakdown of my estimates of the amounts of weapon-grade plutonium produced at Hanford with various Pu-240 contents and the dates and reactors involved in its production.

199. Note that the U.S.-Russian 2000 Plutonium Management and Disposition Agreement defines weapon-grade plutonium as having no more than about 9.1% Pu-240 (a Pu-240 to Pu-239 ratio of no more than 0.1).

Pu-240 Content*	Amount in Metric Tons	Dates Produced and Reactors Used
2.0%	1.6	1945-1948, B, D & F 1954, C & part of the capacity of other reactors
2.5%	1.9	1955-1956, C & part of the of capacity of other reactors
3.8%	0.7	1949-1951 B, D, DR, F & H
4.7%	6.4	1957-1958 All reactors except N
5.5%	2.8	1951-1954 B, D, DR, F, H & C except not C in 1954
6.0%	39.0	1959-1971 & 1983-1987 All reactors
6.8%	1.2	1956 Part of the capacity B, D, DR, F, H, KE & KW
7.5%	0.9	1955 Part of the capacity B, D, DR, F, H, KE & KW
5.6% Weighted Average	54.5 Total	

TABLE 12: Amounts of Weapon-Grade Plutonium Produced at Hanford: Pu-240 Content, Dates Produced & Reactors Used.

*Before 1961 the Pu-240 content varied significantly from batch to batch.

History of the Production of Weapon-Grade Plutonium at Hanford

The declassification of many documents regarding the plutonium production operations at Hanford provides much information but using these documents also presents some difficulties. Only some of the documents produced by Hanford have been declassified, so it is sometimes difficult to place a document in the proper context. Also, the documents use a good deal of jargon (such as "E-metal," i.e. uranium fuel enriched to 0.95%) whose meaning was obvious at the time but not so today.

The meaning of some technical terms is not always clear. An important term for this work is MWD/ton (megawatt-days per ton), which is the measure of fuel burnup. For a number of decades it has been standard to measure burnup in terms of MWD/Te, where the "Te" is a metric ton (2,205 lb). In most of the Hanford documents, it is not obvious what kind of ton is meant. It would be tempting to assume that they meant metric tons but, in fact, they are short tons (2,000 lb.).

Finally, due to the limitations of the time, some of the information was simply incorrect. Of great importance for this work is Hanford's estimate of the Pu-240 content of the plutonium it was producing. But in the 1950s Hanford was not measuring this directly but rather measuring the property that was actually important for weapons use, namely the plutonium's neutron production in units of n/g-s (neutron per gram-seconds). Hanford then converted this neutron measurement into a Pu-240 content by using the neutron production rate of Pu-240. But Hanford's estimate of the Pu-240 neutron production rate in the 1950s was too high by about 30 percent, which meant that its estimate of the Pu-240 content of any given plutonium was about 30 percent too low.[200]

200. Compare Figure 13 (p. 42) from F. E. Kruesi, J. O. Erkman, and D. D. Lanning, "Critical Mass Studies of Plutonium Solutions," General Electric,

Table 13 shows the operating history of the Hanford plutonium production reactors. The B, D, and F reactors were built during World War II. Soon after the war, it was discovered that the operation of the reactors was causing their graphite moderator to expand to such an extent that it threatened the continued operation of the reactors. The B reactor was shut down to preserve some of its operating life and the H reactor started construction. The situation at the D reactor was so serious that the DR reactor was built to replace it. However, a solution was found to the graphite problem and the D reactor was never shut down.[201]

These first five reactors (B, D, F, H, & DR) had an identical design. The C reactor was a slightly improved design. The KW and KE reactors were improved designs with a significantly higher power level and conversion ratio. The N reactor used enriched uranium fuel and was designed to produce electricity as well as plutonium. Most of the plutonium produced by this reactor was not weapon-grade due to the higher burnup of its enriched uranium fuel.

