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Can Bulk Nuclear Fuel Facilities Be Effectively Safeguarded?

A fundamental problem with ensuring the peaceful use of nuclear energy is that the same nuclear material that is used as fuel in nuclear power reactors and the processes that are used to produce this fuel, can be used to produce the nuclear material required for nuclear weapons. Indeed, in many cases these fuel producing processes were first developed as part of nuclear weapon programs.

In an attempt to deal with this issue, peaceful nuclear activities are safeguarded by the International Atomic Energy Agency (IAEA). According to the IAEA the technical objective of these safeguards is:

> the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown and the deterrence of such diversion by the risk of early detection[2]

The IAEA defines a "significant quantity" of "direct use nuclear material" as 8 kilograms of plutonium or U-233 or 25 kilograms of U-235, contained in uranium that is enriched to at least 20%.[3] The IAEA has defined "detection time" as "the maximum time that may elapse between diversion of a given amount of nuclear material and the detection of that diversion by IAEA safeguards activities." The IAEA's detection goals are "one month for unirradiated direct use material."[4]

The most stressing facilities for the IAEA to safeguard are bulk nuclear fuel processing facilities. These are uranium enrichment plants, spent fuel reprocessing plants and fresh fuel manufacturing plants where plutonium fuel is produced (MOX fuel fabrication facilities). These facilities handle large quantities of nuclear material which is already fairly close to being usable in a nuclear weapon. The IAEA's measurements of nuclear materials are often no more accurate than about 1%. Yet the annual throughput of these facilities is large enough that a 1% error can be significantly greater than one "significant quantity."

A further concern is that the IAEA safeguards are designed to protect only against clandestine diversion of nuclear material. However, there is also the threat that a country can simply overtly seize the nuclear material in these facilities and quickly produce nuclear weapons. This problem suggests that bulk nuclear fuel facilities should not be located in nonnuclear weapon states.

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[2] *IAEA Safeguards Glossary 2001 Edition*, International Nuclear Verification Series No. 3, IAEA, Vienna, June 2002, p. 13. https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf
[3] *Ibid.*, p. 23.
[4] *Ibid.*, p. 25.

John Carlson, who was Director General of the Australian Safeguards and Non-Proliferation Office, has cautioned that regarding IAEA safeguards: "It is essential to avoid unrealistic expectations." But he has also said:

> The IAEA's duty to the international community is, where possible, to provide warning before, not after, a nuclear weapons programme has proceeded beyond the point where intervention can be effective.[5]

I would put the matter more strongly; IAEA safeguards are *only* effective if they can provide warning before a nuclear weapons program has proceeded beyond the point where intervention can be effective. Otherwise the safeguards are of no more use than the December 7, 1941 warning telegram sent to Pearl Harbor which arrived when the attack was already underway. It is not at all clear that IAEA safeguards can meet this objective for bulk fuel facilities.

This paper will first discuss the dual nature of nuclear energy. It then discusses the issue of whether the IAEA significant quantities are too large. Then it addresses the problems of safeguarding uranium enrichment plants, both those that produce uranium enriched to 5% or less and those that produce uranium enriched between 5% and 20%. The paper will then show that reactor-grade plutonium can be used to make powerful reliable nuclear weapons that are the same size and weight as weapons using weapon-grade plutonium and require no special cooling. The following sections explore the problems of safeguarding reprocessing plants (including plants that use the PUREX process, alternate aqueous processes and pyroprocessing) and MOX fuel fabrication plants. The paper concludes that if the IAEA cannot effectively safeguard centrifuge enrichment plants, reprocessing plants, MOX fuel fabrication plants and the fresh MOX fuel itself, then these items should not be located in nonnuclear weapon states.

The Duality of Nuclear Energy

Natural uranium consists of two main isotopes: U-235 which is 0.7% and U-238 which is the remaining 99.3%. It is the U-235 that can sustain a nuclear chain reaction. Given the low concentration of U-235 in natural uranium, a chain reaction can only occur if the natural uranium is interspersed with either heavy water or graphite. These latter two materials are termed moderators. Various types of nuclear reactors have been constructed using natural uranium fuel and either heavy water or graphite. However, to create the fast chain reaction needed to produce a nuclear weapon, the concentration of U-235 is typically increased (enriched) to at least 80% and more often to 90% or more. If the U-238 is exposed to neutrons in a nuclear reactor, then it is converted into plutonium. At low irradiations the plutonium is mainly Pu-239. In the United States' Manhattan Project, both enriched uranium and plutonium were used to produce nuclear weapons and the other nine countries that have produced nuclear weapons have used one or the other and often both of these two materials.

Civil nuclear energy, in particular nuclear power, has used both enriched uranium and plutonium as fuel. Generally, the enriched uranium is far less enriched than 90%. By using uranium that is

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[5] John Carlson, "Defining the Safeguards Mission," *Addressing Verification Challenges*, Proceedings of an International Safeguards Symposium, Vienna, 16-20 October 2006, IAEA, Vienna, 2007, pp. 93 and 89. https://www.iaea.org/publications/7730/addressing-verification-challenges

enriched to 2% to 5% U-235, it is possible to use ordinary water (often referred to as light water to differentiate it from heavy water) as the moderator. Most of the nuclear power reactors in the world are of this type. Since the enriched uranium fuel in light water reactors contains substantial amounts of U-238, large amounts of plutonium are produced in the fuel. In the early days of nuclear power, world supplies of natural uranium appeared to be small and there were concerns that the then known supplies could not sustain a large nuclear power industry.

A different type of nuclear power reactor was designed to deal with this problem. It used plutonium as fuel and did not use any moderator. Designed properly, in operation it could convert more U-238 to plutonium than was consumed by the reactor's operation, allowing for the large-scale utilization of the far more abundant U-238. Such fast breeder reactors were thought to be the wave of the future. However, it turned out that the reason why world supplies of natural uranium were so low was that before the nuclear age no one had tried very hard to look for it and there was far more uranium than was initially thought. Additionally, fast breeder reactors are more expensive than light water reactors and have faced various technical challenges. As a result, there are no commercial breeder reactors in the world today, despite various attempts to develop them for the past 60 years.

In anticipation of the large-scale use of the breeder reactor, the fuel from commercial nuclear power reactors was chemically processed (reprocessed) to extract the plutonium. When the breeder reactors failed to materialize, large stockpiles of plutonium began to accumulate such that there are currently over 300 metric tons world-wide. An attempt was made to use some of the plutonium by manufacturing plutonium fuel for light water reactors. Since the plutonium is in the form of an oxide and it is mixed with uranium oxide, it is referred to as mixed oxide fuel or MOX. However, MOX fuel is significantly more expensive than is enriched uranium fuel and few countries have used such fuel.

The first enrichment plants were built to produce HEU for nuclear weapons. The more recently developed centrifuge enrichment plants were intended to produce low enriched uranium for nuclear power reactors but they have a great deal of flexibility about the degree of enrichment that they can produce. This technology has formed the basis of nuclear weapon programs in Pakistan, North Korea and Iran. The chemical process used in reprocessing plants was originally developed to produce plutonium for nuclear weapons. MOX fuel fabrication plants use separated plutonium that is the end product of a reprocessing plant and could be easily used as a source of nuclear material for a nuclear weapons program. This duality of these nuclear facilities underscores the difficulties facing the IAEA safeguards system.

IAEA Significant Quantities Need to Be Decreased

As was discussed above, the IAEA's fundamental goal is to prevent the diversion of a "significant quantity" of nuclear material, a quantity which is intended to be an approximation of the amount of nuclear material required to produce one nuclear weapon. The IAEA has defined a significant quantity as 8 kilograms of plutonium or U-233 and 25 kilograms of U-235 contained in uranium enriched to 20% or more. For uranium that is 90% enriched, this would be 27.8 kilograms. However, there is substantial evidence that the IAEA's significant quantities are too large and need to be decreased.

It is now well-known that a nuclear weapon can be manufactured with less than 8 kilograms of plutonium. 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.[6] 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.[7] 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 that produced yields of 5.8 and 1.6 kilotons respectively.[8] In 2016, the former deputy director general of the IAEA called for this agency to reduce its "significant quantity" for plutonium from the current 8 kilograms to only 2 to 4 kilograms.[9] Certainly the IAEA should use as a significant quantity of plutonium a value of 4 kilograms, if not smaller.

Regarding HEU, the NRDC stated that using low technical capability, just 8 to 11 kilograms produces yields in the low kiloton range. My review of published critical mass data shows that for 93.9% enriched HEU in a Nagasaki type implosion weapon design, the critical mass is 21.5 kilograms.[10] Since the plutonium in the Nagasaki weapon was 95.2% of critical, a similar HEU loading would be 20.5 kilograms. Therefore, the IAEA's value of a significant quantity should be no higher than 20 kilograms of HEU and perhaps a good deal smaller. These reduced values for a significant quantity only increase the difficulty of the IAEA being able to meet its safeguards objectives.

