Excess Plutonium Disposition: The Failure of MOX and the Promise of Its Alternatives

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December 2014

Union of Concerned Scientists

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ACKNOWLEDGMENTS
This white paper was made possible by the generous support of the MacArthur Foundation and members of the Union of Concerned Scientists. The author would like to thank Trudy E. Bell for editing; Teri Grimwood for design and layout of the full report; Cynthia DeRocco and Penny Michalak for design and layout of the Executive Summary; Bryan Wadsworth for overseeing production; and Matthew Bunn, Frank von Hippel, Scott Kemp, and Lisbeth Gronlund for valuable comments.

The opinions expressed herein do not necessarily reflect those of the organizations that funded the work or the individuals who reviewed it. The authors bear sole responsibility for the report's content.

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[GLOSSARY OF ACRONYMS]

AEC	Atomic Energy Commission
AFS	Alternate Feedstock
ARIES	Advanced Recovery and Integrated Extraction System
ASLB	Atomic Safety and Licensing Board
BREDL	Blue Ridge Environmental Defense League
CAB	controlled area boundary
CAR	Construction Authorization Request
Cogema	Compagnie générale des matières nucléaires (became AREVA)
DBT	Design Basis Threat
DCS	Duke Cogema Stone & Webster (became Shaw AREVA MOX Services LLC)
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DWPF	Defense Waste Processing Facility (at SRS)
FNMCP	Fundamental Nuclear Material Control Plan
GANE	Georgians Against Nuclear Energy (became Nuclear Watch South)
GAO	U.S. Government Accountability Office
HEU	highly enriched uranium
HLW	high-level radioactive wastes
IAEA	International Atomic Energy Agency
KAC	K-Area Complex (at SRS)
LEU	low-enriched uranium
LWR	light-water reactor
MC&A	material control and accounting
MFFF	Mixed Oxide Fuel Fabrication Plant (at SRS)
Minatom	Russian Federal Ministry of Atomic Energy (became Rosatom)
MMIS	Manufacturing and Management Information System
MOX	mixed (plutonium and uranium) oxide
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
PDC	Pit Disassembly and Conversion Project (combining PDCF and PuPP functions)
PDCF	Pit Disassembly and Conversion Facility
PIP	Plutonium Immobilization Plant

PLC	Programmable Logic Controller
PMDA	Plutonium Management and Disposition Agreement
PPP	Physical Protection Plan
PuPP	Plutonium Preparation Project
PDWG	DOE's internal Plutonium Disposition Working Group
SEIS	Supplemental Environmental Impact Statement
SGT	Safeguards Transporter
SNM	Special Nuclear Material
SPD	Surplus Plutonium Disposition
SRS	Savannah River Site, South Carolina
SST	Safe Secure Trailer
WIPP	Waste Isolation Pilot Plant, in New Mexico
WSB	Waste Solidification Building

[EXECUTIVE SUMMARY]

"A clear and present danger"

2014 marked the 20th anniversary of a National Academy of Sciences report that issued a stark warning. Growing stockpiles of weapons plutonium, being removed from dismantled U.S. and Russian nuclear warheads that were no longer needed after the end of the Cold War, represented a "clear and present danger."

The National Academy was concerned that plutonium stored in the form of pits, or finished weapon components, could quickly and easily be returned to use in weapons should tensions again increase between the superpowers. The National Academy also feared that separated plutonium could be stolen by sub-national groups, especially in Russia, where the state of nuclear security was precarious amidst the social and economic crisis that followed the collapse of the Soviet Union. Theft of plutonium is a serious risk because the amount of plutonium needed to make a crude nuclear bomb is small and light enough to be easily carried and does not pose an immediate risk of severe injury to the thief.

To deal with these threats, the National Academy recommended that both the United States and Russia undertake efforts to convert surplus separated plutonium into a form much harder to steal or convert back for use in nuclear weapons. The goal was to meet the "spent fuel standard" —that is, to make the plutonium as inaccessible and hard to steal as the plutonium contained in commercial light-water power reactor spent fuel assemblies, which are large, heavy, and lethally radioactive. The National Academy recommended that the two countries' plutonium disposition programs proceed essentially in parallel and operate under stringent bilateral and international monitoring.

The U.S. government heeded the National Academy's call. It designated around 50 metric tons of plutonium as surplus to its weapons programs and initiated a major and costly program to dispose of it. In 2000, the United States and Russia signed an agreement in which each country committed to disposing of 34 metric tons of excess plutonium.

The U.S. Department of Energy (DOE), the agency responsible for management of the plutonium, decided to pursue a "dual track" disposition strategy. The first approach was to blend high-purity plutonium from weapons with uranium and make the mixture into fuel—called mixed-oxide (MOX) fuel—for commercial nuclear power reactors. Once the MOX was irradiated in a reactor, it would meet the spent fuel standard. This approach had appeal because the basic idea was to convert "swords into ploughshares."

The second method, known as immobilization, involved incorporating plutonium into a corrosion-resistant ceramic matrix and then encasing the immobilized plutonium in glass along with highly radioactive nuclear wastes that already existed at DOE sites. Immobilization was intended for impure plutonium that would be difficult to make into reactor fuel, although in principle all surplus plutonium could be immobilized. Immobilization would meet the spent fuel standard by encapsulating plutonium in a large, heavy, and highly radioactive waste form so as to deter theft, without the complication of having to irradiate it in a reactor to achieve a similar end state.

The MOX approach entailed construction of a factory to turn the surplus plutonium into MOX fuel at the DOE's Savannah River Site (SRS) in South Carolina, and recruitment of a number of commercial nuclear power reactors willing to use the fuel.

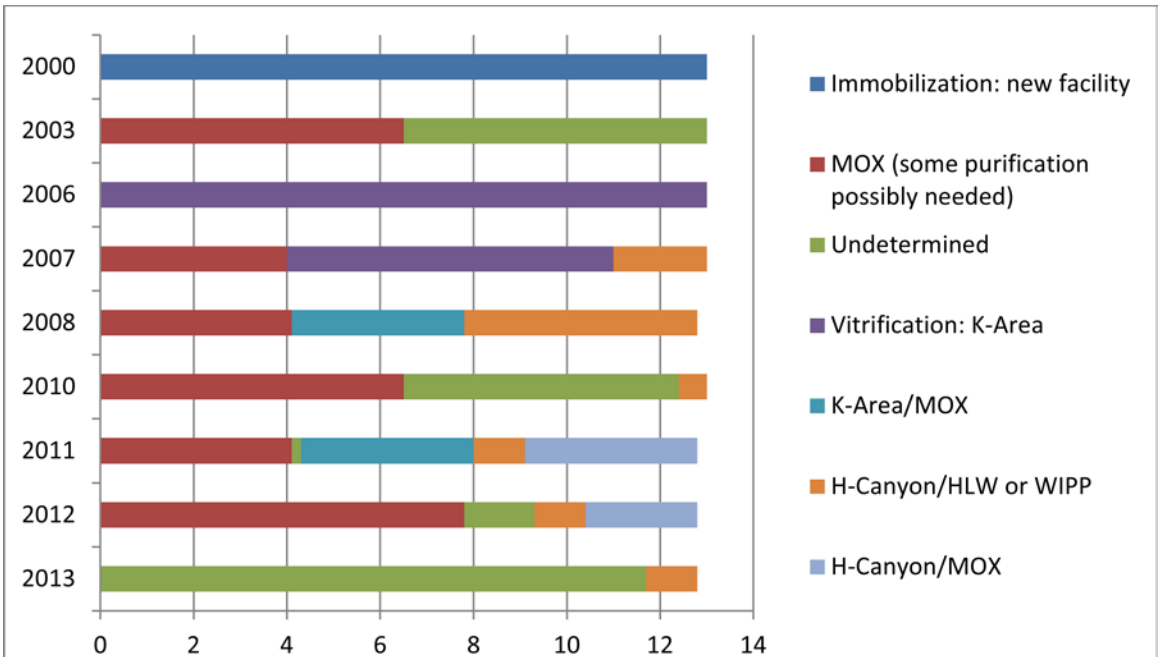
The immobilization approach that the DOE chose, known as "can-in-canister," also required construction of a new facility to incorporate the plutonium in hockey-puck-sized ceramic disks. The ceramic disks would be packed into cans, which then would be loaded into large metal canisters and sent to the Defense Waste Processing Facility (DWPF) at SRS, where the canisters would be filled with vitrified highly radioactive waste (waste converted into a glass form) as a security barrier to theft.

Today the U.S. plutonium disposition effort is floundering.

In 2002 the DOE decided to cancel the immobilization program and focus exclusively on MOX. However, the MOX approach itself has proven far more expensive, technically difficult, and time-consuming than originally anticipated. The MOX Fuel Fabrication Plant at SRS is many years behind schedule. Originally projected to cost about $1.5 billion (in 2014 dollars), it is now estimated to cost at least $30 billion, of which about $4 billion has already been spent. Because of the delays and cost overruns, the DOE now considers the project "unaffordable" and has stated its intention to suspend construction on the plant while it considers alternatives. Congress and the state of South Carolina, however, have other ideas, and have successfully kept the money flowing by compelling the DOE to continue construction of a facility that it no longer wants.

The DOE's mismanagement of the plutonium disposition program was also a major contributor to the cost overruns, delays, and other difficulties that the project is now facing. The DOE was forced to

FIGURE 1. **Evolution of DOE's Plan for Disposition of 13 Metric Tons of Non-Pit Excess Plutonium**



(K-Area is at Savannah River Site; H-Canyon is a chemical processing facility at SRS; WIPP is the Waste Isolation Pilot Project in New Mexico; HLW is high level waste. The total amount of plutonium varies from year to year because of the DOE's changing assumptions and uncertainties.)

Make numerous mid-course corrections to the program due to its chronic inability to resolve problems early or to anticipate all the impacts of its decisions. A good example is the DOE's rapidly shifting strategy to dispose of its stockpile of 13 metric tons of excess non-pit plutonium, most of which is weapons-grade. Much of this material was stranded without a disposition path when the DOE decided in 2002 to cancel the immobilization program. Between 2000 and 2013, the DOE proposed changes to its strategy to dispose of the material no fewer than eight times (Figure 1). To date, the DOE has disposed of only a small fraction of this material.