To a first approximation the amount of plutonium produced is directly proportional to the power level of a reactor. As can be seen from Table 13, the power level of the earliest reactors was increased by nearly a factor of ten over their operating life. This was achieved in steps over time by allowing higher water discharge temperatures, increasing reactor cooling capacity, and providing small amounts of enriched uranium. The reactors at Hanford produced a total of about 54.5 metric tons of weapon-grade plutonium.[202] The annual produc-

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Richland Washington, May 19, 1952, HW-24514 with the more accurate Figure 6 (p.32) "Hanford Reactor and Separations Facility Advantages," Hanford Atomic Products Operation, Richland Washington, June 27, 1963, HW-78100.

201. It was found that heating the graphite annealed the damage caused by irradiation.

202. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from https://www.osti.gov/opennet/servlets/

tion peaked at over 4 metric tons between 1960 and 1965 and was essentially over by 1971.[203]

As was discussed above, the plutonium in the Nagasaki weapon had a Pu 240 content of 1.0%. But even before the Nagasaki weapon had been used in combat, General Groves, the head of the Manhattan Project, reported that the Pu-240 content of the plutonium was going to be increased.[204] In August, "the customer" requested that the reactor fuel burnup be limited to 200 MWD/ton, which would result in a Pu-240 content of about 2.0%.[205] An operating report from November 1945 refers to 200 MWD/ton as "normal discharge material."[206] Apparently this fuel burnup goal lasted until about the end of 1948. Between 1944 and the end of 1948, Hanford produced about 800 kilograms of plutonium.[207]

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purl/219368/219368.pdf.

203. The N reactor produced 2,778 kilograms of weapon-grade plutonium between 1983 and 1987. Ibid.

204. General Leslie Groves, "Memorandum to the Chief of Staff," July 30, 1945, Manhattan Engineering District Papers, Box 3, Folder 5B, Record Group 77, Modern Military Records, National Archives, Washington, D.C.

205. W.O. Simon, "Hanford Engineer Works monthly report, August 1945," September 9, 1945 HW-7-2361-Del.

206. W.E. Jordan "100 Area Technical Activities Report-Physics, 10/25/45 to 11/25/45," November 29, 1945, E.I. Du Pont De Nemours & Company.

207. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf.

Reactor	Operating Dates	Design Power Level MWt	Highest Sustained Power Level MWt
B	9/44-3/46 7/48-2/68	250	2210
D	12/44-6/67	250	2165
F	2/45-6/65	250	2040
H	10/49-4/65	400	2140
DR	10/50-12/64	250	2015
C	11/52-4/69	650	2500
KW	1/55-2/70	1850	4400
KE	4/55-1/71	1850	4400
N	12/63-1/87	4000	4000

TABLE 13: Operating History of the Hanford Plutonium Production Reactors

At the beginning of 1949, the fuel burnup discharge goal was raised to 400 MWD/ton, which is a Pu-240 content of about 3.8%. During the first half of 1949, the fuel burnup was gradually raised from 200 MWD/ton to 400 MWD/ton.[208] It continued at this level until March 1951. During this time, Hanford produced about 700 kilograms of plutonium.[209]

In March 1951, the burnup goal was raised to 600 MWD/ton which yields a Pu-240 content of about 5.5%.[210] Apparently, the burnup

208. Various P Division monthly reports.

209. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf.

210. DL Deneal, "Historical Events-Single Pass Reactors and Fuels Fabrication," April 10, 1970, DUN-6888, p. 7.

was raised to this new level almost immediately. Unfortunately, this burnup increase led to an immediate increase in the number of fuel ruptures.

Fuel ruptures were a major concern for the operations at Hanford. When a fuel element ruptured, the hot metallic uranium was exposed to the water coolant. It would oxidize and expand blocking, the fuel channel. This would cut off the flow of coolant to the other fuel elements and in the worst case, these fuel elements could catch fire and set the entire reactor ablaze. Therefore, there were systems that quickly detected any fuel rupture. Once detected, the reactor would be shut down and the ruptured element removed.