Uranium Enrichment Plants

Enrichment Plants Producing Uranium Enriched to 5% or Less

In enrichment plants used to produce fuel for current nuclear power plants, the U-235 content of uranium is typically increased from the 0.7% concentration of natural uranium to 2%-5%. Indeed, current fuel production facilities and commercial nuclear power plants are only licensed to use uranium that is no more than 5% enriched. Uranium with this enrichment cannot create a fast critical mass. Since nuclear weapons use uranium with a U-235 content of typically at least 80% and more often 90% or more, uranium with an enrichment of only 2%-5% would not seem to be much of a problem. Unfortunately, that is not the case.

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[6] Thomas B. Cochran, "Technological Issues Related to the Proliferation of Nuclear Weapons," Natural Resources Defense Council, August 23, 1998. http://www.npolicy.org/article.php?aid=1310&rtid=2

[7] "North Korea Declares 31 Kilograms of Plutonium," *Global Security Newswire*, October 24, 2008. https://www.nti.org/gsn/article/north-korea-declares-31-kilograms-of-plutonium/

[8] Pavel Podvig, "Amounts of fissile materials in early Soviet nuclear devices," International Panel on Fissile Materials Blog, October, 1, 2012. http://fissilematerials.org/blog/2012/10/amounts_of_fissile_materi.html

[9] Olli Heinonen, "North Korea's 5th Nuclear Test—What Now?" Foundation for Defense of Democracies Policy Brief, September 16, 2016. https://www.belfercenter.org/publication/north-koreas-5th-nuclear-test-what-now

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

In an isotope separation process, most of the effort is expended in the stages where the desired product is least concentrated since in these stages large quantities of material must be handled. For example, Table 1 compares producing 90% enriched uranium directly from natural uranium verses a two-step process where natural uranium is enriched to 4.1% and then the 4.1% enriched uranium is enriched to 90%. As is shown, producing one kilogram of 90% enriched uranium by the two-step process requires the same amount of natural uranium feed and enrichment effort (separative work, measured in separative work units--SWU) as producing 90% enriched uranium directly from natural uranium. However, in enriching uranium to 4.1%, one has already expended 78% (178.4/227.3) of the separative work that would be required to enrich natural uranium to 90% enriched uranium.[11] Therefore 4.1% enriched uranium is already dangerously close to the highly enriched uranium needed to produce a nuclear weapon.

Table 1

Comparison of Producing HEU directly from Natural Uranium vs Two Step Process Enriching Natural Uranium to 4.1% Enrichment and then Enriching from 4.1% Enriched Uranium to HEU

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Tails Enrichment and Quantity	Separative Work Required (SWU)
One Step to HEU	90.0% 1 kg	0.711% 175.7 kg	0.2% 174.7 kg	227.3
Two Steps to HEU	4.1% 26.4 kg	0.711% 201.1 kg	0.2% 174.7 kg	178.4
Two Steps to HEU	90.0% 1 kg	4.1% 26.4 kg	0.711% 25.4 kg	48.9
Net Total Two Step	90.0% 1 kg	0.711% 175.7 kg	0.2% 174.7 kg	227.3

Additionally, the technology used to produce enriched uranium has changed. Until the 1980s the main uranium enrichment process was gaseous diffusion, with large plants in the U.S. and France. This process has a large in-process inventory which results in a long equilibrium time. Producing highly enriched uranium for nuclear weapons would require many months. The process also used large amounts of electricity and the physical plants themselves were fairly large, making it rather difficult to possess one clandestinely.

However, since the 1970s centrifuges have gradually become the dominant uranium enrichment technology, with the last of the large gaseous diffusion plants closing in 2013. Centrifuge

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[11] That even low enriched uranium is already close to being highly enriched uranium was first pointed out in 1969. See V. Gilinsky and W. Hoehn, "The Military Significance of Small Uranium Enrichment Facilities Fed with Low-Enrichment Uranium," RM-6123-ARPA, REDACTED, RAND, Santa Monica, CA, December 1969. https://apps.dtic.mil/dtic/tr/fulltext/u2/a613260.pdf

enrichment plants have a much smaller in-process inventory, giving them equilibrium times on the order of hours or days rather than months. The electricity consumption of a centrifuge enrichment plant is only about one-fiftieth that of a gaseous diffusion plant. The physical size of a centrifuge enrichment plant is also much smaller.

Safeguards are generally aimed at preventing the clandestine misuse of the enrichment plant. This would include the production of uranium with an enrichment greater than declared. In the worst case, the higher than declared enriched uranium would be 80% to 90% enriched and suitable for direct use in a nuclear weapon. It would also include the diversion of declared LEU product and the production of LEU product in excess of what is declared.[12]

Safeguards have generally been effective in meeting their objectives but there are problems. Safeguards can only measure to within a certain percentage of the plant's throughput and the larger the plant, the larger the absolute value of the uncertainty in the amount of enriched uranium produced. Further, the change to centrifuge enrichment technology has increased the difficulty of achieving effective safeguards. In a gaseous diffusion plant, there was only a single production line but a centrifuge plant might consist of 100 separate production lines (cascades) operating in parallel. Such a setup makes it easier to clandestinely produce HEU for nuclear weapons, since some plant cascades can be used to successively increase the enrichment of the plant's low enriched uranium product until it is able to be used in a nuclear weapon. Typically, for enrichment plants designed to produce enrichment levels of 5% or below, it would take 3 additional passes though the enrichment cascades until it has reached a sufficiently high enrichment level.

A more serious problem can occur if a country overtly breaks out of safeguards and produces HEU for weapons as fast as possible. Centrifuge enrichment plants are particularly concerning in this regard, since even if they are configured to produce only low enriched uranium, they can easily be modified to produce HEU using a batch recycling process.[13] Take the case of an enrichment plant producing the 4.1% enriched uranium product. Sending the 4.1% enriched uranium product through the plant three more times will produce HEU suitable for use in nuclear weapons. In the first step, the enrichment would be increased to 20.2%, the second step to 60.2% and the third step to 90.0%.[14] Only minor modifications to the centrifuge plant are needed to carry out batch recycling and the short equilibrium time associated with centrifuge enrichment will allow this process to be carried out quickly.

An example of how this could be accomplished is shown in Table 2. The table assumes that a country has a small centrifuge enrichment plant (100,000 SWU per year) capable of producing enough 4.1% enriched uranium to fuel only one large nuclear power plant.[15] Starting with 5,110

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[12] Brian D. Boyer et. al., "Defining the Needs for Gas Centrifuge Enrichment Plants Advanced Safeguards," LA-UR-10-02071, Los Alamos National Laboratory, Intended for: Pacific Northwest International Conference on Global Nuclear Security—the Decade Ahead, April 11-16, 2010, p. 2.
https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-10-02071
[13] "Safeguards Training Course: Nuclear Material Safeguards for Enrichment Plants, Part 4. Gas Centrifuge Enrichment Plant: Diversion Scenarios and IAEA Safeguards Activities," K/ITP--156/P4/R1, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, October 1988, p. 178. https://www.osti.gov/servlets/purl/5567442
[14] The tails for these three steps are 1.2%, 6.6% and 29.7% respectively.
[15] Tails are 0.2%.

kilograms of 4.1% enriched uranium, by using batch recycling, a country could produce 100 kilograms of HEU which is enough for 5 nuclear weapons.

Table 2

Time, Product and Feed Requirements for a Centrifuge Enrichment Plant to Produce 100 kg of HEU by Batch Recycling (Enrichment Capacity 100,000 SWU per year, Product 4.1% Enriched)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	20.2% 779 kg	4.1% 5,110 kg	16.4 to 19.3*
Second	60.2% 198 kg	20.2% 779 kg	2.6 to 4.9
Third	90.0% 100 kg	60.2% 198 kg	0.7 to 2.5
Total			26 to 33**

* The range depends on whether the taper of the cascade can be adjusted to operate optimally at high enrichments. See discussion in the text.
**Includes six days to account for equilibrium and cascade fill time, two days per each cycle.

Cascades that are designed to produce 4.1% enriched uranium from natural uranium feed are improperly tapered to operate optimally at higher enrichments. If the taper cannot be changed, then, for a 100,000 SWU per year plant, it would take 33 days (less than 5 weeks) to produce 5 weapons' worth of HEU. If the uranium hexafluoride gas flow can be adjusted so that the centrifuge plant can operate optimally, then it would only take 26 days (less than 4 weeks) to produce 5 weapons' worth of HEU. Either way, the time required is rather short. For a large centrifuge enrichment plant (2,000,000 SWU per year), the time required to produce 5 weapons' worth of HEU is about one week.

Walker and Goldston have performed a sophisticated analysis that has confirmed the dangers of centrifuge enrichment plants.[16] They found that a 4,000,000 SWU per year plant could produce about 40 weapons' worth of HEU from 5.1% enriched uranium feed in just one week.[17] Further they found that with a simple and quick reconfiguration, the plant could produce over one weapon's worth of HEU daily using natural uranium feed. This latter production could go on indefinitely.

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[16] Mark E. Walker and Robert J. Goldston, "Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants," *Science and Global Security*, Vol. 25, No. 2, 2017. http://scienceandglobalsecurity.org/archive/sgs25walker.pdf
[17] *Ibid.* p. 68. Mark and Goldston calculated that 29 significant quantities (as defined by the IAEA) could be produced in a week. However, as was discussed above, it is well-known that nuclear weapons can be produced with less material and this paper uses 20 kilograms of 90% HEU as one weapon's worth.