Is the Cure Worse Than the Disease?

In addition to cost, there are other reasons why it makes sense to end the MOX program and replace it with an alternative. Perhaps most notably, the U.S. MOX program is actually helping to weaken domestic and international standards for securing nuclear materials, rather than strengthening them as the National Academy envisioned.

Fundamentally, the purpose of plutonium disposition is to increase international security by reducing the risk that the plutonium will be used again in nuclear weapons. When it first proposed a plutonium disposition program, the National Academy cautioned that the temporary plutonium storage, transportation, and processing activities needed to achieve the spent fuel standard and eventual permanent sequestration in a repository would themselves increase the risk that plutonium could be stolen in the near-term. Every year, several metric tons of plutonium would be processed—enough for hundreds of nuclear weapons. When so much material is being handled and moved around, it is very difficult to protect and keep track of all of it down to a precision of eight kilograms, the approximate amount that terrorists could use to make a bomb.

Unless authorities can minimize the in-transit and in-process risks by requiring very stringent measures for security and accounting for material, the cure for the problem of separated plutonium—disposition—could well be worse than the disease. The goals of the program would be undermined if terrorists were able to divert or steal plutonium made more vulnerable during the disposition process. To address this concern, the National Academy also introduced the concept of the "stored weapons standard": that is, "an agreed and stringent standard of security and accounting must be maintained throughout the disposition process, approximating as closely as practicable the security and accounting applied to intact nuclear weapons."

If the DOE had accepted the National Academy's recommendation and adopted the stored weapon standard for plutonium disposition, it likely would have had to strengthen security relative to its normal practices. Instead, it went in the other direction. The cost and inconvenience of meeting existing security and accounting requirements proved too burdensome for the disposition program contractors, who sought and received numerous exceptions from the Nuclear Regulatory Commission (NRC). (Congress gave the NRC, which licenses commercial nuclear facilities, the authority to license the MOX plant, even though it is a government facility.)

One example of an exception that lowered security is the plan developed by the MOX plant contractor, Shaw AREVA MOX Services, for accounting for plutonium within the plant. Because of flaws in the plant's design, Shaw AREVA MOX Services was unable to demonstrate that it could meet the NRC's requirements for detecting diversions or thefts of small quantities of plutonium in a timely manner. But the NRC overlooked these flaws (whether intentionally or accidentally is not known) and in 2005, authorized Shaw AREVA to begin constructing the plant. Because it was too late to make major changes to the plant's design after construction began in 2007, Shaw AREVA proposed a novel approach to meeting the requirements. Instead of direct inspection of plutonium items to ensure that they were where they were supposed to be at all times and had not been tampered with, the plant operator would rely on computer data. Despite a challenge by public interest groups, the NRC's technical staff and a majority of its board of administrative judges accepted this approach—which renders the MOX plant's material accounting system unacceptably vulnerable to cyberattack. If this decision stands, as is likely, it would set a dangerous precedent.

Shaw AREVA and other MOX program contractors also argued that unirradiated MOX fuel is less attractive to terrorists than separated plutonium and does not need to be protected as rigorously when stored at reactors. This assertion is highly dubious because a single MOX fuel assembly contains several bombs' worth of plutonium, and the plutonium can be separated from the uranium in the fuel assembly using relatively simple chemical techniques. Nonetheless, the NRC accepted the argument and authorized a reduction in security requirements. Even worse, the agency is now proposing to weaken security standards more broadly in the United States by applying this concept of "attractiveness" to all facilities and materials through a wide-ranging rulemaking that will be finalized in 2018. It is also promoting the material attractiveness concept internationally, sending a dangerous signal to Russia and other countries with MOX programs. There is little reason to hope that Russia would adopt stronger security standards on its own without the United States leading by example.

A pause in the MOX program would give the DOE a badly needed opportunity to review all security and material accounting problems, and correct them as it pursues an alternative.

The Way Forward

That early period of "clear and present danger" has now passed without serious incident. Russia is no longer in desperate financial straits, and fears of significant diversions of plutonium from Russia's military stockpile have not been realized (although security of the large stocks of plutonium at less well-protected civil facilities remains a major concern). Nonetheless, even though the situation today may be less urgent, it could change rapidly in the future. The long-term objectives of plutonium disposition are still worthwhile. However, the benefits are not unlimited, and the costs of achieving them must be considered in the context of a constrained security budget.

Finding a practical and cost-effective alternative to MOX for plutonium disposition is not a simple task. The DOE put all its eggs in the MOX basket more than a decade ago, and the state of development of immobilization technology was essentially frozen at that time. Moreover, the physical infrastructure that has already been built to support the MOX approach may be difficult to repurpose for other options. This is unfortunate because at the beginning of the disposition program, it appeared that immobilization had the potential to be faster and cheaper than MOX. However, in order for immobilization to be a viable option today, the DOE would have to invest heavily in its development to make up for lost time.

There is another alternative approach that the DOE has already used to dispose of several metric tons of surplus plutonium, and in principle it also could be implemented more cheaply and quickly than immobilization. This third alternative is downblending: diluting plutonium with an inert and non-radioactive material, to a concentration of less than 10 percent by weight, and disposing of it underground at the Waste Isolation Pilot Plant (WIPP) in New Mexico. (Currently WIPP cannot accept more concentrated and sensitive forms of plutonium because it does not have the appropriate level of security.) WIPP is the only functioning geologic repository for nuclear waste in the United States, so this approach could potentially result in the most rapid disposal of the surplus plutonium. The key word here is "potentially." In February 2014, operations at WIPP were halted indefinitely after a barrel of radioactive waste overheated and released plutonium into the repository and the environment. However, even if the repository does not reopen for several years, downblending would still be a relatively attractive disposition option compared to the costly and slow MOX approach.

The WIPP approach does not strictly meet the "spent fuel standard" as defined by the National Academy, in that it does not add a radiation barrier to make the waste forms as hazardous for a thief to access as spent nuclear fuel. The DOE asserts that the material it uses to blend down the plutonium, referred to informally as "stardust," has special chemical properties that would make it difficult for

terrorists to extract the plutonium for use in weapons. Although the DOE has stated that this approach provides a level of protection equivalent to that of the spent fuel standard, the National Academy report rejected the notion that simply mixing plutonium with non-radioactive chemicals would be adequate. Nevertheless, if the diluted plutonium can be moved quickly to a geologic repository where it would be permanently sealed off, the addition of a radiation barrier may be less important. To directly address the Academy's concerns and provide convincing assurance to the public, the DOE should make the analysis underlying its conclusion— that the combination of dilution and early geologic disposal would provide a level of security comparable to that of a radiation barrier—publicly available.

The specific composition and properties of stardust are classified information. The disposal of classified materials in WIPP is problematic for a number of reasons. First, it makes it more difficult—or even impossible—for civil environmental authorities and the public to fully assess and approve the safety risks posed by the material. Complete knowledge of all materials is particularly important in the wake of the February 2014 event, which was caused by a still-yet-to-be-determined chemical reaction that occurred after an unapproved combination of materials was placed in the drum. Second, classified materials place an obstacle in the way of international verification of the disposition program. Inspectors from the International Atomic Energy Agency would likely be unable to directly access and verify the contents of waste drums that contain classified materials.

Any disposition alternative would likely have to leverage the DOE's existing infrastructure to the greatest extent possible, given the prohibitive capital cost of building entirely new facilities. The DOE has an array of facilities that could play a role in implementing a disposition option. These include:

- Defense Waste Processing Facility (DWPF): The SRS facility that vitrifies high-level radioactive wastes for eventual geologic disposal. The original plutonium immobilization program would have piggy-backed on DWPF operations.
- K-Area Complex: A former plutonium production reactor at SRS that has been converted to a storage facility for non-pit plutonium and has available space that could be used to house plutonium processing equipment.
- H-Canyon: A chemical processing plant at SRS originally used to support nuclear weapon production.
- HB-Line: A plutonium processing facility on top of H-Canyon.
- Mixed-Oxide Fuel Fabrication Facility (MFFF): now partially complete, the building could potentially be used for purposes other than MOX production.
- Waste Solidification Building (WSB): A nearly complete facility at SRS intended to solidify and prepare certain types of radioactive waste from the MOX plant for disposal.
- TA-55: The plutonium processing facility at Los Alamos National Laboratory in New Mexico.

While using existing infrastructure has inherent advantages, these would be offset if significant upgrades were needed to maintain high levels of safety and security, or if the project would significantly extend the operating lifetimes of facilities that were scheduled for shutdown and decommissioning.

In April 2014, DOE released the report of the internal Plutonium Disposition Working Group that it had convened a year earlier to evaluate alternatives to the MOX program. The report discussed three non-reactor disposition options: immobilization with high-level radioactive waste, downblending and disposal, and disposal in deep boreholes.

The report's examination of the alternatives fell short in a number of respects. With regard to immobilization, the report considered only a couple of options and judged they had insurmountable problems. It did not attempt to come up with ideas about how to make immobilization work.

For instance, the report claimed that can-in-canister immobilization could not be implemented at SRS because there is not enough high-level

radioactive waste remaining there to provide a sufficient radiation barrier to dispose of 34 metric tons of surplus plutonium (the quantity subject to the U.S.-Russian agreement) in a way that meets the spent fuel standard. But in fact, because of ongoing delays in waste vitrification at SRS's Defense Waste Processing Facility (DWPF), there appears to be sufficient cesium-137 still left in the liquid waste tanks to accomplish the task without causing further significant disruptions to the DWPF schedule, provided that immobilization can begin by around 2025.

The DOE is now conducting a follow-on study to the April 2014 report. In this follow-on study, DOE should consider a broader range of non-reactor alternatives, either singly or in combination, in order to establish which are compatible with the capabilities of the existing infrastructure. Combinations of options might work where there are commonalities in the processes needed to prepare plutonium for disposition.

