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

Part Two: Short History of Reactor-Grade Plutonium and Plutonium Recycle: Why Does the Nuclear Industry Downplay the Danger of Reactor-Grade Plutonium?

Introduction

This paper is the second of a series that will comprehensively examine the nuclear weapon dangers posed by reactor-grade plutonium. The first paper described 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.[2]

This paper will provide a short history of views regarding the nuclear weapon dangers of reactor-grade plutonium. It will also discuss how the nuclear industry's desire to recycle plutonium has led it to downplay its dangers.

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

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[2] Gregory S. Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part One: Introduction, Plutonium Basics, Definitions of Grades of Plutonium, Variation in Fuel Burnup, and the Properties of Plutonium Produced in Different Reactor Fuels," July 26, 2016. Link

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 actually had 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.[3] 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.[4] 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.

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."[5] 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 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."

[3] Pu-239 also undergoes spontaneous fission but the spontaneous fission rate of Pu-240 is 40,000 times higher.
[4] 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.
[5] "The Acheson-Lilienthal Report on the International Control of Atomic Energy," Washington, D.C., March 16, 1946.

It was only with the release of the Manhattan Project history in 1961 that the problem with Pu 240 was officially made public.[6] 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 U.S. 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 U.S. 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.[7]

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 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.[8]

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 U.S. 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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[6] 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.

[7] Shri N. Srinivasan, "Fuel Reprocessing-The Initial Years," *IANCAS Bulletin*, July 1998, p. 4.

[8] 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*, MIT Press, Cambridge, 1971.

The Germans defended their Brazil deal by claiming that weapon-grade plutonium could contain no more than 2% Pu 240. I recently published a history of the Pu 240 content of U.S. weapon-grade plutonium.[9] 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 U.S. from producing plutonium with a Pu 240 content greater than 5.5%. 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[10] discovered two declassified memos from 1945 that revealed the predetonation characteristics of the Nagasaki nuclear weapon.[11] In particular there is a lower limit on the yield of any predetonating weapon, which is referred to as the fizzile 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 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[12] 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.

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.[13] 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

[9] Gregory S. Jones, "The History of the Pu 240 Content of U.S. Weapon-Grade Plutonium," May 4, 2016, Link
[10] In addition to Albert Wohlstetter, the key persons involved in this discovery were Arthur Steiner and myself.
[11] Albert Wohlstetter, "Spreading the Bomb without Quite Breaking the Rules," *Foreign Policy*, No. 25, Winter 1976-77, pp. 160-161. http://www.npolicy.org/userfiles/file/Nuclear%20Heuristics-Spreading%20the%20Bomb%20without%20Quite%20Breaking%20the%20Rules.pdf
[12] Robert W. Selden, "Reactor Plutonium and Nuclear Explosives."
[13] "Additional Information Concerning Underground Nuclear Weapon Test of Reactor-Grade Plutonium." https://www.osti.gov/opennet/forms.jsp?formurl=document/press/pc29.html

of this low yield test, reveals that weapons can be constructed with reactor-grade plutonium.

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."[14] [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.[15] 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.[16] Mark expanded on this work in 1993 and added a discussion of the problem of the plutonium's heat output.[17] 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.[18] 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.[19] He calibrated Mark's analysis by providing the actual neutron output of the Nagasaki plutonium and extended

[14] "Pu—an element of concern in Japan," *Nuclear Engineering International*, July 1993.
[15] P. Wydler *et al.*, "A Uranium-Plutonium-Neptunium Fuel Cycle to Produce Isotopically Denatured Plutonium," *Nuclear Technology*, Vol. 49, No. 1, June 1980.
[16] J. Carson Mark, "Reactor-Grade Plutonium's Explosive Properties," Nuclear Control Institute, August 1990.
[17] J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security*, Vol. 4 1993.
[18] *Management and Disposition of Excess Weapons Plutonium*, Committee on International Security and Arms Control, National Academy of Sciences, 1994, pp. 32-33.
[19] 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 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 the fizzile 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 Pellard, 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.[20] 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%.[21]

Pellard 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 its safeguards reactor-grade plutonium.

In 2011 Gunther Kessler published a book which contains several chapters on reactor-grade plutonium.[22] 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 analysis is restricted to just Nagasaki type weapons with very large plutonium cores and he does not discuss more advanced but still quite primitive weapons that the U.S. 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 this series of papers and explore the myth that reactor-grade plutonium can be denatured. In later papers, I will discuss in further detail the issues raised by Pellard, Kessler and others.

[20] Bruno Pellaud, "Proliferation aspects of plutonium recycling," *Journal of the Institute of Nuclear Material Management*, Fall 2002.
[21] Gregory S. Jones, "What was the Pu-240 Content of the Plutonium Used in the U.S. 1962 Nuclear Test of Reactor-Grade Plutonium?" May 6, 2013, http://www.npolicy.org/article.php?aid=1212&rid=3
[22] G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles*, KIT Scientific Publishing, 2011.

Plutonium Recycle: Why Does the Nuclear Industry Downplay the Danger 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 recycle has always been uneconomical and commercial breeder reactor are at least thirty years away, even though they have already been delayed by over thirty five years. Some countries such as the U.S. 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 and in particular 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 thinking of the nuclear industry regarding reprocessing and plutonium recycling can be found in an introductory lecture included in a course on reprocessing in Norway in 1967.[23]

> 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 because no one had tried very hard to look for uranium since before the nuclear age there was no need to. In the 1950s the U.S. used a price incentive program and provided technical information to spur uranium exploration in the U.S. and large amounts of uranium were discovered in the Western U.S..[24] That higher uranium prices would lead to an increase in uranium supplies is a lesson that the nuclear industry has repeatedly failed to learn.

Never the less 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 twenty years that uranium production would have to increase nine fold.[25] 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 U.S. alone.[26]

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

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[23] 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, Norway, September 1967, pp. 2-3.

[24] Robert D. Nininger, *Minerals for Atomic Energy*, D. Van Nostrand Company, Inc., 1954.

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

[26] 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.

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 U.S. 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. 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 burnout 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 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.[27]

The U.S. 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 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.[28] 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 IAEA held a conference in 1993.[29] At this conference, the IAEA predicted that by the year 2000 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"),[30] 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.[31]

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

[27] 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.
[28] Albert Wohlstetter, Thomas A. Brown, Gregory Jones, David C. McGarvey, Henry Rowen, Vince Taylor and Robert Wohlstetter, *Swords from Plowshares: The Miliitary Potential of Civilian Nuclear Energy*, The University of Chicago Press, 1979, Chapter IV.
[29] "Problems concerning the accumulation of separated plutonium," IAEA-TECDOC-765, IAEA, Vienna, 1994.
[30] Pierre M. Chantoin and James Finucane, "Plutonium as an energy source: Quantifying the commercial picture," *IAEA Bulletin*, 3/1993, p. 41.
[31] "Global Fissile Material Report 2015," Eighth annual report of the International Panel on Fissile Materials.

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.[32] France, which uses far more 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.[33] It has found that viable breeder reactors are still many decades away. The recycling of plutonium in current nuclear power reactors remains uneconomical and less 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.

[32] Brian G. Chow and Gregory S. Jones, "Managing Wastes With and Without Reprocessing," P-8035, RAND, Santa Monica, California, 1999.

[33] 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, 2015 and "Plutonium Separation in Nuclear Power Programs: Status, Problems and Prospects of Civilian Reprocessing Around the World," International Panel of Fissile Materials, 2015.