However, Walker's and Goldston's focus is on the prevention of the clandestine production of HEU. They have suggested various technical means whereby the production of HEU at the centrifuge plant can be detected rather quickly. They suggest that "…the Director General [of the IAEA] could call a meeting to consult with the IAEA Board of Governors on very short notice, even a few hours…"[18] They claim that this possibility "should function as a powerful deterrent."

But Walker and Goldston seem to greatly overestimate how quickly the world might respond to the production of HEU. Gilinsky and Sokolski have given a more realistic picture:

> A week's warning does not permit any sort of meaningful diplomatic response— we know these things take months, if not longer. A week leaves only time for a military reaction, which is not something undertaken lightly, especially when a report of an IAEA violation is likely to be subject to all sorts of uncertainties. This also assumes that such a week's warning would actually be received, which is problematic as there are many ways to game the system.[19]

Further, a country can produce the nonnuclear weapon components of a nuclear weapon before the production of HEU takes place. The HEU can be converted into a weapon core in only about a week.[20] After that the country producing the HEU would have its own powerful deterrent. The fact is that large uranium centrifuge enrichment plants cannot be effectively safeguarded, even if they are designed to produce only low enriched uranium fuel for nuclear power plants.

Enrichment Plants Producing High-Assay Low-Enriched Uranium (HALEU)

As was discussed above, uranium used in nuclear weapons is usually enriched to at least 80% and more typically to 90% or more. However, lower enrichments could be used to produce nuclear weapons. Just how low is classified. For the purposes of safeguards an enrichment level of 20% has been chosen as the lowest level that might be used to produced nuclear weapons. The IAEA terms any uranium with an enrichment of 20% or more high enriched uranium (HEU).[21] Efforts have been made to limit or eliminate the use of HEU in nonnuclear weapon states.

The IAEA terms uranium with an enrichment of less than 20% low enriched uranium (LEU). While a number of research reactors use uranium with an enrichment just under 20%, all commercial nuclear power plants use uranium with an enrichment of 5% or less. However, there have been various proposals to develop nuclear power reactors that would use uranium with an

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[18] *Ibid.*, p. 76.

[19] Victor Gilinsky and Henry Sokolski, "Is the IAEA's Safeguards Strategic Plan Sufficient?," Paper presented at the IAEA Symposium on International Safeguards, "Linking Strategy, Implementation and People," held in Vienna, Austria, October 22, 2014, p. 4. http://npolicy.org/article.php?aid=1262%26rtid=6

[20] Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project," December 16, 2015. https://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[21] *IAEA Safeguards Glossary 2001 Edition*, International Nuclear Verification Series No. 3, IAEA, Vienna, June 2002, p. 32. https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf

enrichment of greater than 5% and less than 20%. Such enriched uranium has been termed "High-Assay Low-Enriched Uranium" (HALEU).[22]

One of the problems with the proposed use of HALEU in commercial nuclear power plants is that there is currently no source that can produce the large quantity of HALEU that would be required if these new reactor designs were to enter widespread use. The U.S. Department of Energy (DOE) has recently called for the U.S. to "fund R&D for High-Assay Low-Enriched Uranium (HALEU)" and to "complete HALEU enrichment demonstration program."[23]

U.S. interpretations of international nonproliferation agreements consider that the European based Urenco which has the only operating enrichment plant in the U.S., is barred from providing the required HALEU. U.S. DOE has awarded a no-bid contract to Centrus Energy to develop a 16 centrifuge demonstration cascade for HALEU production.

Ironically Urenco is willing to provide the needed HALEU but Melissa Mann, the president of Urenco USA, has said that there are various licensing hurdles that must be overcome first. The Urenco plant in the U.S. would need to be relicensed to produce HALEU. In addition, new containers must be developed and licensed to transport HALEU. This step alone could take up to seven years.[24]

If a large number of commercial nuclear power plants begin to use HALEU, then uranium enrichment plants, including those in nonnuclear weapon states, will start producing HALEU. The higher enrichment of HALEU will make these centrifuge enrichment plants more dangerous from a nonproliferation point of view. This will be especially the case should a country break out of safeguards and begin to produce HEU for nuclear weapons as fast as possible. As in the case of enrichment plants producing uranium with an enrichment of less than 5%, a country could use batch recycling to produce HEU by putting the HALEU product through the enrichment plant additional times.

Table 3 is analogous to Table 2 except that instead of starting with uranium enriched to 4.1%, the starting uranium has an enrichment of 7.2%. Due to the higher enrichment of the feed and the greater enrichment produced by the plant, the uranium need only be sent though the enrichment plant twice instead of the three times required for uranium with an enrichment of 4.1%. In the first step the enrichment is increased to 45.5%, and the second step to 90.0%.[25] Only minor modifications to the centrifuge plant are needed to carry out this batch recycling. Using 2,280 kilograms of 7.2% enriched uranium feed would produce 100 kilograms of HEU, which is enough for five nuclear weapons.

[22] "What is High-Assay Low-Enriched Uranium (HALEU)," Office of Nuclear Energy, U.S. Department of Energy, April 7, 2020. https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu

[23] "Restoring America's Competitive Nuclear Energy Advantage: A strategy to assure U.S. national security," U.S. Department of Energy, 2020, p. 28. https://www.energy.gov/sites/prod/files/2020/04/f74/Restoring%20America%27s%20Competitive%20Nuclear%20Advantage_1.pdf

[24] David Kramer, "DOE uranium contract raises fairness concerns," *Physics Today*, March 2019, p. 30. https://physicstoday.scitation.org/doi/abs/10.1063/PT.3.4161?journalCode=pto

[25] The tails for these two steps are 2.1% and 18.9% respectively.

Table 3

Time, Product and Feed Requirements for a Centrifuge Enrichment Plant to Produce 100 kg of HEU by Batch Recycling (Enrichment Capacity 100,000 SWU per year, Product 7.2% Enriched)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	45.5% 267 kg	7.2% 2,280 kg	8.8 to 13.8*
Second	90.0% 100 kg	45.5% 267 kg	1.2 to 5.2
Total			14 to 23**

* The range depends on whether the taper of the cascade can be adjusted to operate optimally at high enrichments. See discussion in the text.

**Includes four days to account for equilibrium and cascade fill time, two days per each cycle.

As in the case of an enrichment plant producing 4.1% enriched uranium, the cascades that are designed to produce 7.2% enriched uranium from natural uranium feed are incorrectly tapered to operate optimally at higher enrichments. If the taper cannot be changed, then, for a 100,000 SWU per year plant, it would take 23 days (just over 3 weeks) to produce 5 weapons' worth of HEU. If the uranium hexafluoride gas flow can be adjusted so that the centrifuge plant can operate optimally, then it would only take 14 days (2 weeks) to produce 5 weapons' worth of HEU. These times are a significant reduction compared to the 5 weeks and 4 weeks respectively in the 4.1% enriched uranium case and are quite short.

All of the proposed uses of HALEU involve uranium with an enrichment of greater than 7.2% and in a number of cases, the enrichment is very close to 20%.[26] For an enrichment plant producing enriched uranium close to 20%, its product need only be sent though the plant once to produce HEU for use in a nuclear weapon. Table 4 shows the case for a 100,000 SWU per year enrichment plant producing 19.7% enriched uranium. The enrichment product is 100 kilograms of 89.4% enriched uranium which is enough for five nuclear weapons.[27] The time required ranges between 5 days and 18 days depending on whether the taper of the enrichment cascade can be properly adjusted. These times are quite short.

Recall that for a small 100,000 SWU per year plant that was producing 4.1% enriched uranium, these times were on the order of a month but for a large enrichment plant (several million SWU

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[26] John W. Herczeg, Deputy Assistant Secretary, Office of Fuel Cycle and Supply Chain, Office of Nuclear Energy, U.S. DOE, "High-Assay Low Enriched Uranium (HALEU), Nuclear Energy Advisory Committee Meeting, March 28, 2019, p. 3.
https://www.energy.gov/sites/prod/files/2019/04/f61/HALEU%20Report%20to%20NEAC%20Committee%203-28-19%20%28FINAL%29.pdf

[27] The plant would need to be producing uranium enriched to 20.2% in order to produce uranium enriched to 90.0% in one step but 20.2% enriched uranium is HEU and not HALEU. The enrichment tails are 6.4%.

per year) producing 4.1% enriched uranium, the time dropped to just one week. Table 4 shows that for even a small enrichment plant producing 19.7% enriched uranium, the time required to produce enough HEU for 5 nuclear weapons may also be only about one week and certainly no more than half a month. Clearly the production of HALEU will only increase the difficulty of safeguarding a centrifuge enrichment plant.

Table 4

Time, Product and Feed Requirements for a Centrifuge Enrichment Plant to Produce 100 kg of HEU by Batch Recycling (Enrichment Capacity 100,000 SWU per year, Product 19.7% Enriched)

Cycle	Product Enrichment and Quantity	Feed Enrichment and Quantity	Time for Cycle (Days)
First	89.4% 100 kg	19.7% 624 kg	3.2 to 16.4*
Total			5 to 18**

* The range depends on whether the taper of the cascade can be adjusted to operate optimally at high enrichments. See discussion in the text.
**Includes two days to account for equilibrium and cascade fill time.