In its review, the DOE should also reconsider the original goals of plutonium disposition and to what extent they continue to be the right ones today. In particular, it should reexamine the spent fuel standard and determine whether alternatives to a strict interpretation may achieve an acceptable outcome at an affordable cost. In doing so, it should develop—and make public to the extent possible—a framework in which to compare the security benefits of various options on a consistent basis, as well as to make plutonium disposition compatible with the DOE's overall policy on nuclear material security.

Revisiting the spent fuel standard could extend the range of acceptable options for disposition. For instance, if the DOE lowered the acceptable radiation- barrier dose rate, the issue of the remaining supply of cesium-137 would be less critical. However, options that can fully meet the spent fuel standard should be given priority consideration. The options that should be studied further include:

Can-in-canister immobilization. Can-in-canister immobilization at SRS should remain the top alternative. In this option, a glovebox line (where personnel could carry out operations manually) to immobilize plutonium in glass or ceramic would be installed in the K-Area Complex. The issues associated with this option include how long it would take to start up such a facility and whether its production capacity could be high enough to achieve a reasonable disposition rate. The approach must also be compatible with the DWPF waste vitrification schedule.

Homogeneous immobilization. Another immobilization alternative would entail dissolving the plutonium in acid in the H-Canyon/HB-Line and transferring the liquid solution to the high-level waste tanks for vitrification in DWPF. The resulting glass canisters could accommodate about 1 percent plutonium by weight and would be a relatively homogenous waste form. Such homogeneous immobilization would be relatively slow because it is limited by the rate at which plutonium could be dissolved in H-Canyon/HB-Line. However, it could be a useful approach to dispose of a fraction of the surplus plutonium inventory in parallel with one of the other options.

Downblending and WIPP disposal. The range of potential options for downblending and disposal in WIPP is also broader than that considered in the DOE's April 2014 report. For instance, the amount of plutonium that could be disposed of in WIPP per unit volume of waste could be increased, thereby increasing the amount of plutonium without using up more of the available disposal volume. Our estimate indicates that several downblending approaches would allow 34 metric tons of plutonium to be disposed of in WIPP without requiring an increase in the maximum waste volume capacity as established by the Waste Isolation Pilot Plant Land Withdrawal Act. Not requiring additional capacity is important because a disposition option that would require a change in the law to increase capacity would likely be very controversial.

An attractive option for downblending is not to use a classified material such as stardust to dilute plutonium below a concentration of 10 percent by weight but to further dilute it to below 1 weight-percent in a matrix of concrete. This would not increase the number of waste drums necessary to dispose of a given quantity of plutonium. Downblending into concrete can be done at a far lower temperature than either immobilization into glass or producing MOX fuel, and therefore would

pose a lower accident risk. In addition, by not using stardust, the DOE can avoid the problems associated with placing substances with classified compositions into WIPP.

All WIPP options, of course, are contingent on the DOE's ability to safely reopen the repository, determine the root cause of the February 2014 waste drum release, and take all necessary steps to ensure that such an event does not occur again.

Conclusion

The MOX program has veered off on the wrong track. Immobilization or downblending are the only technologies clearly capable of handling the bulk of the current and projected future inventories of excess plutonium. The DOE should explore the full range of options before making a decision and revising its disposition plan. Given the lengthy period of time that will be needed to complete the task under any option, the DOE should take the time it needs to carefully consider the options and to make the right decision. A well-justified proposal will also help to obtain Russia's consent, which will be required for any change to the U.S. plan for disposing of the 34 metric tons of plutonium covered under the bilateral agreement.

And finally, every dollar spent on finishing construction and installing equipment in the MOX plant that may never be used is a wasted dollar, and moves a potential repurposing of the structure further out of reach. Congress should give the DOE the flexibility to stop throwing good money after bad while it determines the best path to future success.

[INTRODUCTION]

When first proposed in the early 1990s, the idea sounded like a good one: Take separated plutonium from nuclear warheads that are no longer needed by the U.S. and Russia, blend the material with uranium to produce fuel, and use the fuel in civilian nuclear reactors. By irradiating this so-called "mixed-oxide" (or MOX) fuel, two objectives could be achieved. First, the material would be converted into a highly radioactive waste form that would be very difficult to use again in nuclear weapons compared to plutonium in weapon components (known as "pits.") And second, some of the energy content of the plutonium would be used to generate electricity.

Proponents dubbed the concept "swords to ploughshares." And why not? A similar approach had been adopted for disposal of highly enriched uranium (HEU), another weapons-usable fissile material, and was working well. In 1993, Russia had agreed to blend down 500 metric tons of HEU by diluting it with uranium-238 to lower the uranium-235 fraction (or enrichment) from over 90 percent to 5 percent low-enriched uranium (LEU). Unlike HEU, LEU cannot be used directly to make nuclear weapons, but it can be sold to make fuel for nuclear reactors. The HEU agreement, which reduced the threat posed by Russia's enormous HEU stockpile while providing the financially strapped nation with badly needed revenue, was a classic "win-win" solution.

However, the situation is far different if the material to be disposed of is plutonium. While the dilution of HEU to LEU can be reversed only by using uranium enrichment techniques—which are technically challenging and very costly—there is no feasible way to dilute plutonium from weapons with other plutonium isotopes to render it comparably less dangerous.[1] And while LEU is a valuable material that is used in hundreds of light-water reactors operating today to generate electricity around the world, plutonium is much more expensive and cumbersome to use as fuel. For one thing, the additional safety and security measures needed for plutonium processing facilities relative to uranium facilities make plutonium-based fuels far more expensive. In addition, reactors designed for LEU typically also need safety modifications and security upgrades to use plutonium-based MOX fuel. As a result, in contrast to the LEU resulting from the Russian downblending program, governments effectively would have to pay utilities a premium to take plutonium off their hands (assuming they would take the troublesome material at any price).

Of course, the fact that taxpayers would have to pay for disposing of separated plutonium is not itself a reason to abandon the effort. Garbage disposal is never a free service, and the potential security benefit of reducing the threat posed by stockpiles of weapons-usable plutonium is a

[1] To clarify terminology that can be confusing at the outset, an explanation is needed. Plutonium (Pu) exists in several different isotopic forms. The "weapons-grade" plutonium used in U.S. nuclear weapons consists primarily of two isotopes, Pu-239 and Pu-240. "Weapons-grade" plutonium typically means a Pu-239 concentration of above 90%. When weapons-grade plutonium is irradiated in a light-water nuclear reactor, the Pu-239 content decreases and the concentration of Pu-240 and other isotopes increase. "Reactor-grade" plutonium typically refers to a mixture with about 60% Pu-239 and 24% Pu-240. Although weapons-grade plutonium is the most convenient isotopic mixture to use in nuclear weapons, all other isotopes can in principle be used: hence the distinction between "weapons-grade" and "weapons-usable" plutonium. Because reactor-grade plutonium is a dangerous weapons-usable material, there is little security benefit from changing the isotopic mixture of plutonium alone.

public good. But the benefits are not unlimited, and the costs of achieving them must be justified in the context of a constrained security budget.

Moreover, government also has an obligation to taxpayers to seek to reduce the costs of its programs where possible, without compromising safety and security. The U.S. government had an opportunity to reduce the cost of disposing of excess plutonium by choosing an alternative—immobilizing it in glass or ceramic, without irradiating it in a reactor—that also could meet the program's objectives. However, for a variety of reasons, including bureaucratic inertia and the control of decision-making by plutonium fuel advocates, the MOX program proceeded despite all signs that it was heading toward a fiscal meltdown.

Today, plutonium disposition is in a holding pattern. After spending more than $4 billion over 14 years in studies and partially built facilities, the U.S. Department of Energy (DOE) has finally acknowledged that the MOX program is unsustainable. Moreover, once again it has undertaken a search for more affordable alternatives, while seeking to put the partially built MOX fuel fabrication plant on "cold standby." However, the DOE is being compelled to continue construction of the plant by the project's Congressional supporters, even as it becomes ever more apparent that the facility will never be used for its original purpose, if at all.

In order to understand how the MOX program ended up in its current predicament, it is instructive to review its history. The DOE's bad decisions and lack of foresight in anticipating problems contributed in large part to the delays and cost overruns that now threaten to sink the program.

History of the Plutonium Disposition Program

National Academy Study

2014 marked the 20th anniversary of a stark warning by the National Academy of Sciences (NAS) that the accumulation of excess weapon plutonium stockpiles in the U.S. and Russia represented a "clear and present danger" (NAS 1994). First and foremost, the NAS was concerned that separated plutonium was vulnerable to diversion or theft by subnational groups, especially in Russia, where serious questions about the state of nuclear security arose amidst the social and economic crisis that occurred in the aftermath of the collapse of the Soviet Union. The NAS was also concerned that plutonium stored in the form of pits (the fission "trigger" of a thermonuclear weapon) could quickly and easily be returned to use in weapons should tensions again increase between the superpowers.

To deal with these threats, the NAS recommended that both the U.S. and Russia undertake programs to convert surplus separated plutonium into a form much less vulnerable to rapid use in weapons. The NAS cited three objectives for this undertaking. The first was to minimize the risk that unauthorized parties could obtain weapons-usable materials—in other words, the risk of nuclear terrorism. The second was to minimize the risk that the superpowers could rapidly reverse nuclear arms reductions ("breakout"). The third objective was "to strengthen the national and international arms control mechanisms and incentives designed to ensure continued arms reductions and prevent the spread of nuclear weapons."

To meet the first two objectives, the NAS recommended that both the U.S. and Russia undertake efforts to physically transform separated plutonium to render it much harder to reuse in weapons. The two programs were intended to proceed essentially in parallel and to be under stringent bilateral and international monitoring.

To deal with the question of how much inaccessibility was enough, the NAS developed the concept of the "spent fuel standard" —the goal of making the plutonium as inaccessible as the plutonium contained in commercial light-water reactor (LWR) spent fuel assemblies, which are large, heavy and lethally radioactive. At that point the excess plutonium would be no more attractive than the much larger quantity of plutonium in commercial spent fuel. To go beyond that would be a pursuit of rapidly diminishing returns. On the other hand, to fall far short of the spent fuel standard would mean the material would remain relatively attractive to subnational groups and perhaps even states, and therefore would continue to pose a comparatively high risk.