In the best case, the ruptured element could be removed in just a half an hour. In the worst case, the fuel element would be stuck and so much force would be required to remove it that the aluminum fuel channel would be damaged and would have to be replaced. Or the swollen ruptured fuel element could rupture the fuel channel, leading large amounts of water to spill into the reactor. The reactor's graphite would then need to be dried before the reactor could be restarted. In either case, days of reactor operation could be lost to a fuel rupture. In optimizing the plutonium production operations at Hanford, the likelihood of fuel ruptures needed to be taken into account. Since this likelihood increased with fuel burnup as well as reactor power level, the threat of fuel rupture tended to limit the fuel burnup and thereby the Pu-240 content of the plutonium produced. By improving fuel quality, it was possible to reduce the fuel rupture rate and maintain the 600 MWD/ton goal at the five oldest reactors (the B, D, F, H, and DR) through the end of 1954.

In 1954, the new C reactor was tasked to produce low burnup plutonium. In that year it produced fuel with a burnup of about 200 MWD/ton which would be a Pu-240 content of about 2.0%. Additional reactors apparently operated with duel burnup goals and also produced this low burnup plutonium in addition to high burnup plu-

tonium. In 1955, the low burnup goal was raised to 250 MWD/ton, which is a Pu-240 content of about 2.5%. This program continued until about the end of 1956. It is unclear which of the various other reactors produced low burnup plutonium or how much each reactor produced. However, reporting from January through August 1955 indicated that about half of Hanford's plutonium production was low burnup material.[211] I assume that this was the case for the entire 1954-1956 period. The production of 2.0% Pu-240 plutonium in 1954 would have been about 800 kilograms. The production of 2.5% Pu-240 plutonium in 1955 and 1956 was about 1,900 kilograms. Presumably this low Pu-240 plutonium was intended for the primaries of the unboosted thermonuclear weapons in use at this time.

A 1954 document reveals the specific maximum plutonium neutron output in terms of n/g-s values that were required by the U.S. Atomic Energy Commission.[212] For the low burnup plutonium, its n/g-s should not exceed 20, which would be a Pu 240 content of about 2.2%. For all other weapon-grade plutonium its n/g-s should not exceed 80 which would be a Pu-240 content of about 8.8% (a burnup of about 1,050 MWD/ton).

In 1955, Hanford tried to move towards the high burnup plutonium goal by increasing the burnup to 900 MWD/ton (7.5% Pu-240), but fuel ruptures became a problem.[213] In 1956 Hanford lowered the goal to 800 MWD/ton (6.8% Pu-240) but the fuel rupture problem continued. I estimate that Hanford produced about 900 kilograms of high burnup plutonium in 1955 and about 1,200 kilograms in 1956. In the mid-1950s, it was the fuel rupture rate, not the plutonium

211. K. F. Paulovich, "Monthly Reports, January-December 1955, Reactor Operation Branch, HAN-58378, September 1, 1955.

212. R. O. Gumprecht, "Plutonium Product Quality," May 28, 1954, HW-31952, General Electric, Richland Washington.

213. "1955 at Hanford," HW-39900, General Electric, Richland, Washington.

neutron output that determined the Pu-240 content of the plutonium produced.[214]

As the power levels of the reactors continued to increase, the fuel ruptures increased as well. As a result, in 1957 and 1958 the fuel burnup was reduced to 500 MWD/ton (a Pu-240 content of about 4.7%). Hanford produced about 6,400 kilograms of plutonium during these two years.[215] Yet it appears that through 1958 the high 8.8% Pu-240 limit remained in effect and Hanford planned to adopt the goal of 800 MWD/ton (6.8% Pu-240) when better fuel became available.[216]

However, in 1959 just as the less rupture prone tubular fuel elements (I & E fuel elements in Hanford jargon) became available, the Pu-240 limit was set at 6.0%, which limited fuel burnup to just 675 MWD/ton. In early 1961, Hanford was given an explicit Pu-240 goal of 6.0%, instead of the goal being set in terms of fuel burnup. Further, this new goal had to apply to all the plutonium produced, whereas in the past there had been significant variation in the Pu-240 content from batch to batch as Hanford optimized the reactor operations to maximize plutonium output. This new goal caused Hanford some concern since it would was difficult to convert this requirement into a fuel burnup (it was difficult to keep track of the fuel burnup in each fuel channel).[217] In the end, it appears that Hanford had no trouble meeting this goal.