Reactor-Grade Plutonium[28]

The next sections will discuss the difficulties of safeguarding reprocessing plants and MOX fuel fabrication plants. In both cases, the nuclear material of concern is plutonium. But before discussing these two types of facilities, it is necessary to examine the often repeated claim that the plutonium used in civil nuclear facilities, which is generally "reactor-grade," cannot or will not be used to produce nuclear weapons. Therefore, it would make little difference if this plutonium were to be diverted from these facilities. Indeed, in 2002, Bruno Pellaud, a former Deputy Director General of the IAEA, argued that safeguards on reactor-grade plutonium should be relaxed.[29] However, the IAEA continues to safeguard all plutonium in the same manner, for reasons that will be discussed below.[30]

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[28] I have extensively discussed the issue of reactor-grade plutonium in Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons: Exploding the Myths*, Nonproliferation Policy Education Center, 2018 https://nebula.wsimg.com/3fd1e3cfbbf101d6c4f562e17bc8604c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1 and Gregory S. Jones, "Reactor-grade plutonium and nuclear weapons: ending the debate," *The Nonproliferation Review*, February-March 2019 Vol. 26, No. 1-2. The technical appendix to the latter work can be found here:
https://nebula.wsimg.com/4eb6ba13bee5765c8e2aec7d658c7cde?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[29] Bruno Pellaud, "Proliferation aspects of plutonium recycling," *C. R. Physique 3*, 2002, p. 1070. https://ac.els-cdn.com/S1631070502013646/1-s2.0-S1631070502013646-main.pdf?_tid=0977685b-a61b-40a7-8a9e-f5e06b4d61bc&acdnat=1539621205_ef6fcb7665c8f8cbada94a0373616ee9

[30] The only exception is for plutonium that is more than 80% Pu-238. This plutonium, which is used in radioisotope power systems on spacecraft, is very hot and would be difficult to use in a nuclear weapon.

Natural or low enriched uranium contains a large percentage of U-238. When such uranium is used as a fuel in a nuclear reactor it is exposed to neutrons some of which are absorbed by the U-238 which decays into Pu-239. Ideally, one would use pure Pu-239 to produce nuclear weapons but that is not possible. To create significant quantities of plutonium (in the case of the production of plutonium for weapons) or to use the fuel economically (in the case of nuclear power reactors), it is necessary to leave the uranium in the reactor for extended periods of time. As the irradiation of the uranium continues some of the Pu-239 is transformed into Pu-240. Further irradiation of the fuel converts some of the Pu-240 into Pu-241 and then Pu-241 into Pu-242. If low enriched uranium is irradiated, significant amounts of Pu-238 are produced as well. All plutonium is a mixture of isotopes.

The even numbered plutonium isotopes (Pu-238, Pu-240 and Pu-242) have a much higher production of spontaneous fission neutrons than do the odd numbered ones. The presence of these isotopes greatly increases the neutron background of plutonium. These neutrons can significantly affect the performance of a nuclear weapon by causing the weapon to predetonate, resulting in a lower, possibly much lower, yield than intended.

Plutonium isotopes produce heat due to their decay. The isotope Pu-238 produces far more heat than any other reactor produced plutonium isotope. Reactor-grade plutonium produced in a commercial light-water reactor can contain several percent of Pu-238, significantly increasing the plutonium's decay heat. This heat could adversely affect the high explosives in a nuclear weapon, which, in turn, could adversely affect the weapon's functionality.

Table 5 shows the composition, spontaneous neutron output and decay heat of various kinds of plutonium. Plutonium produced specifically for weapons (weapon-grade) is left in a reactor for a relatively short time and is mostly Pu-239. Natural uranium fueled CANDU commercial nuclear power reactors burn their fuel for a significantly longer time since their goal is to produce economical electricity. As a result, CANDU produced plutonium has a much larger spontaneous fission neutron output but the plutonium is not that much hotter than that produced specifically for weapons. Plutonium produced by high burnup (51,000 MWD/Te) in a commercial pressurized water power reactor (PWR—the most common type of nuclear power reactor in the world) has not only a high spontaneous fission neutron output but also high heat output. However, not all fuel in a PWR reaches high burnup, in particular the fuel that is discharged when the reactor first starts operation. The Iranian have published data on the plutonium in the first discharge fuel at their Bushehr PWR.[31] This plutonium has a spontaneous fission neutron output intermediate to that of weapon-grade plutonium and plutonium produced in a CANDU reactor. Its heat output is no higher than that of plutonium produced in a CANDU reactor.

The phenomenon of predetonation is often cited as the reason that reactor-grade plutonium cannot or will not be used to produce nuclear weapons. Due to reactor-grade plutonium's higher

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[31] Fuel aged to 10 years after discharge. See: Yashar Rahmani et al., "Calculation of the fuel composition and the thermo-neutronic parameters of the Bushehr's VVER-1000 reactor during the initial startup and the first cycle using the WIMSD5-B, CITATION-LDI2 and WERL codes," *Annals of Nuclear Energy*, Vol. 57, 2013, pp. 68-83. https://ac.els-cdn.com/S030645491200463X/1-s2.0-S030645491200463X-main.pdf?_tid=265afa87-895d-42db-b110-52cdbd488ddf&acdnat=1539107995_47ac68425544f3db1f9c01078a4fe753

spontaneous fission neutron output, for a given unboosted nuclear weapon design such plutonium will have a higher chance of predetonating, producing a lower yield. Since a predetonating weapon can produce a range of yields depending on when the chain reaction begins, it has also been argued that such weapons will be unreliable. However, even for such weapons, the yields produced by predetonation are still substantial. Further, by simply reducing the amount of plutonium in the weapon, it is possible to produce weapons that have the same predetonation probability as those produced using weapon-grade plutonium, though at the expense of reducing somewhat the maximum yield.

Table 5

Spontaneous Fission Neutron and Decay Heat of Plutonium Produced in Different Types of Reactors with Different Burnups
(Ten Years After Discharge)

Reactor Type and Burnup (MWD/Te)	Pu-238%	Pu-239%	Pu-240%	Pu-241%	Pu-242%	Spontaneous Fission Neutrons (n/g-s)	Decay Heat (watts per kilogram)
Weapon-Grade Pu		93.4	6.0	0.6		55	2.2
PWR 1st Discharge	0.1	77.8	18.1	3.5	0.5	176	3.4
CANDU 7,000	0.07	69.2	26.4	3.0	1.3	264	3.6
PWR 51,000	2.6	54.3	25.8	9.7	7.6	432	17.8

Most discussions of the usability of reactor-grade plutonium focus on weapons using the Nagasaki design but this is totally unrealistic. It is well-known that simple fission weapons can be significantly improved by introducing an airgap between the nuclear material and the high explosives. Such weapons are said to use a levitated design. The airgap allows the implosion wave to gain speed and compress the nuclear material more efficiently. The yield, size and weight of the first French and Chinese nuclear weapons suggest that, even over 55 years ago, they were levitated. An Israeli acquired diagram of Iran's 2003 nuclear weapon shows that its design was clearly a levitated one. As a result, it was much smaller and lighter than the Nagasaki

weapon.[32] A levitated design can produce a weapon with an assembly speed about three times faster assembly than that of the Nagasaki weapon.[33]

A subcritical mass of nuclear material increases the background neutrons by producing subcritical chain reactions which eventually die out (the definition of subcritical). The closer a mass of nuclear material is to being critical the greater the increase. Since the Nagasaki core was 0.952 of critical, the increase in spontaneous fission background neutrons was a factor of 21. Levitated U.S. weapons in the early 1950s used plutonium with a spontaneous neutron background of 50 n/g-s. Using a core that was only 0.6 of a critical mass would increase the spontaneous fission neutron background by a factor of only 2.5. This is a reduction compared to the Nagasaki core of a factor of 8.4 (21/2.5). This reduction, combined with a decrease in the amount of plutonium in the core, means that plutonium produced by high burnup in a PWR (Table 5, spontaneous fission neutron output 432 n/g-s) would have a predetonation probability a little less than that of a near critical core weapon using weapon-grade plutonium. The full yield of the reactor-grade plutonium weapon would be 5 kilotons (Table 6).[34]

Table 6

Yield Produced by Plutonium with Different Spontaneous Fission Neutron Backgrounds Using Fractional Critical Mass Cores Equal Predetonation Probability (Early 1950s U.S. Implosion Technology with an Assembly Speed Three Times that of the Nagasaki Weapon)

Plutonium Type	Spontaneous Fission Neutrons n/g-s	Fraction of Critical Mass	Yield Kilotons
Weapon-Grade 5.5% Pu-240*	50	0.952	20
1st Discharge PWR	176	0.81	13
CANDU	264	0.72	9
PWR 51,000 MWD/Te	432	0.60	5

*In the early 1950s, U.S. weapon-grade plutonium was 5.5% Pu-240.