Although the third objective of the NAS has never gotten the same level of attention as the other two, it is no less important. Intrinsic material barriers to proliferation and terrorism are of limited value in the absence of complementary institutional measures for international monitoring, physical protection, and material

accounting. The NAS also highlighted a crucial aspect of the problem: the plutonium storage, transportation, and processing activities needed to achieve the spent fuel standard would increase the risk of theft or diversion of plutonium over the near-term. Unless authorities fully addressed and controlled these risks by requiring very stringent measures for material protection, control, and accounting, the cure for the problem of separated plutonium could well be worse than the disease. If terrorists were able to divert or steal plutonium made more vulnerable during the disposition process, the effort would be fatally undermined. To address this concern the NAS also introduced the concept of the "stored weapons standard:" that is, "an agreed and stringent standard of security and accounting must be maintained throughout the disposition process, approximating as closely as practicable the security and accounting applied to intact nuclear weapons" (NAS 1994, p. 12).

After reviewing a large number of proposed alternatives, the NAS identified two technical approaches for meeting the spent fuel standard that it believed were feasible and cost-effective, and that could be implemented relatively quickly. The first was to build a facility to fabricate mixed-oxide (MOX) fuel, a combination of plutonium and uranium oxides, for use in operating light-water reactors. The second method, which was in the category of options that the NAS called "immobilization," involved vitrifying (converting into glass) the plutonium along with other highly radioactive wastes that already exist at DOE sites. Vitrification would embed plutonium in a waste form along with highly radioactive materials, without having to go to the additional expense and complexity of irradiating it in a reactor. In a 1995 report, the NAS proposed that the DOE pursue development of both approaches. This "dual track" strategy would accomplish disposition more quickly and would provide an insurance policy in case one of the options did not work.

The NAS did not invent the concept of immobilizing plutonium. In fact, other researchers had proposed it in the early 1990s (Berkhout et al. 1993). To them, the idea seemed simple and elegant: to dispose of weapon plutonium by mixing it back with the fission products that were generated during production of the plutonium in the first place. At both the Savannah River Site (SRS) in South Carolina and the Hanford Site in Washington State, the DOE had accumulated huge quantities of liquid high-level radioactive wastes (HLW) produced primarily by the reprocessing of uranium targets irradiated in plutonium production reactors. These liquid wastes, stored in vast tank farms at both sites, contained hundreds of millions of curies of radioactive isotopes, primarily the intensely radioactive fission product cesium-137, with a half-life of 30 years. For decades, the DOE has been pursuing projects to vitrify the HLW into glass logs for eventual underground disposal in suitable geologic formations. HLW vitrification is much further along at SRS, but progress was (and today remains) slow at both sites.

At the time of the NAS study, the DOE was nearing startup of a plant at SRS called the Defense Waste Processing Facility (DWPF) for vitrification of HLW, while construction of a similar plant at Hanford had not yet begun (the project at Hanford was more difficult in part because the waste stream was much more complex). At the DWPF, liquid HLW would be concentrated and fed into a large melter, along with glass-forming materials. The molten mixture would then be poured into stainless steel canisters and cooled into glass logs. Because of the intense radioactivity of the HLW, the DWPF was built with heavy radiation shielding and could only be operated remotely.

The NAS identified two approaches to plutonium vitrification. One was to build a new, or "greenfield," plant to incorporate plutonium and fission products together into a homogeneous glass waste form. In addition to liquid HLW, the DOE had stocks of other highly radioactive materials that could be used to provide a radiation barrier around the vitrified plutonium waste glass as a security deterrent to unauthorized access to it.

For instance, the DOE possessed a stockpile of purified cesium-137 that had been separated from HLW and was stored at Hanford in capsules. This new facility would be relatively costly because, like a reprocessing plant, it would require heavy radiation shielding and be remotely operated and maintained.

The second concept for plutonium vitrification did not require construction of a new, remote-handled facility to produce highly radioactive glass; instead, it would take advantage of the already planned operation of the DWPF. In this option, plutonium oxide would be shipped to the DWPF and added directly to the HLW and the glass formers in the DWPF melter to produce a homogenous waste form. By pigging-backing on DWPF operations in this manner would require the smallest investment in new facilities, and seemed to the NAS and other observers as potentially the most efficient and quickest way to dispose of excess plutonium.

However, plutonium vitrification had its naysayers from the beginning. Within the DOE, the U.S. national labs, and the Russian Federal Ministry of Atomic Energy (Minatom), there was strong opposition to any action that treated plutonium as a waste product instead of a valuable resource. Governmental and nongovernmental advocates for different types of reactor systems that could use plutonium fuel, such as fast reactors and gas-cooled reactors, tirelessly promoted their pet projects.

Minatom and others also challenged the effectiveness of immobilization of weapons plutonium because it would not change the isotopic content of the initial plutonium from weapons-grade (>90 percent plutonium-239). Despite the efforts of authoritative experts such as J. Carson Mark, former head of the theoretical division at Los Alamos National Laboratory, to publicize the fact that reactor-grade plutonium is weapons-usable, many continued to perpetuate the false belief that irradiating weapons-grade plutonium in a nuclear reactor to increase the plutonium-240 fraction rendered it unusable in weapons.

Finally, the most attractive option, direct immobilization, raised safety issues associated with the introduction of plutonium into the DWPF melter. An important criterion in operation of facilities that process fissile materials is the potential for an inadvertent criticality—that is, an uncontrolled chain reaction—which could rapidly raise temperature and pressure, generate additional fission products, and injure or kill workers. Because of the very low residual concentration of plutonium and other fissile materials in the regular high-level waste, the DWPF was not designed for criticality control; but feeding additional plutonium into the melter could potentially cause a criticality accident if the plutonium were not well-mixed in the melt. However, the NAS concluded that such technical issues were solvable in a reasonable time frame if the DOE made a concerted effort.

Notably, the NAS studies rejected several categories of options that it judged did not meet the spent fuel standard. One was immobilization without the fission products that would provide a radiation barrier comparable to that of spent fuel, except as a first step toward adding substantial radiological or physical barriers. In particular, the NAS dismissed the option of directly disposing of plutonium, either as pits or in other forms, in the Waste Isolation Pilot Plant (WIPP) in New Mexico, a facility then under development by the DOE.[2] WIPP was not intended to accept thermally hot and highly radioactive wastes like spent nuclear fuel, so waste forms meeting the spent fuel standard could not be disposed of there. However, the NAS judged that the combination of any chemical barrier with the geologic barrier provided by emplacement in WIPP did not

[2] WIPP is a mined geologic repository in a bedded salt formation where DOE disposes of transuranic waste, which is a type of waste typically containing low but radiologically significant concentrations of plutonium and other elements heavier than uranium. It began operations in 1998.

provide comparable security protection to the radiation barrier of spent fuel.

The NAS also rejected options that involved the construction of new nuclear reactors, especially those of experimental design. The NAS believed that the length of time needed for research, development and deployment of advanced reactor systems would cause delays compared to what it perceived as the relatively mature alternative of using MOX fuel in operating reactors.

Government Decisions

Following the release of the NAS recommendations, in the mid-1990s the U.S. government began the long process of implementing a program to dispose of excess plutonium. The United States first designated 52.5 metric tons (MT) of plutonium as excess to military (and other programmatic) needs: 38.2 MT of weapons-grade plutonium and 14.3 MT of non-weapons–grade plutonium. The excess plutonium inventory consisted of plutonium in various forms, from weapon pits containing pure metal to highly impure residues and spent fuel. To dispose of this material, the DOE decided to pursue the NAS "dual track" (or hybrid) strategy, converting the purer materials into MOX fuel and immobilizing the impure materials that would be too difficult and costly to fabricate into MOX fuel.

In order to undertake this major federal action, the DOE was required to evaluate the environmental impacts of the proposed plutonium disposition program and its alternatives in accordance with the National Environmental Policy Act (NEPA). It began a lengthy, multiyear process of identifying and assessing the various alternatives and their impacts in a series of generic and then site-specific environmental impact statements. The process involved a large number of moving parts that required close coordination. First, as a prerequisite for both MOX fuel fabrication and immobilization, the DOE needed a facility to convert weapons components and other plutonium metal items, some aspects of which are classified, into an unclassified plutonium oxide powder. Second, it needed a MOX fuel fabrication facility. Third, it needed to develop a strategy for immobilization, which would also require both modifying existing facilities and building new ones. Fourth, it needed to obtain the participation of a sufficient number of operating commercial nuclear power reactors to use the MOX fuel at the desired rate. In addition, it needed to define and evaluate storage, transportation, and final disposal strategies to support all of the activities in each alternative.

After completing two lengthy NEPA environmental impact statements, the DOE decided in 2000 to build a Pit Disassembly and Conversion Facility (PDCF), a Mixed Oxide Fuel Fabrication Plant (MFFF) and a Plutonium Immobilization Plant (PIP) at SRS. The PDCF would to convert weapons pits and other plutonium metal to plutonium oxide feedstock for the MFFF and the PIP. In that way, the metal pits, which have classified characteristics, could be converted to an unclassified material before being sent to the other facilities. This would at least make it possible for those facilities to be subject to bilateral or international inspections.

The DOE needed to build a PIP for immobilizing the non-pit plutonium because it had quickly ruled out the option of feeding plutonium directly into the DWPF melter to produce a homogeneous waste form. Instead, it proposed a heterogeneous, two-step option that would also piggy-back on DWPF operations, known as "can-in-canister." In this approach, a new facility would be built to first incorporate plutonium into ceramic pucks, which would then be placed in cans. No radiation barrier for security would be incorporated at this stage. The plutonium-filled cans would then be arranged in metal racks that had been installed in DWPF metal canisters during canister fabrication. The canisters would then be sent to DWPF and filled with molten HLW glass, which would surround and immobilize the plutonium cans, also acting as a highly radioactive security barrier. The DOE settled on a

configuration in which the rack would hold seven "magazines," each containing four 10- kilogram cans with up to 1 kilogram of plutonium per can, for a maximum of 28 kilograms of plutonium per canister, amounting to 10 percent plutonium by weight of the entire canister. This 10 weight-percent limit on plutonium concentration was below the maximum that the ceramic could contain, but was driven by security considerations (as discussed below).