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214. R. A. Pugh, "Final Report-Production Test 200-2 Processing of Special Irradiated Plutonium," September 27, 1956, HW-45940, p. 4.

215. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf.

216. Hanford Atomic Products Operation, Five-Year Program," HW-55767, General Electric, Richland, Washington, May 19, 1958.

217. See, L. W. Lang & W. I. Neef, "Notes on Reactor Operation within a Prod-

There is no indication that there were any further changes to the Pu-240 requirement for weapon-grade plutonium. By the mid-1960s the plutonium production declined as various reactors were shut down and some plutonium was produced for non-weapon purposes. Weapon-grade plutonium production at Hanford ended in 1971 with the shutdown of the KE reactor.

The N reactor continued in operation until 1987. However, most of the plutonium this reactor produced was for non-weapon purposes though it did produce 2,778 kilograms of weapon-grade plutonium between 1983 and 1987.[218] From 1959 through 1987, when the Pu-240 specification was 6.0%, Hanford produced 39,000 kilograms of plutonium.[219] This was about 72% of Hanford's total weapon-grade plutonium production.

Much less is known about the plutonium production at Savannah River since far less has been declassified about the reactor operations there. However, of the 36.1 metric tons of weapon-grade plutonium produced there, 32.5 metric tons (90 percent of the total) were produced after 1958. Therefore, it is safe to say that the vast majority of the weapon-grade plutonium produced at Savannah River had a Pu-240 content of 6.0%.[220]

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uct Specification," June 9, 1961, HW-69904 and T. Prudich, "Product Quality and an Interim Goal Exposure Plan," June 12, 1961, HW-69912.

218. *Plutonium: The First 50 Years*, DOE/DP-0137, U.S. Department of Energy, February 1996, pp. 28-29, available from https://www.osti.gov/opennet/servlets/purl/219368/219368.pdf.

219. Ibid.

220. Between 1981 and 1990, Savannah River produced plutonium with a Pu-240 content of 3%. This material was blended with fuel-grade plutonium to produce weapon-grade plutonium. See Ibid., pp. 30-31.

Table 12 gives a breakdown of the amounts of weapon-grade plutonium produced at Hanford with various Pu-240 contents. The Nagasaki weapon used plutonium that was only 1.0% Pu-240. Soon after the Nagasaki weapon was employed, the limit was increased to 2.0% Pu-240. In 1949, the limit was increased to 3.8% and in March 1951 to 5.5%. This high limit is an indication of the rapid improvement of unboosted implosion fission weapon technology in the U.S. arsenal. New nuclear weapon states today would likely develop weapons similar to U.S. 1951 technology. Indeed, even more than 50 years ago, both France's and China's first nuclear test devices were clearly much superior to the U.S. Nagasaki design.

Until 1951 the Pu-240 content was determined by the specifications for plutonium neutron output. Between 1951 and 1959, it appears that fuel ruptures, not plutonium neutron output, determined the Pu-240 content of the plutonium.

Though at one time plutonium with a Pu-240 content of 8.8% was acceptable from a neutron output standpoint, Hanford could not efficiently produce such plutonium. If Hanford had been able to produce large amounts of plutonium that was 8.8% Pu-240, such plutonium might have become the standard and all U.S. weapon-grade plutonium today might have an 8.8% Pu-240 content. It is interesting to note that 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).

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