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[32] The Nagasaki weapon was 5 feet in diameter. In contrast, the Iranian design was only about 2 feet in diameter and could be carried on a Shahab-3 ballistic missile. Presentation of Israeli Prime Minister Benjamin Netanyahu, April 30, 2018. The Iranian nuclear weapon design is shown from 5:45 to about 7:35. https://www.c-span.org/video/?444882-2/prime-minister-netanyahu-iran-nuclear-agreement

[33] Technical Appendix to Gregory S. Jones "Reactor-grade plutonium and nuclear weapons: ending the debate," *The Nonproliferation Review*, February-March 2019 Vol. 26, No. 1-2, p. 12. https://nebula.wsimg.com/4eb6ba13bee5765c8e2aec7d658c7cde?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[34] For the details of the calculations in this paragraph and the following paragraph see *Ibid.*

For plutonium from CANDU fuel, the spontaneous fission neutron output is less than that of reactor-grade plutonium produced by high burnup in an LWR. As a result, a weapon that used plutonium produced in CANDU fuel could produce a core that was 0.72 of a critical mass and have a predetonation probability a little less than that of a weapon using weapon-grade plutonium. The weapon would have a yield of 9 kilotons. For the first discharge plutonium from the Iranian Bushehr PWR, the weapon core could be 0.81 of a critical mass and the yield 13 kilotons.

Therefore, by simply using an unboosted levitated weapon with a reduced mass of plutonium without making any other design changes, plutonium that is routinely discharged from a PWR can produce a yield of between 5 and 13 kilotons, with a predetonation probability a little less than that of a weapon using weapon-grade plutonium. It is also important to note that the lethal area of a nuclear weapon does not scale linearly with the yield. A 13 kiloton weapon has a lethal area that is 75% that of a 20 kiloton weapon; a 5 kiloton weapon, 40% that of a 20 kiloton weapon. Exploded in a large urban area, nuclear weapons using reactor-grade plutonium could kill tens of thousands of people.

Since the late 1970s, it has also been suggested that the heat output of reactor-grade plutonium could make it difficult or impossible to use such plutonium to produce nuclear weapons. Much of this discussion has been qualitative but Gunter Kessler, a proponent of view that reactor-grade plutonium cannot be used to produce nuclear weapons, has produced some quantitative analysis. He has calculated that plutonium with a heat output of 13 watts per kilogram would melt World War II type high explosives in a nuclear weapon.[35]

Even if this were true, it would hardly solve the proliferation concerns regarding reactor-grade plutonium. Natural uranium fueled reactors (Table 5), as well as other types that use a fuel enrichment lower than that used in a PWR, have produced much cooler plutonium. I have estimated that the majority of the 300 metric tons of separated plutonium that exists in the world today has a heat output of less than 10 watts per kilogram. Kessler does not have any suggestions on how to deal with this vast quantity of low heat reactor-grade plutonium.

Kessler's analysis focuses on near critical cores. Simply by using a core that was only 0.6 critical, Kessler's 13 watt per kilogram limit would become 21 watts per kilogram.[36] The world's entire current stockpile of separated reactor-grade plutonium, which has a heat output of less than 20 watts per kilogram, can be used to produce nuclear weapons even by Kessler's analysis.

Further, Kessler's 13 watts per kilogram applies only to the Nagasaki weapon design and World War II type high explosives. If one uses modern high explosives, a levitated weapon design and a reduced mass core, then one could use reactor-grade plutonium with a heat output of 40 watts

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[35] G. Kessler, *Proliferation-Proof Uranium/Plutonium Fuel Cycles*, KIT Scientific Publishing, 2011, p. 265. https://www.ksp.kit.edu/9783866446144 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 that contains 9.24 kilograms of plutonium.

[36] Kessler erroneously assumes that the plutonium in the Nagasaki weapon was 0.98 of critical. 13 x (0.98/0.6) = 21

per kilogram to produce a nuclear weapon.[37] This weapon could have exactly the same design as that of a weapon that used weapon-grade plutonium and would not require special cooling.

These are not the only techniques to deal with high heat plutonium. In the early 1950s, the U.S. 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, in which the plutonium core was only inserted into the high explosive assembly after the weapon was in flight, meaning that insertion 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.

As it is, the nuclear weapon potential of plutonium with a heat output of 40 watts per kilogram is largely academic. The world's entire massive 300 metric ton plutonium stockpile of separated plutonium has a heat output of less than 20 watts per kilogram and the majority of it has a heat output of less than 10 watts per kilogram. Therefore, the increased heat from reactor-grade plutonium is not an impediment to using this material to produce nuclear weapons.

In sum, powerful, reliable nuclear weapons can be manufactured using reactor-grade plutonium simply by using reduced mass plutonium weapon cores. These weapons can be the exact same design, size and weight as weapons using weapon-grade plutonium and would require no special cooling. The only penalty would be that the yield and destructive area of the reactor-grade plutonium weapons would be somewhat reduced compared to weapons manufactured using weapon-grade plutonium.

Safeguarding Reprocessing Plants

Aqueous Separation—PUREX

Once the uranium fuel is discharged from a nuclear power reactor and some of its radioactivity is allowed to decay away (the fuel is "cooled"), it can be chemically processed (reprocessed) to separate the plutonium and residual uranium from the remaining highly radioactive fission products, other actinides (neptunium, americium and curium) and from each other. An aqueous separation process known as PUREX has been used since the 1960s for reprocessing spent uranium fuel.

In the PUREX process, the fuel is chopped into small sections and concentrated nitric acid is used to dissolve the fuel. As a result, the plutonium, uranium, the other actinides and most of the fission products wind up in the nitric acid solution. The fuel cladding (typically zirconium or stainless steel) and some residual fuel and fission products are left behind. The fission products, krypton and iodine, as well as some tritium are vented into the atmosphere.

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[37] Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons: Exploding the Myths*, Nonproliferation Policy Education Center, 2018, pp. 82-83.
https://nebula.wsimg.com/3fd1e3cfbbf101d6c4f562e17bc8604c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

The main separation process is solvent extraction. The nitric acid solution is brought into contact with an immiscible organic solvent and most of the plutonium, uranium and only a small amount of the fission products wind up in the organic solvent. This organic solvent is further processed to separate the plutonium and uranium from each other as well as to remove most of the remaining fission products. The original nitric acid solution containing the fission products and the other actinides along with some small amount of plutonium and uranium, is initially stored in tanks and eventually converted into glass blocks for disposal.

The PUREX process was originally developed in the 1950s to recover plutonium for the production of nuclear weapons. Spent fuel from commercial nuclear power reactors began to be reprocessed in the 1960s. The main objective was to recover the plutonium from the spent fuel for use in breeder reactors. However, as was discussed above, no breeder reactors have been commercialized and as a result most fuel from commercial nuclear power plants today is not reprocessed. Still, many in the nuclear industry will not abandon the breeder reactor dream. Large stockpiles (300 metric tons) of plutonium have been accumulated world-wide in anticipation of the breeder reactor. Some countries such as France, Japan, India and Russia have large reprocessing plants and some countries such as China and perhaps South Korea, plan to build ones.

As with an enrichment plant, IAEA safeguards are designed to prevent the clandestine diversion of nuclear material, mainly plutonium. They are also concerned with the detection of the reprocessing of undeclared spent fuel. The IAEA has been clear that the safeguarding of large reprocessing plants poses serious problems. For small facilities the nuclear material is directly measured but in a large facility this "would require huge resources."[38] The IAEA also admits that its measurements can have errors of "1-2%."[39] A large reprocessing plant, such as Rokkasho in Japan, can reprocess enough spent fuel to produce 8 metric tons of plutonium per year. A 1-2% error rate would amount to 80 to 160 kilograms of plutonium per year. The IAEA's goal is to detect the diversion of a "significant quantity" of nuclear material, which in the case of plutonium is 8 kilograms. The inaccuracy uncertainty is then 10 to 20 IAEA significant quantities.

As was discussed above, a more realistic value for a significant quantity of plutonium is in the range of 2 to 4 kilograms of plutonium, which means that the inaccuracy uncertainty is more likely 20 to 80 significant quantities. The IAEA has suggested using short notice random inspections, unannounced inspections, and data from the plants own sensors to try to deal with this problem.

Another problem, one that does not affect enrichment plants, is the significant uncertainty in the amount of material is being put into the plant to begin with. Measuring the amount of plutonium in the intact spent fuel assemblies as received at the plant is to be preferred but the IAEA has said, "this may not be feasible or cost effective."[40] Therefore, only after the fuel has been

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[38] *International Safeguards in the Design of Reprocessing Plants*, IAEA Nuclear Energy Series, No. NF-T-3.2, International Atomic Energy Agency, Vienna, 2019, p. 11. https://www.iaea.org/publications/13454/international-safeguards-in-the-design-of-reprocessing-plants
[39] *Ibid.*, p. 13.
[40] *Ibid.*, p. 35.

dissolved, and the plutonium put into the nitric acid solution, is the amount of plutonium measured in an "accountability tank." The IAEA admits that accounting problems can be caused by undissolved fuel solids and incomplete fuel dissolution. Additionally, the IAEA would prefer that plants use batch dissolution of the spent fuel but modern reprocessing plants use continuous dissolution. This can cause problems since the nitric acid solution from different batches of fuel are mixed together making it difficult to compare the power plant's fuel burnup estimates to the amount of plutonium in solution.