This can-in-canister approach would avoid the need for significant retrofits of DWPF, eliminate uncertainties associated with the behavior of plutonium in the melter, and better control the structure of the final waste form. However, it would also require construction of another facility to produce the plutonium cans, and thus would not share some of the cost and schedule advantages of the homogenous DWPF option. Such a facility, though, would not be as costly as one in which fission products would be added directly to the plutonium ceramic, since it would need less shielding and would not have to use remotely operated equipment. Under those circumstances, workers could carry out the processing manually in "gloveboxes."

The DOE acknowledged at the time that the hybrid option utilizing both MOX and immobilization would be more expensive than pursuing only immobilization. It also noted that only immobilization, and not MOX, was capable of dealing with the entire excess plutonium inventory, including highly impure materials. However, it accepted the NAS committee's reasoning that pursuing both tracks would provide "important insurance against uncertainties of implementing either approach by itself" (DOE 1999, 1-10).

In March 1999, even before its formal Record of Decision in 2000 to initiate a MOX program, the DOE had awarded a conditional contract to a consortium called Duke Cogema Stone and Webster (DCS) to provide MOX fabrication and irradiation services. The members of the consortium included the U.S. subsidiary of the French national nuclear company Cogema, which would design and build the MFFF, modeled after the MOX fuel fabrication facility called MELOX in Marcoule, France. Another member of the consortium was Duke Energy, a large Southeast utility that would provide four nuclear reactors for irradiation of MOX fuel: McGuire Units 1 and 2 in North Carolina and Catawba Units 1 and 2 in South Carolina. Stone and Webster was an architecture/engineering firm.

The DOE also moved forward with research and development for the PDCF and the PIP. For the latter, after deciding to proceed with a ceramic-based can-in-canister approach, three facilities were constructed to support development. One, at Clemson University in South Carolina, was a cold (non-radioactive) mockup of the PIP furnace to test the ceramic sintering process. Another, at the Savannah River Site, was designed to test the impact of the can-in-canister insert on the quality of the HLW glass that would form around it. The third was a Plutonium Ceramification Test Facility in the Plutonium Facility at Lawrence Livermore National Laboratory, which would test the production of full-scale ceramic pucks for different ceramic compositions using actual plutonium. Design work was also slated to begin on the PIP itself at the Savannah River Site, with an option to build a plant capable of immobilizing up to 50 metric tons (MT) of plutonium in 10 years.

Since a major rationale of the U.S. plutonium disposition program was to encourage Russia to follow suit, the U.S. also began negotiations with Russia on a bilateral agreement that would include firm commitments. In September 2000, the U.S. and Russia signed the Plutonium Management and Disposition Agreement (PMDA), which committed each nation to dispose of 34 MT of surplus weapons-grade plutonium at an initial rate of 2 MT per year, commencing in 2007. According to the agreement, on the U.S. side, 25.6 MT of weapons-grade plutonium from dismantled warheads and other relatively clean sources would be fabricated into MOX fuel and irradiated to

create a radiation barrier, and 8.4 MT of impure plutonium would be immobilized in a ceramic form and disposed of through the can-in-canister method at SRS.[3] In signing the agreement, Russia demonstrated its acceptance of the U.S. plan to utilize immobilization for about one-third of the stockpile.

The International Atomic Energy Agency (IAEA) standard for radiological self-protection of an item containing plutonium or other weapon-usable materials is 1 Sievert per hour at 1 meter from the accessible surface at the centerline. For both MOX and immobilization, the PMDA defined an acceptable radiation barrier by requiring that the IAEA standard be met for 30 years after irradiation or canister production.

On the Russian side, MOX fuel use (in both light-water and fast reactors) was the only designated option in the final version of the agreement. However, there was a tacit understanding at the time that Russia would develop immobilization technology for disposal of plutonium-laden scrap resulting from MOX fuel fabrication, rather than purifying and recycling the scrap. And Russia had actually proposed to commit to immobilize approximately 1 MT of plutonium that was contained in existing wastes, but the U.S. negotiators refused to accept that material as part of the agreement because it was so impure (Lyman 2001).

Cancellation of Immobilization

Notwithstanding the PMDA commitment, in December 2000 the Clinton administration reduced the budget for immobilization, postponing the commencement of PIP design work and causing a delay in the schedule. When George W. Bush became president in 2001, the White House ordered a suspension of immobilization work pending a review of the plutonium disposition program by the National Security Council (as part of a broader review of all nonproliferation assistance to Russia). But work on the PDCF and MFFF facility design continued (Gordon 2001), and it was apparent that immobilization's days were numbered.

In 2002, following the conclusion of the National Security Council review, the Bush Administration formally decided to cancel the immobilization program and only pursue the MOX option. The DOE argued that this was necessary because it could afford to pursue only one of the two tracks, and that option had to be MOX because Russia would not accept an all-immobilization option. (The DOE never explained the logic of why Russia would accept the immobilization of some weapons-grade plutonium but not all of it.) Yet even though the DOE justified the decision in terms of its impact on Russian participation in the program, Russia's degree of commitment to the plan in the PMDA only continued to dwindle.[4]

In contrast to the uncertainties in cost and schedule associated with the revised all-MOX program, the DOE's 2002 Report to Congress acknowledged that immobilization of plutonium "achieves full disposition of 34 MT of U.S. plutonium inventory with the lowest cost" (DOE 2002, 4-23). While the report claimed that immobilization of all U.S. plutonium would have been unacceptable to Russia because immobilization does not degrade the isotopic content of the plutonium, the fact remains that Russia had agreed in the PMDA to allow the U.S.

[3] The agreement also stipulated that the isotopic content of the plutonium to be disposed of through irradiation be changed so that the ratio of plutonium-240 to plutonium-239 would be greater than 0.1.There was no such requirement for the plutonium to be immobilized.

[4] Russia strongly preferred to utilize its excess plutonium in fast neutron reactors, and was never enthusiastic about its commitment in the 2000 PMDA to use most of it in LWRs. The U.S. and Russia began negotiations on a revised protocol during the Bush administration that would allow Russia to use the BN-800 fast breeder reactor, which was only partially complete at that time, instead of LWRs. The revised protocol was adopted in 2010.

to dispose of 8.4 MT of non-pit, weapons-grade plutonium through immobilization without changing the isotopic content. The lower purity of the non-pit plutonium was irrelevant, since the degree of processing needed to extract plutonium from the immobilization waste form would be similar no matter what the feedstock. Moreover, in the PMDA Russia had committed to irradiate a portion of its surplus plutonium in the BN-600 fast reactor, which would barely shift the plutonium from a weapons-grade composition. Despite being inconsistent, the Russian position was very convenient for those in the U.S. government who did not like immobilization.

The DOE's cancellation of the immobilization program was a major blow to development of a promising technology and caused chaos within DOE's nuclear material management programs. Its repercussions are still being felt today. The Plutonium Ceramification Test Facility equipment that had been procured and partially installed at Lawrence Livermore was dismantled and scavenged for use in weapons programs. The expert teams that had been assembled at several of the national labs were disbanded, and the members retired or were reassigned. But the most significant impact of the cancellation was on the MOX program itself.

The history of the U.S. plutonium disposition program following the cancellation of immobilization is a study in rapid reversals so numerous that it is best depicted in a chart. Figure 1 displays the evolution of changes in the DOE's proposed plans for a subset of its excess plutonium inventory: 13 metric tons of plutonium not in the form of pits. Below is a guided tour through the intricate maze.

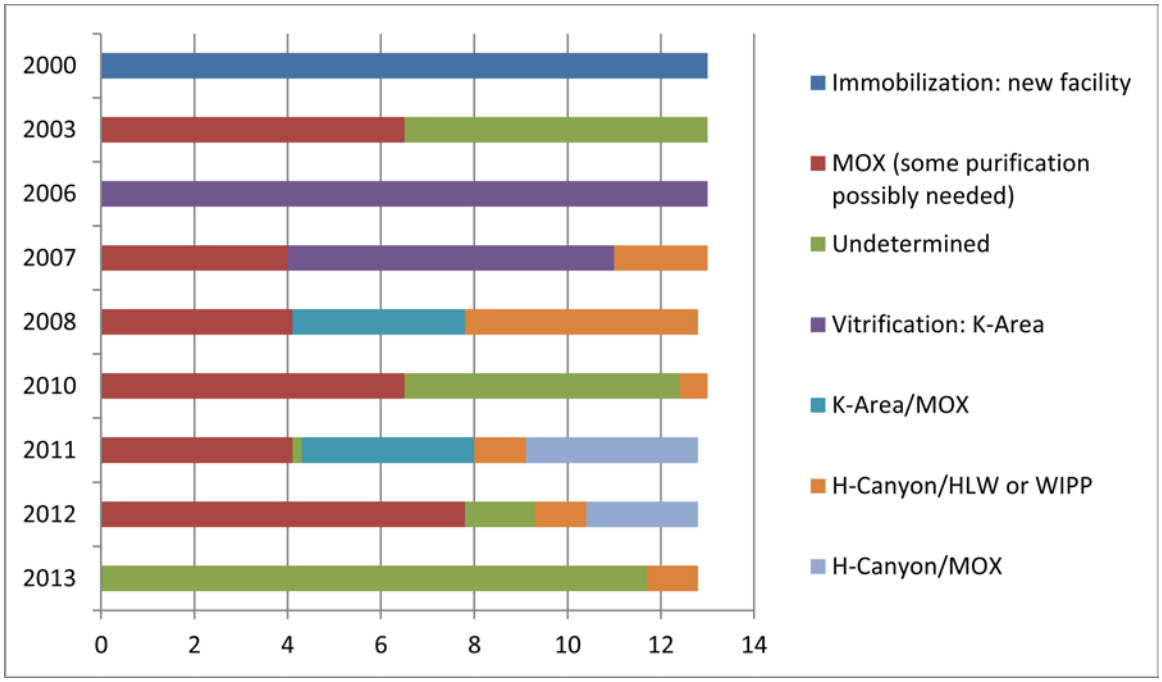
Alternate Feedstock

The 8.4 MT of weapons-grade plutonium that the U.S. had committed to immobilize in the PMDA was too impure to be used as feed at the MFFF as designed at the time. It contained impurities including metallic salts, chlorides and even uranium-235, rendering it incompatible with the baseline MOX fuel fabrication process. Thus, it was effectively stranded without a disposition path.

In order to accommodate the stranded material, the MFFF had to be redesigned to accommodate additional process equipment that could treat it. The MFFF design already included a capability for dissolution and purification called the Aqueous Polishing line for removal of gallium (an alloying metal in plutonium pits that would cause problems for reactor fuel), as well as americium-241 ingrowth from the decay of plutonium-241. However, aqueous polishing was not capable of dealing with the additional complexities of the impure material. The additional processing lines to treat the impure material, which the DOE called Alternate Feedstock (AFS), increased the footprint (the length and width of the exterior) of the MFFF by about 10 percent, and increased the cost accordingly. But even with the addition of these aqueous processing lines, the DOE said at the time that 2 MT of the 8.4 MT of impure material would still be too costly and difficult to convert into MOX fuel. This meant that after the 2002 decision, the amount of U.S. excess weapons-grade plutonium with a well-defined disposition path was 2 MT short of its commitment under the PMDA. The U.S. would have to designate additional weapons- grade plutonium as excess to make up for the shortfall.

In fact, the situation was worse. The DOE was merely guessing when it asserted that 6.4 MT of the plutonium slated for immobilization could be sent to the MOX facility. Even with the planned AFS modifications to the MFFF, the DOE was unsure how much, if any, of that plutonium would meet the specifications of the planned system. This

FIGURE 1. **Evolution of Disposition Plans for Approximately 13 MT of Non-Pit Plutonium**



K-Area is at Savannah River Site; H-Canyon is a chemical processing facility at SRS; WIPP is the Waste Isolation Pilot Project in New Mexico; HLW is high level waste. The total amount of plutonium varies from year to year because of the DOE's changing assumptions and uncertainties.)

is because even though the DOE had a general idea of the types and amounts of impurities within the inventory of non-pit plutonium, it did not know precisely what was contained in thousands of cans of plutonium-containing materials that had been filled at Hanford, the Rocky Flats Environmental Technology Site, and the other DOE sites during cleanup. The contents of less than 10 percent of the cans had been sampled and undergone destructive analysis. Most cans were assayed using only much less accurate nondestructive analysis techniques.

The uncertainties regarding feedstock acceptability at the MFFF were exacerbated, ironically, by a process that the DOE had employed to increase the safety of plutonium storage. The DOE developed a plutonium packaging standard known as "3013" that required stabilization of plutonium oxide prior to loading in storage cans (known as "3013 cans") via a "high-firing" process, in which the material is heated in air to a high temperature (950°C) for two hours. To perform this process, plutonium materials were placed in metallic trays. If the impure plutonium contained significant amounts of corrosive materials such as chlorides, the trays themselves corroded, introducing high levels of metallic impurities such as chromium, nickel and iron into the stabilized plutonium. At high levels, those contaminants are incompatible with the AFS aqueous process. Statistical analysis suggested that an unacceptably high number of 3013 cans would contain levels of those impurities outside of the AFS specs, if uncertainties are taken into account (Moore and Allender 2010).

When the DOE cancelled the immobilization program, it not only stranded the 8.4 MT of

weapons-grade plutonium included in the PMDA commitment, but also a substantial quantity (approximately 4.6 MT) of other excess plutonium materials that it had planned to immobilize. Together, they totaled around 13 MT of plutonium that the DOE was not sure could be made into MOX fuel without more extensive purification than the AFS treatment would provide. Yet the DOE concealed from the public the fact that the 13 MT of material that it said was stranded without a clear disposition path included a large part of the material that it said could be made into MOX and in fact had committed to dispose of in the PMDA.

For example, the DOE hid this problem behind legalese when it published a second amended Record of Decision in April 2003. In that document, the DOE announced its decision to

> pursue a program of fabricating into MOX fuel (after appropriate sampling to determine actual material characteristics) approximately 6.5 MT of surplus weapons-grade plutonium originally intended for immobilization, including the material transferred from RFETS [Rocky Flats Environmental Technology Site] to SRS for storage that after appropriate sampling is determined to meet the MOX fabrication facility's specifications (DOE 2003).

Without knowing the context, a reader would be forgiven for not understanding what this decision actually meant: namely, that whether or not any of this material could be made into MOX within the scope of the program depended on the outcome of the determination of "actual material characteristics."

For instance, in a report to Congress in June 2004, the DOE erroneously implied that the 13 MT of plutonium without a disposition path was in addition to the 34 MT that was committed to MOX (DOE 2004). In fact, at the time the DOE only had a firm disposition path for 25.6 MT of pits and other relatively pure materials.

The DOE was motivated to maintain this ambiguity because in 2001, Congress had required the DOE to present it with a plan for how it would deal with all excess plutonium slated for disposition if it were to cancel either the PIP or the MFFF, and prohibited the DOE from shipping additional plutonium to SRS until it provided such a plan (U.S. Congress 2001). The DOE would have been on shaky ground with Congress, the state of South Carolina, and Russia if it had to admit that it did not know if all the material that it said could be made into MOX could actually be made into MOX. Even so, the report the DOE provided Congress in February 2002 failed to include in its plan the 4.6 MT of excess impure plutonium that was not included in the PMDA, and was not fully compliant with the Congressional requirement.

Immobilization Revival

Given the problems caused by the Bush Administration's 2002 cancellation of the plutonium immobilization program, it shouldn't be a surprise that the DOE began plans to revive it not long afterward, at least for the plutonium that would be exceptionally difficult to make into MOX fuel. In a 2003 report to Congress, the Defense Nuclear Facilities Safety Board (DNFSB)—an independent government agency formed in 1988—pointed out that the MOX project was "risky" and that the DOE did not yet have a plan for disposal of the plutonium not expected to be made into MOX fuel. It recommended that the DOE expedite development of a "complete, well- considered plan for the disposition of all excess plutonium…" (DNFSB 2003).

In response, the DOE told Congress in June 2004 that it was conducting a preliminary investigation into reviving its can-in-canister technology (this time based on glass, not ceramic) at SRS for disposal of stranded plutonium and

installing a process line in an existing facility. However, the Defense Nuclear Facilities Safety Board, which often urged the DOE to find additional missions for the aging and obsolete reprocessing facilities at SRS, questioned the maturity of the vitrification technology for plutonium can production and said that the DOE should also consider using H- Canyon/HB-Line to process the impure materials, presumably so that they could be used to make MOX fuel.[5] Despite the Board's call for the DOE to expedite development of a plan, it took nearly two years until the DOE formally approved a "mission need" for a new program, aptly called the "Plutonium Disposition Project," to figure out what to do with excess plutonium that could not be made into MOX.

A team of DOE experts at SRS then undertook a yet another study of the various options for disposing of the 13 MT of impure plutonium (DOE 2006). This material included metals, oxides, and unirradiated fuel from the Fast Flux Test Facility, a defunct experimental reactor at Hanford. The study considered all 13 MT because "although there has been much consideration for a portion (up to 6.5 MT) of the 13 MT Pu inventory being accepted as feed material for the MOX program, there are considerable uncertainties with how much … material will be accepted by the program due to uncertainties with characterization data and acceptance of material based on an ability to meet the MOX fuel specification" (DOE 2006, 4).

The study examined 11 alternatives and numerous variations against a number of criteria, including theft resistance, technical viability, cost, and timeliness. Although it considered both glass and ceramic-based immobilization, given that the study was done by SRS, it recommended glass arguing that it was a more mature technology. It also pointed out that glass was more flexible, because it would be more tolerant than ceramic to impurities.[6]

The most highly ranked option was installation of a new facility in SRS's K-Area Complex for can-in-canister immobilization of the entire 13 MT. The K-Area Complex was a fancy name for one of the old SRS plutonium production reactors, the K-Reactor. The reactor had been deactivated and decontaminated years earlier, but parts of the reactor building and its support systems were being used for other purposes, including the storage of many tons of non-pit plutonium from Rocky Flats and other DOE sites at the K-Area Material Storage Facility. This facility was built with Category I security to allow it to store a large quantity of plutonium.[7]

The study found that a new immobilization facility installed in the basement level of the K-Reactor building could achieve a plutonium throughput of about 2.2 MT per year, enabling 13 MT of plutonium to be vitrified in six years.

The study also screened in a few other alternatives. One alternative involved using H-Canyon to dissolve all of the plutonium and send it to the SRS's high-level radioactive waste (HLW) tanks and Defense Waste Processing Facility (DWPF). Another, based on a preliminary estimate that about half the plutonium being evaluated would be within the AFS specifications, assumed that half of the 13 MT would be sent to the MFFF, and the other half would go directly to the HLW tanks and eventually DWPF.

[5] H-Canyon is one of the two reprocessing plants at SRS. HB-Line is a glovebox facility on top of H-Canyon that can process plutonium and other fissile materials into various forms for various purposes.

[6] The glass versus ceramic debate was to some extent a surrogate for the competition between SRS and Lawrence Livermore for control of the immobilization program. SRS had experience in glass because of the ongoing work to vitrify HLW at the DWPF, whereas Livermore had established itself as a center of ceramic immobilization research. After the Livermore program was disbanded, SRS had the upper hand and a wider reign to set the direction of the subsequent project.

[7] The security level of a special nuclear material storage facility is ranked according to the quantity and type of material the facility contains. Category I denotes the highest security level.