A striking example of this problem occurred at the UK's THORP reprocessing plant. THORP was a large plant with a nominal processing capacity of 800 metric tons of heavy metal per year. Sometime around August 2004, a pipe associated with one of the two accountability tanks at THORP developed a leak. This was apparently caused by the agitation needed to homogenize the tank's contents so as to get an accurate measurement of the amount of plutonium and uranium in solution. The leak grew worse over time and the pipe eventually broke. Between, August 2004 and April 2005, 83,000 liters of solution containing 160 kilograms of plutonium spilled into the interior of the plant and were unaccounted for.

For the plant's reprocessing campaign which ended in late January 2005, a difference of 3.5% was measured between the amount of plutonium in the plant and the amount that the nuclear power plant operators estimated should have been in the spent fuel.[41] At this point about 30 kilograms of plutonium were unaccounted for and the discrepancy was reported in the media.[42] British Nuclear Fuels Limited (BNFL), the plant's operator, took the position that plutonium was not missing because it had never existed i.e. the nuclear power plant operators had overestimated how much plutonium was in the fuel to begin with. As a spokesman said, "From our point of view, no nuclear material is physically missing."

The reprocessing campaign in February 2005 had a 3.9% discrepancy in the plutonium accounting. For a campaign in March 2005, the discrepancy was 10.0%. Only when a similarly large level of discrepancy occurred during a campaign in April did BNFL realize that the plutonium was missing. The plant stopped operation and the leakage problem was discovered.

It seems clear that discrepancies of 10% were needed to eventually indicate a problem but if the level had remained at 3-4% how long would it have taken to discover the problem? For a large reprocessing plant such as Rokkasho discrepancies of 3-4% would translate into 240-320 kilograms of plutonium missing each year. Even the 30 kilograms of plutonium that was missing at THORP at the end of January 2005, would have been sufficient to build 5 to 15 nuclear weapons yet it took three months to discover what had happened to the material.

As in the case of enrichment plants, a more serious problem with reprocessing plants is the case of a country overtly breaking out of safeguards and producing plutonium for weapons as fast as possible. In the reprocessing plant, the plutonium, once it has been separated from the uranium

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[41] "A report of the investigation into the leak of dissolver product liquor at the Thermal Oxide Reprocessing Plant (THORP), Sellafield, notified to HSE on 20 April 2005," UK Health and Safety Executive, February 2007, p. 9. http://www.onr.org.uk/periodic-safety-review/thorpreport.pdf

[42] Philip Ball, "Plutonium books don't balance at UK plant," *Nature*, February 17, 2005, p. 14. https://www.nature.com/articles/news050214-14

and the purification completed, is contained as a nitrate in a nitric acid solution. The plutonium is then converted into an oxide, which is the chemical form that is used to store and ship the plutonium.

For a large reprocessing plant such as Rokkasho, which produces 8 metric tons of plutonium per year, even if the plutonium oxide was shipped to the MOX fuel fabrication plant monthly, almost 700 kilograms of plutonium could be stored at one time at the reprocessing plant. In fact, compared to the amount of plutonium produced by a reprocessing plant, there tends to be less demand for MOX fuel and the plutonium required to manufacture it. As a result, sizable amounts of plutonium are stored at the reprocessing plant long-term. At the end of 2018, at Rokkasho, over 3 metric tons of plutonium, in the form of oxide, was being stored.[43]

The process to convert plutonium oxide into plutonium metal is well-known. The oxide is fluorinated to produce plutonium fluoride and a thermite type process using calcium metal produces plutonium metal. The metal is then alloyed with gallium and is fashioned into a weapon core. This is not a long-involved process. During World War II, the U.S. carried out all of these steps in less than a week.[44]

To address such concerns at Rokkasho, the plutonium oxide is mixed with an equal quantity of uranium oxide to produce a 50-50 mix. However, this does not greatly increase the time required to produce plutonium metal for a nuclear weapon. A simple solvent extraction step could be added to separate the plutonium and the uranium. A similar step is used in a reprocessing plant to separate these two elements but in the breakout case, it would be much simpler since the 50-50 plutonium-uranium oxide mix is not very radioactive and the plutonium is 50 times more concentrated than in spent fuel. The facilities to carry out this conversion to metal could have already been constructed in advance in the guise of research facilities. Further a country can produce the nonnuclear weapon components of nuclear weapons before producing plutonium metal. Then once the plutonium metal cores were produced, a country would have nuclear weapons.

The discussion in the section on uranium enrichment about the difficulties of the world responding in a timely fashion to the seizure of the enriched uranium and the production of HEU, applies to a reprocessing plant as well. The suggestion of Gilinsky and Sokolski that a violator might game the safeguards system seems particularly relevant to a reprocessing plant. A country would only need to take a few tens of kilograms of plutonium to start their weapon program. This might be only about 1% of the total plutonium stored at the site. With such a large plutonium store, it might well take some time to perform a full inventory and confirm that plutonium is missing. By then weapons could have already been manufactured.

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[43] "The Status Report of Plutonium Management in Japan-2018," Japanese Office of Atomic Energy Policy, July 30, 2019, p. 4. http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set_20190730.pdf

[44] Gregory S. Jones, Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project," December 16, 2015. https://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

Aqueous Separation—Alternate Process Configurations—UREX

For more than two decades alternatives to the basic PUREX reprocessing method have been considered, which would change the chemistry as well as add additional process steps. The purpose of these changes would be three-fold. One, the fission products could be partitioned into several groups, easing the disposal of the nuclear waste. Two, the other actinides (neptunium, americium and curium) would be removed from the waste and incinerated in a nuclear reactor, which would also ease the disposal of the nuclear waste. Three, plutonium would never be produced in a pure form, which, it is hoped, would help with nonproliferation concerns. In addition, processes and equipment would be changed to reduce radioactive emissions from reprocessing plants and improve plant performance.

In 2006, the U.S., as part of The Global Nuclear Energy Partnership, proposed the UREX process as an alternative to PUREX. In 2010 this initiative's name was changed to the International Framework for Nuclear Energy Cooperation. There are nine proposed variants of the UREX process depending on exactly which final products are desired.[45] The Europeans have also suggested variants of PUREX which contain some aspects of the various UREX processes. The development of any of these alternatives to PUREX has proceeded slowly and the various UREX steps have only been tested in the laboratory. No pilot plant has been built that uses any UREX variant.

An example of UREX is the UREX+3 process. All of the UREX variants use the same starting point as PUREX, namely the dissolution of the spent fuel in nitric acid, which puts almost all of the uranium, plutonium, other actinides and fission products into solution. Solvent extraction is carried out using the PUREX reagents but the process has been adjusted so that only the uranium and the fission product technetium are recovered. The uranium and technetium are separated from each other as final products.

The remaining solution is then treated by a different solvent extraction process known as FPEX which uses different reagents than does PUREX. The cesium and strontium fission products are recovered. The remaining solution is then treated by solvent extraction using PUREX reagents and the plutonium and neptunium are recovered and kept together as a product. The remaining solution is then treated by a solvent extraction process called TRUEX which uses reagents that are different from either PUREX or FPEX. The americium, curium and all the lanthanide fission products are extracted from the rest of the fission products. This extract is treated by yet another solvent extraction process that uses reagents different from PUREX, FPEX or TRUEX. It is called TALSPEAK and separates the americium and curium from the lanthanides. The americium and curium are kept together as a product and the lanthanides are mixed back with the other fission products.

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[45] J.J. Laidler, "Development of partitioning methods in the United States of America nuclear fuel cycle program," Argonne National Laboratory, p. 135 in *Spent Fuel Reprocessing Options*, IAEA-TECDOC-1587, International Atomic Energy Agency, August 2008, https://inis.iaea.org/collection/NCLCollectionStore/_Public/40/018/40018312.pdf?r=1   These variants are UREX+1, UREX+1a, UREX+1b, UREX+2, UREX+2a, UREX+3, UREX+3a, UREX+4, UREX+4a.

The final products are uranium, plutonium/neptunium mixture, americium/curium mixture, technetium fission product, cesium/strontium fission products and all of the rest of the fission products including the lanthanides. The uranium would be reenriched and used as reactor fuel. The plutonium/neptunium mixture would be mixed with uranium and used as reactor fuel. The americium/curium mixture would be manufactured into targets and incinerated in a reactor.[46]

The technetium is an especially troublesome fission product from the point of view of long-term waste disposal. It has a 214,000 year half-life and it constitutes the bulk of the long-term fission product radioactivity. It is mobile in water, so if a nuclear waste repository is breached even tens of thousands of years from now, it would be readily released from the repository. By separating the technetium, it is possible to put it into a waste form that is especially resistant to water.

The cesium/strontium are significant short-term generators of heat which would constrain the amount of waste that could be placed into a repository. However, the key isotopes (Cs-137 and Sr-90) only have half-lives of 30 years and 29 years respectively. They could be immobilized and allowed to decay away without being placed in a repository, though this would take hundreds of years.