The study also evaluated options for disposal in WIPP in New Mexico. The DOE had ruled out WIPP disposal for excess plutonium in its 1997 Record of Decision, asserting that there would be insufficient capacity in WIPP after disposing of all the department's transuranic wastes, based on the legal limit specified in the 1992 Land Withdrawal Act.[8] However, the study team believed that WIPP options should be reevaluated because the DOE had gone ahead and disposed of several tons of plutonium in WIPP anyway after the 1997 Record of Decision was issued, establishing it as a reasonable path.[9] Nevertheless, if WIPP disposal were to be used for a larger quantity of excess plutonium, the DOE would have to address the issues that the NAS had raised about the potential retrievability of waste forms from the repository. Plutonium waste forms disposed of in WIPP could not be spiked with highly radioactive fission products to meet the spent fuel standard because WIPP has strict limits on acceptance of waste that is too radioactive to be contact-handled. Also, problems could result from the thermal heat generated by highly radioactive materials.

The study considered various approaches for converting plutonium into a stabilized matrix for WIPP disposal instead of disposal at the proposed nuclear waste repository at Yucca Mountain in Nevada. Although one option assumed immobilization in robust glass or ceramic matrices, the team recognized that such high-temperature stabilization methods would not be required for disposal at WIPP. Unlike Yucca Mountain, WIPP could accept wastes with a wide range of material properties. Therefore, the study also considered the possibility of less costly and simpler low temperature immobilization matrices such as grout, concrete or epoxy. Although the report judged these approaches to be feasible, in the end it ruled out the WIPP option was because of statutory language that was included in the FY 2006 Energy and Water Development Appropriations Act by New Mexico Senator Pete Domenici (R–NM). The provision prohibited the expenditure of funds under the Act to dispose of any plutonium materials that were greater than 20 percent plutonium at the time of the bill's passage. Domenici inserted the language specifically to prevent the DOE from expanding the scope of its program for downblending and WIPP disposal of Rocky Flats plutonium to other stocks. However, subsequent appropriations laws did not contain this prohibition.

Based on the SRS team's recommendation that can-in-canister vitrification at the K-Area Complex was the best option, DOE Deputy Secretary Clay Sell approved the plan in August 2006. The preliminary cost range for the project was $300–500 million. In March 2007, the DOE published a Notice of Intent to prepare a supplemental environmental impact statement (SEIS) to analyze its preferred alternative for plutonium without a disposition path: a combination of K-Area vitrification and dissolution in H-Canyon. Those two, together with the MFFF for fabricating MOX fuel, represented what the DOE now called a "three-pronged" approach to disposing of excess weapons-grade plutonium.

Six months later (September 2007), the DOE finally admitted that only 25.6 MT of plutonium—about sixty percent of the U.S.'s total excess stock of 43 MT—was sufficiently pure and well-characterized that it could be made into MOX fuel with certainty (DOE 2007a, 11). The DOE still was not sure that any the plutonium originally designated for immobilization under the PMDA could be used at the MFFF, even with the AFS modifications. However, it estimated that, based on extrapolation from sampling results, about 4.1 MT of the stranded plutonium could be

[8] The 1992 Land Withdrawal Act authorized radioactive waste operations at WIPP and established certain criteria, including a cap on the volume of waste that could be buried there.

[9] DOE had subsequently undertaken additional environmental reviews to allow such disposal to take place. An agency can always change its mind and amend a Record of Decision as long as it follows the proper legal procedures under the National Environmental Policy Act.

sent to the MFFF without additional purification. Still, the U.S. was as much as 4.3 MT short of the 34 MT that it had committed to dispose of as MOX. In order to bring the U.S. into compliance with its commitment under the PMDA, in late 2007 Energy Secretary Bodman declared an additional nine tons of weapons-grade plutonium as excess and available for disposition.

Cancellation of Immobilization (Take 2)

Despite the DOE's public statement in March 2007 that its preferred alternative was K-Area Complex can-in-canister vitrification, it was already backing away from the decision, based on escalating cost projections. The DOE then undertook yet another analysis, which recommended reversing course again and eliminating the K-Area plan, which was the top option in the previous analysis. Instead, it would utilize the MFFF to fabricate as much plutonium as possible into MOX fuel. Any leftover plutonium would be dissolved in H-Canyon and sent to the DWPF melter to be directly vitrified into radioactive glass logs. In a report to Congress in April 2007, the DOE disclosed that it was also examining alternative strategies to can-in-canister immobilization. And in June 2008, less than two years after the DOE revived plutonium immobilization, it once again pulled the plug on it, and the three-pronged approach became a two-pronged approach. The DOE's lack of interest in pursuing immobilization, despite its advantages, was again obvious.

In accordance with this change in direction, the Plutonium Disposition Project—which, recall, the DOE had created in 2006—was replaced by the Plutonium Preparation Project (PuPP). Like the vitrification project, the PuPP would install equipment in the K-Reactor basement to prepare the stranded plutonium, but instead of vitrifying it for can-in-canister disposal, it would process it for transfer to the MFFF as feedstock to make MOX fuel, or to H-Canyon for dissolution and transfer to the HLW stream, where it would eventually be vitrified homogeneously along with the HLW.

The PuPP plan called for utilizing 7.8 MT of plutonium as MFFF feedstock to produce MOX fuel. Since the DOE believed 4.1 MT could meet the AFS specs directly (a category of feedstock it now designated as "AFS-1"), this left 3.7 MT that would require some type of processing before it could be shipped to MFFF (a category of feedstock designated as "AFS-2"). This 3.7 MT included at least 2.4 MT of plutonium metal that the DOE believed would meet the AFS specs after conversion to plutonium oxide, as well as cans of plutonium oxide that would meet the AFS specs if they were subdivided into smaller amounts to reduce quantities of impurities in each can. The remaining stranded plutonium, approximately 5 MT, which was mostly not weapons-grade, would be sent to H-Canyon for dissolution and disposal as HLW.

The new capabilities would require furnaces for converting plutonium metal to oxide and for restabilizing and repackaging plutonium in 3013 cans, equipment for disassembling Hanford's Fast Flux Test Facility unirradiated fuel assemblies into pellets, and instruments for conducting non-destructive and destructive analyses. The PuPP concept did not envision processing the most impure, non-AFS plutonium for use in MFFF: all impure material transferred to H-Canyon would end up in the HLW. The estimated cost of the project was $340-$540 million, which was higher than the initial estimate of the vitrification option.

The DOE commissioned a panel of external experts to conduct a technical review of the PuPP to "verify that the process, cost and programmatic assumptions … were appropriate and reasonable." The review, issued in October 2008, did not have a favorable view of the plan to dispose of 5 MT through H-Canyon dissolution and vitrification in DWPF. In particular, it pointed to the fact that the waste acceptance criteria for Yucca Mountain strictly limited the amount of plutonium per DWPF canister, and this limit would have to be raised in order for the DOE's plan to work. It

recommended that the DOE find another approach for the 5 MT. Accordingly, DOE moved away from the H-Canyon/DWPF approach (Kosson et al. 2008).

One reason that the DOE was now proposing to install a furnace in K-Area to oxidize AFS metal was because its development of the Pit Disassembly and Conversion Facility (PDCF), a stand-alone facility at SRS to convert weapons pits and other plutonium metal to oxide feedstock for the MFFF, which the DOE decided to build in 2000, was also running into problems and was behind schedule. The PDCF design was itself highly complex: It required capabilities to disassemble a variety of pit types, to oxidize plutonium metal, to extract and oxidize plutonium from pits where it was chemically bonded to uranium, and to process and package these other materials. Moreover, the PDCF needed to "sanitize" (e.g. convert to a declassified form) and package non-fissile (yet plutonium-contaminated) pit components such as depleted uranium, beryllium, stainless steel and aluminum for disposal (Lewis 2009). In 2002, the National Nuclear Security Administration (NNSA)[10] reported to Congress that the facility would cost $1.7 billion and would be operational in FY 2009. Yet by 2005, a DOE Inspector General audit concluded that the startup would be delayed by at least four years and that the cost would be considerably greater than the 2002 estimate (DOE 2005). The PDCF process was based on a small-scale system that had been designed and tested at Los Alamos National Laboratory called the Advanced Recovery and Integrated Extraction System (ARIES). However, the DOE Inspector General found that a primary reason for the schedule slippage was the difficulty that NNSA was experiencing in scaling up the ARIES prototype for full-scale production. The Inspector General also found that NNSA had initially significantly underestimated the cost of the facility by not taking waste disposal into account: a huge omission.

The PDCF delay was of particular concern because even under the initial schedule, it was not slated to begin operation until two years after the MFFF had started up. Therefore, until the PDCF were operational, the MFFF would have to rely on other sources of plutonium: non-pit AFS and plutonium oxide produced by the ARIES prototype testing at Los Alamos. Since those sources were limited, a further PDCF delay might cause the MFFF to run out of feedstock and force it to idle, increasing the project cost even more. The PDCF's problems and escalating cost led the DOE to consider more changes to the plutonium disposition program: first, it sought to maximize the amount of AFS material that could be sent to MFFF; and second, it looked for alternatives for pit conversion that could allow it to scale back or even eliminate the PDCF altogether. Over the next several years, the DOE continued to consider various options to accomplish these tasks, and delayed action on issuing the draft supplemental environmental impact statement for which it had issued a Notice of Intent in 2007.

In 2010, the DOE amended the 2007 Notice of Intent, and said it would also evaluate an option that did not involve building a stand-alone PDCF but would combine the PDCF functions with the PuPP in K-Area, thereby creating a facility to prepare both pits and non-pit plutonium for disposition. The proposal envisioned that the throughput of the PDCF capability would be maintained at 3.5 MT of plutonium in pits per year, implying that there was sufficient process area in the K-Reactor building to support both a full-sized PDCF

[10] The NNSA was created by Congress in 2000 as a separately organized agency within the DOE and was given management authority over the DOE's national security missions, including nuclear weapons and nuclear nonproliferation. The program to dispose of the weapon-grade plutonium covered by the Plutonium Management and Disposition Agreement was placed under NNSA's purview, but the management of the additional excess plutonium outside of the agreement was the responsibility of the Office of Environmental Management, which remained in the DOE. As one might expect, this division contributed to the agency's ongoing difficulties in developing a consistent strategy for all the material.

capability and the non-pit preparation equipment. This option was named the Pit Disassembly and Conversion (PDC) Project (DOE 2010b).