The remaining fission products would be immobilized in glass and placed in a repository. By having the other actinides, technetium, cesium and strontium removed, this waste would be much cooler and less toxic, allowing for a repository to hold the waste from many more reactors.

This particular UREX process requires three new solvent extraction steps which will drive up the technical complexity and the costs. Oak Ridge National Laboratory has reported, "While this scheme provides extensive partitioning of the fuel constituents, it also requires a significant amount of primary process equipment and support processes to manage the large number of individual extractants required."[47] It is not at all clear that the increased costs of these alternative aqueous reprocessing processes can be justified by the improvement in nuclear waste forms.

In this UREX variant as well as two others (UREX+2 and UREX+4) the plutonium would be separated as a pure plutonium/neptunium mixture (the neptunium would comprise only 5% of the product). A Brookhaven National Laboratory report found that the proliferation risk for these three UREX variants was "essentially equivalent to that of the PUREX process."[48] That is to say, essentially equivalent to pure plutonium.

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[46] The manufacture of these targets would be complicated by the high spontaneous fission rate of Cm-244. As a result, the UREX+4 and UREX+4a variants would separate the americium and curium from each other by a process that has yet to be developed. The americium would be incinerated in a nuclear power reactor. The curium would be stored to allow the Cm-244 (18 year half-life) to decay away, though this would take more than a century.

[47] Robert Jubin, "Spent Fuel Reprocessing," Oak Ridge National Laboratory. http://www.cresp.org/NuclearChemCourse/monographs/07_Jubin_Introduction%20to%20Nuclear%20Fuel%20Cycle%20Separations%20-%20Final%20rev%202_3_2_09.pdf

[48] R. Bari et. al., "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing," BNL-90264-2009-CP, Brookhaven National Laboratory, July 2009. https://cybercemetery.unt.edu/archive/brc/20120621001801/http://brc.gov/sites/default/files/meetings/presentations/tom_clements_brookhaven_on_reprocessing_risks_2009.pdf

For three other variants (UREX+2a, UREX+3a, and UREX+4a) the plutonium is contained in a plutonium/neptunium/uranium mixture which is about 80% to 90% uranium. This product would be similar to the uranium/plutonium mixture to be produced at the Japanese Rokkasho reprocessing plant discussed in the previous section. The addition of the uranium does not add much to the time required to produce plutonium metal for a nuclear weapon, as a simple solvent extraction step could separate the plutonium from the uranium and neptunium.

For the final three UREX variants (UREX+1, UREX+1a and UREX+1b) the plutonium is contained in a mixture which would include the neptunium, americium and curium. It may also contain uranium and for UREX+1, the lanthanide fission products as well. Again, a simple solvent extraction step could separate the plutonium from all of these other elements. Referring to all nine UREX variants, the Brookhaven report concluded "that for state-level threats, the differences [in proliferation risk] among the technologies…are not very significant."

All of the concerns about safeguarding PUREX-based reprocessing plants apply to plants using UREX type processes. Further, the IAEA has raised additional concerns about safeguarding these alternate aqueous reprocessing systems.[49] One of the justifications for these alternate reprocessing systems is to increase throughput and decrease processing time, which the IAEA says could possible make "the application of safeguards more difficult."[50] The IAEA says that the stability of the operation of these more complicated reprocessing methods may be harder to maintain and that instability or process upsets can "require more operator interaction with the process in the process areas, making misuse easier to accomplish and more difficult to detect."[51]

The IAEA is also concerned about the variety of product forms that these alternate reprocessing methods may produce. It has said:

> If the next generation process yields different material forms or product purities that require measurement, measurement capabilities will need to be developed. The presence of measurement interferences due to other isotopes can be a cause of measurement bias, increasing measurement uncertainty or possibly cause an inability to perform measurement with some techniques. Some of the new product forms may not be clearly defined in the IAEA material categories.[52]

The IAEA has proposed that research be undertaken to address these problems. Fortunately, the slow development of these alternate aqueous reprocessing methods means that there is plenty of time to address these issues. Indeed, given the cost and complexity of these alternate reprocessing methods, it is unclear if they will ever be used.

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[49] *International Safeguards in the Design of Reprocessing Plants*, IAEA Nuclear Energy Series, No. NF-T-3.2, International Atomic Energy Agency, Vienna, 2019, pp. 37-38.
https://www.iaea.org/publications/13454/international-safeguards-in-the-design-of-reprocessing-plants
[50] *Ibid.*, p. 37.
[51] *Ibid.*, p. 38.
[52] *Ibid.*

Non-aqueous Separation—Pyroprocessing

While the aqueous PUREX reprocessing method is the one in use world-wide today, there have been various suggestions to use non-aqueous methods. One process that has seen significant developmental effort over the past two decades is pyroprocessing, which was initially developed at the Idaho National Laboratory in the U.S. Pyroprocessing has been touted as being proliferation resistant and the U.S. has been helping South Korea develop this reprocessing method, though at the moment it is still in the R&D phase.

Pyroprocessing was originally developed to process HEU spent fuel from the EBR-II experimental fast breeder reactor. Pyroprocessing is an electro-chemical process. The metallic uranium fuel is dissolved into a LiCl-KCl molten salt solution in an electrorefiner. An electric current is passed though the salt and pure uranium metal is collected at the cathode. If the spent fuel contains significant amounts of plutonium and other transuranic actinides (neptunium, americium and curium), they accumulate in the salt in the electrorefiner and are not separated with the uranium. An additional electro-chemical step is underdevelopment to separate the other actinides. The salt from the electrorefiner containing the other actinides would be placed in an electrowinner, which uses a cadmium cathode. It is expected that a metal containing all of the transuranic actinides plus some uranium can be produced. Since no pure plutonium is produced, the process is thought to be proliferation resistant. If the spent fuel is in oxide form, an additional initial electro-chemical step is needed to reduce the oxides to metallic form before the fuel can undergo pyroprocessing.

While some thought has been given on how to safeguard a pyroprocessing plant against diversion, it must be noted that pyroprocessing has not been fully developed. It has been stated "Pyroprocessing flowsheet design is highly application specific."[53] Therefore, since there is no standard pyroprocessing design, there cannot be any standard safeguards procedure. Indeed, it is not clear that any serious effort has been expended considering how a potential proliferator might misuse a pyroprocessing plant. For example, it may well be possible to use the process to produce pure plutonium metal free from any other actinides.

As at a PUREX reprocessing plant, it is not possible to measure how much plutonium is in the spent fuel and being input into the plant. But this problem of determining how much plutonium should be in the plant is more serious than even the one in a PUREX plant since a pyroprocessing plant will not have any accountancy tanks to measure the input. In a MOX fuel fabrication plant (discussed below), the amount of plutonium can be estimated by measuring the radiation emitted and in particular, the spontaneous fission neutrons (especially from Pu-240). However, in a pyroprocessing plant this will not be possible since the plutonium will be processed along with the other actinides including curium. The much greater spontaneous fission neutron output of curium, compared to plutonium, will mask the plutonium's signature. It has been suggested that measuring the curium could be used as a proxy for the plutonium. However, it is not clear that the plutonium/curium ratio can be accurately determined for all types of fuels and burnups or that the ratio will be stable throughout the pyroprocessing plant,

[53] Guy Fredrickson, Idaho National Laboratory, "Overview of Pyroprocessing," ImPACT International Symposium: New Horizons of Partitioning and Transmutation Technologies with Accelerator Systems, December 2-3, 2018 https://www.jst.go.jp/impact/hp_fjt/news/images/20181202_04.pdf

since the reduction potential of the two metals is not the same. The batch nature of pyroprocessing leads to additional accountancy problems, since the plutonium and other actinides accumulate in the electrorefiner salt for multiple fuel batches before being transferred to the electowinner and recovered. This will make it impossible to assign specific plutonium amounts to specific fuel batches.[54]

As with the PUREX reprocessing plant, an overt seizure of the plutonium is a serious threat. Even if the plutonium is mixed with the other actinides, it would only take a solvent extraction step to separate the plutonium. This step would be much simpler than in a PUREX plant, since the pyroprocessing will have already removed most of the fission products and the plutonium would be much more concentrated.   A Brookhaven study stated that the proliferation risk difference of the plutonium products produced by pyroprocessing compared to those produced by the PUREX process (i.e. pure plutonium) is "not very significant."[55]

MOX Fuel Fabrication Facilities

If the plutonium that is recovered at a reprocessing plant is to have any value, it must be fabricated into fuel for use in a nuclear power plant. Since, as was discussed above, breeder reactors have not been developed and deployed as was once anticipated, the fuel will need to be used in light water reactors which form the bulk of the power reactors in operation today. Such fuel contains plutonium in the form of an oxide. The plutonium oxide will make up roughly 5%-7% of the fuel. The rest of the fuel will be a uranium, i.e. natural or depleted. This uranium will also be in the form of an oxide, so that the fuel is called Mixed Oxide Fuel or MOX.

The plutonium already arrives at the MOX fuel fabrication plant in oxide form. Given the quantity of plutonium produced annually at a large reprocessing plant, the MOX plant must handle a number of metric tons of plutonium each year to avoid the accumulation of large stockpiles of plutonium. Given that the deliveries of plutonium from the reprocessing plant will occur only intermittently, substantial amounts of plutonium will need to be stored at the MOX fuel fabrication plant in order to ensure uninterrupted operation. For example, at the end of 2018, Japan had over 2.5 metric tons of plutonium oxide stored at its fuel fabrication facilities.[56] This amount is probably larger than would be typical given that the Japanese facilities are not in operation but even if they were, there would still probably be on the order of a metric ton of plutonium oxide stored at its MOX fuel fabrication plant. Additional amounts of plutonium would be in process in the fabrication plant and still more in completed fuel assemblies awaiting delivery to the nuclear power plants.

[54] P.C. Durst *et. al.*, "Advanced Safeguards Approaches for New Reprocessing Facilities," PNNL-16674, Pacific Northwest National Laboratory, June 2007, p. 32.
https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-16674.pdf
[55] R. Bari et. al., "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing," BNL-90264-2009-CP, Brookhaven National Laboratory, July 2009.
https://cybercemetery.unt.edu/archive/brc/20120621001801/http://brc.gov/sites/default/files/meetings/presentations/tom_clements_brookhaven_on_reprocessing_risks_2009.pdf
[56] "The Status Report of Plutonium Management in Japan-2018," Japanese Office of Atomic Energy Policy, July 30, 2019, p. 4. http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set_20190730.pdf

Safeguarding a MOX fuel fabrication plant poses different problems than that of safeguarding a reprocessing plant. Since the plutonium is in the form of a powder and not a liquid, it is hard to homogenize the powder and take a small sample to confirm its composition. Rather the amount of plutonium in a particular container is confirmed by a combination of the material's weight and the neutron and gamma radiation it is emitting.

This method works well when the composition is well-known and the plutonium oxide-uranium oxide mixture is "clean." However, scrap can be rather difficult to assay since contaminants such as water can change the amount of radiation emitted by the material.[57] Plutonium powder can also accumulate on the insides of glove boxes and other processing equipment. It can be difficult to determine the quantity of such material leading to large uncertainties in the plutonium inventory. In one case, gloveboxes had to be physically dismantled, at the cost of $100 million, to determine how much plutonium they actually contained.[58]

As with the reprocessing plants, MOX fuel fabrication plants can be overtly seized by the country and the stored plutonium oxide quickly converted into plutonium metal nuclear weapon cores. The procedure and time required would be the same as in the case of the reprocessing plant, since in both cases the starting point is the stored plutonium oxide.

Given the proliferation concerns about MOX fuel fabrication in nonnuclear weapon states, there have been some proposals to build such facilities only in nuclear weapon states or in international fuel cycle centers. Then only the MOX fuel itself would be sent to nonnuclear weapon states. In the past a number of nonnuclear weapon states used MOX fuel which was manufactured in other countries but the uneconomic nature of this fuel has led most countries to give up the use of MOX fuel. An exception is the Netherlands, which in 2014 began to burn MOX fuel manufactured in France in its sole nuclear power reactor. Each year, the Netherlands receives fresh MOX fuel containing around 300 kilograms of plutonium.

The case of the Netherlands sets a dangerous precedent since a recipient country could seize the fresh MOX fuel and extract the plutonium for nuclear weapons. The fresh MOX fuel's radioactivity levels are far below that of spent fuel and the plutonium is 5 to 7 times more concentrated than in spent fuel. It would be fairly easy to set up a simple solvent extraction facility to recover the plutonium. In 1977 the Oak Ridge National Laboratory proposed that potential proliferators could clandestinely build a "Simple, Quick Processing Plant," to extract the plutonium from spent fuel.[59] Whether this plant could actually carry out this difficult task is unclear but it could certainly carry out the much simpler task of extracting the plutonium from fresh MOX fuel. Oak Ridge estimated that plutonium could be produced in one week.

The use of MOX fuel in light water reactors raises proliferation concerns that will greatly increase the stresses on the IAEA safeguards systems. The fresh MOX fuel will need to be

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[57] Specifically, the contamination with unknown amounts of light elements causes the production of neutrons by the alpha-n reaction.
[58] Alan J. Kuperman, David Sokolow, Edwin S. Lyman, "Can the IAEA Safeguard Fuel-Cycle Facilities?, p. 18. http://www.aec.go.jp/jicst/NC/iinkai/teirei/3-3set_20190730.pdf
[59] Intra-Laboratory Correspondence, "Simple, Quick Processing Plant," From D. E. Ferguson to F. L. Culler, Oak Ridge National Laboratory, August 30, 1977. http://fissilematerials.org/library/fer77.pdf

continuously monitored during its transport to, and its storage at, a nuclear reactor. Since the use of MOX fuel is not economical, its use should be discontinued.

Conclusions

The fact that the same nuclear materials and fuel production processes that can produce fuel for nuclear power reactors can also produce nuclear material for nuclear weapons has led to the need for the IAEA to safeguard nuclear activities that are nominally peaceful. These safeguards face their greatest challenge at bulk nuclear fuel facilities (uranium enrichment plants, reprocessing plants and MOX fuel fabrication plants) that handle large quantities of nuclear materials that can be quickly converted into the form needed for nuclear weapons. It is not clear that the IAEA safeguards are up to the challenge.

IAEA safeguards have some difficulty protecting against clandestine diversion or misuse of these bulk fuel facilities but a greater threat is the overt seizure of these facilities to produce nuclear material for nuclear weapons as quickly as possible Large uranium centrifuge enrichment plants, even if they are designed to produce uranium with an enrichment of 5% or less, can be quickly converted into producing HEU for weapons by using batch recycling. The low enriched uranium product of the enrichment plant would be the feed used as the starting point for this process. Only slight changes would be needed to the enrichment plant in order to produce this HEU. A large centrifuge enrichment plant could produce enough HEU for tens of nuclear weapons in the space of a week. The plant could then be repiped and start using natural uranium feed to produce enough HEU for one nuclear weapon every day. This latter HEU production could continue indefinitely. The times required to produce HEU in an enrichment plant that produces HELEU is even shorter, given the higher enrichment of the starting uranium. In these breakout scenarios, IAEA safeguards would be meaningless.

Concerning the production of plutonium in a reprocessing plant, it is still too often said that plutonium produced in commercial nuclear power plants is of no proliferation concern because it is reactor-grade. In fact, powerful, reliable nuclear weapons can be manufactured using reactor-grade plutonium simply by using reduced mass plutonium weapon cores. These weapons can be the exact same design, size and weight as weapons using weapon-grade plutonium and would require no special cooling. The only penalty would be that the yield and destructive area of the reactor-grade plutonium weapons would be somewhat reduced compared to weapons manufactured using weapon-grade plutonium.

The current standard fuel reprocessing method for recovering plutonium relies on the PUREX process. Protecting even against clandestine diversion of plutonium at such a plant poses problems for IAEA safeguards as the amount of plutonium that is in the plant is only an estimate based on a nuclear power plant's fuel burnup calculations. An incident at the UK's THORP reprocessing plant in 2004-2005 illustrates this problem. A leak in the plant led to some 30 kilograms of plutonium to go missing. But the plant operators denied that there was any problem claiming that the plutonium had never existed because of erroneous power plant burnup calculations. It was only when the amount of missing plutonium reached 160 kilograms did the plant operators realize that the problem was real and the leak discovered.

Since metric ton quantities of separated plutonium oxide are stored at a PUREX reprocessing plant, the threat of overt seizure of the plutonium stocks is also a serious problem. The plutonium oxide can be converted into plutonium metal and fashioned into a nuclear weapon core in only about a week.

Proposed reprocessing plants that would use alternate aqueous reprocessing methods have the same difficulties being safeguarded as do plants that use the PUREX process plus some additional ones. Though these proposed plants would not produce plutonium in a pure form, a Brookhaven study found that the differences in the proliferation risk posed by these plants compared to that of a PUREX plant "are not very significant."

Pyroprocessing is another proposed alternative reprocessing method. Thus far pyroprocessing is still under development and there is no standard pyroprocessing flowsheet. As a result, there is not yet any standard safeguarding procedure. Since, in the proposed pyroprocessing design, the plutonium remains mixed with the other transuranic actinides, pyroprocessing is thought to be proliferation resistant. However, this may not actually be the case as it is not clear that any serious effort has been devoted to considering how a potential proliferator might misuse a pyroprocessing plant. The process could possibly be used to produce pure plutonium metal free from any other actinides. This is an issue that requires further research.

Just as at a PUREX reprocessing plant, a MOX fuel fabrication plant will have many hundreds of kilograms of plutonium oxide stored onsite. As with the reprocessing plant there is the threat of the overt seizure of the plutonium oxide which can be converted into plutonium metal and fashioned into a nuclear weapon core in only about a week. Sending the MOX fresh fuel to nuclear power reactors also poses problems for IAEA safeguards, since the plutonium can be recovered from this fuel in just one week using a simple quick processing plant designed in the 1970s.

It is not clear that the IAEA can effectively safeguard bulk nuclear fuel facilities, especially from the threat of overt seizure. If this is the case, centrifuge enrichment plants, reprocessing plants (regardless of the process used), MOX fuel fabrication plants and the fresh MOX fuel itself, should not be allowed in nonnuclear weapon states.