The 2010 Amended Notice of Intent also contained another significant change. The DOE now proposed an additional disposal option for up to 6 MT of non-pit plutonium: using SRS facilities to prepare the plutonium for disposal in WIPP. While this had been ruled out in the 2006 review, the legislative prohibition inserted by Sen. Domenici at that time no longer applied. The DOE also believed that it had excess capacity in WIPP, based on its estimate of the remaining volume of transuranic waste around the DOE complex. Although the DOE had recently approved a plan to downblend and dispose of about 0.6 MT of additional plutonium at WIPP by using SRS's HB-Line facility (built on top of H-Canyon), this new proposal was significant because it proposed disposing of a far larger amount of plutonium in WIPP without meeting the radiological barrier criterion of the spent fuel standard.

The DOE's FY 2012 budget, issued in February 2011, stated that DOE expected to soon approve the plan to go forward with the PDC at the K-Area Complex, combining the functions of the PDCF and the PuPP. However, the proposal got caught up in the politics surrounding the H-Canyon reprocessing plant. A long-standing goal of SRS site boosters was to keep finding missions to justify continued operation of H-Canyon, the only usable spent fuel chemical separation plant in the United States. H-Canyon, which had begun operations in 1955, had been limping along for years, supplied with various "cats and dogs"— assorted nuclear material odds-and-ends—from around the complex. Its operations were shored up by a requirement in the FY 2004 National Defense Authorization Act that the DOE maintain H-Canyon in "a high state of readiness," a provision that cost about $200 million a year. This made it easy for the DOE to justify additional processing operations at H-Canyon, since the incremental cost of operating a facility that was being maintained in "a high state of readiness" was usually low compared to the alternatives.

However, by 2011 H-Canyon had run out of the materials that it was legally authorized under NEPA to reprocess, primarily spent fuel and other materials that were degraded and needed stabilization for safe storage. By then, the DOE also had abandoned the plan to use H-Canyon to dissolve 5 MT of non-MFFF–grade plutonium for vitrification with other HLW in the DWPF. As a result, the DOE planned to put H-Canyon in standby in FY 2012. (HB-Line, on top of the H-Canyon building, would continue to operate to prepare plutonium for WIPP disposal.) In a July 2011 letter, the DOE SRS site manager said that "there are no materials identified within the Department's inventory that require future processing in H-Canyon for either disposition or stabilization purposes" (Moody 2011).

The DOE's proposal to put H-Canyon on standby was vigorously opposed by supporters of the facility, such as the Defense Nuclear Facilities Safety Board and the South Carolina congressional delegation, primarily Senator Lindsey Graham (R–SC). In August 2011—a month after the DOE said that it could not identify any materials requiring processing at H-Canyon—the DOE issued a letter of direction to the site management to prepare to ramp up operations at H-Canyon, rather than put it in standby, thereby retaining 90 jobs. The rationale was to process plutonium material to make it suitable as feed for the MFFF. And in November, the DOE sent a follow-on letter instructing the site to assume that H-Canyon would receive up to 3.7 MT of plutonium material to purify and convert to oxide feed for the MFFF. This would also require an upgrade to HB-Line (Gunter 2011). This 3.7 MT was a portion of the 5 MT that the DOE had just a few months earlier decided not to send to H-Canyon for dissolution and disposal as HLW. But now, this material would be sent to H-Canyon, not for disposal as waste but for purification for use in MOX fuel. The decision represented a victory for proponents of using additional aqueous purification (beyond

the capabilities of the MFFF AFS process) to maximize the amount of impure plutonium that could be used to produce MOX fuel, with little regard for the associated cost, waste generation and environmental risk. Sen. Graham put out a statement taking credit for the DOE's reversal and crowing that using the facility to purify feed for the MOX plant was the "ultimate example of turning swords to plowshares" (Graham 2011).

At first glance, this would seem to be a reasonable and cost-effective approach: utilizing an existing facility rather than starting a new project. However, there are other costs associated with continuing to operate H-Canyon, a Cold War-era reprocessing plant that has experienced many safety problems and generates vast quantities of radioactive waste, that were not adequately taken into account. And this approach using H-Canyon, in the context of the plutonium disposition program, was also troublesome on a conceptual level: using a reprocessing plant to purify plutonium-bearing materials that were at one point regarded as worthless waste products and slated for disposal. The signal that this reversal projected—that plutonium was so valuable that it needed to be salvaged from scrap— ran counter to the message about the core purpose of the plutonium disposition program that the U.S. wanted to communicate internationally.

Soon after the DOE made its decision to ramp up operations at H-Canyon, in January 2012, it issued yet another amendment to the 2007 Notice of Intent to prepare the Surplus Plutonium Disposition (SPD) supplemental environmental impact statement (SEIS). In this amendment, the proposal to prepare non-pit plutonium in the K-Area Complex had disappeared completely, although the DOE still wanted to consider the option of using K-Area for some pit disassembly and conversion activities. DOE also proposed to expand the list of potential approaches for preparation of both pit and non-pit plutonium to include a combination of the H-Canyon/HB-Line, the PF-4 facility at Los Alamos where the ARIES equipment was housed, and even the MFFF itself (DOE 2012a, A-11).

Incredibly, the DOE was now considering modifying the MFFF yet again, although it was already under construction, by installing furnaces and other equipment so that it could have the capability to accept pits and convert them to plutonium oxide for MOX fuel production. The paperwork needed for such a change would be almost as daunting as the required retrofitting. To proceed would require amending the construction license granted by the Nuclear Regulatory Commission (NRC) in 2005, the operating license application that the NRC had been reviewing and litigating since 2006 (and which the NRC staff had already recommended be approved), and both the DOE's and NRC's NEPA documentation. The additional equipment and processes would require a significant revision to the safety analyses that had already been submitted to and approved by the NRC. Also, the security and material control and accounting plans would need to be revised to accommodate the receipt and storage of classified parts and materials.

In June 2012, the DOE followed through with its promise to Senator Domenici to keep H-Canyon going and issued an "Interim Action Determination" to authorize the use of H-Canyon/HB-Line for processing 2.4 MT of AFS-2 plutonium metal. Although processing of plutonium metal in H-Canyon for production of MFFF feedstock was not an activity that the DOE had previously analyzed under NEPA, it argued that the Interim Action was compliant with NEPA because the 2.4 MT of plutonium metal had previously been evaluated for conversion to oxide in the PDCF.

The Interim Action Determination was written in a way that implied that this 2.4 MT of AFS-2 metal, with the 4.1 MT of AFS-1 oxide, comprised the 6.5 MT of AFS plutonium that the DOE had previously evaluated in the 2003 amended Record of Decision. However, it isn't that simple. The DOE's initial excess plutonium declaration included 25.6 MT of pits, clean metal and clean

oxide; but subsequently it stopped tracking clean metal in this category and instead designated it as AFS-2. At the same time, because of tightening specifications for impurity concentrations in the AFS that could be shipped to the MFFF for MOX fuel production, some of the 4.1 MT that the DOE had previously believed to be AFS-1 was now considered AFS-2—that is, it required some preparation or processing before it could go to the MFFF.

It now appears that some of the AFS-2 metal could not have been simply oxidized at the K- Area Complex and sent to the MFFF anyway, because it has chemical impurities exceeding the MFFF AFS specs (Kyser and King 2012). What is most astonishing is that the levels of the metal gallium, removal of which was one of the main purposes of the MFFF aqueous polishing process, appear to be too high for the MFFF's own system. And it also turns out that dissolution of the AFS-2 metal in H-Canyon itself introduces impurities into the material that then have to be removed by further purification in HB-Line (Kyser and King 2012). All these complications could have been avoided if the DOE had pursued immobilization. The bottom line is that a significant fraction of the 6.5 MT of the material designated as AFS is too impure to be sent to the MFFF's own AFS processing lines, and would require additional purification. Therefore, the AFS system that was added to the MFFF design in 2002 appears to have been largely a waste of time and money.

In July 2012, the DOE finally released the draft Surplus Plutonium Disposition supplemental impact statement (SPD SEIS)—more than five years after it had announced its intention to do so. For the 34 MT of plutonium that the DOE had previously decided to make into MOX fuel, the draft evaluated the options for preparing the material to go to MFFF that had been included in the revised scoping document: that is, either building a standalone PDCF or utilizing some combination of existing facilities. The Preferred Alternative in the draft SPD SEIS was not to build the standalone PDCF but to use existing facilities. For the additional 13.1 MT of plutonium: a nominal 6 MT of non-pit plutonium and 7.1 MT from the Bodman declaration of excess pits, the DOE was clear: "The MOX Fuel Alternative is DOE's Preferred Alternative for surplus plutonium disposition." Thus, even though DOE had duly considered non-MOX alternatives for the remaining plutonium, its intention was to make as much of that material into MOX as possible. This meant up to about 11.1 MT would be processed for acceptance at the MFFF. The remaining 2 MT, including 0.7 MT of Hanford's Fast Flux Test Facility fuel, was mostly fuel-grade material that was outside of the isotopic specifications of the MFFF.

Despite the DOE's confidence in its Preferred Alternative, trouble was brewing within the MOX program itself. The estimated total project cost had ballooned. Less than a year after release of the draft SPD SEIS, the DOE made the surprise announcement that it intended to slow down work on the MOX plant and to conduct "an assessment of alternative plutonium disposition strategies." This marked the first time since its original decision in 1997 that the DOE publicly displayed a lack of support for the MOX route for the bulk of the surplus plutonium inventory and began to contemplate a non-MOX alternative.

However, turning around the MOX ship would not be an easy task. When the DOE cancelled the immobilization program in 2002 and focused all its resources on MOX, it severely hampered its ability to stand up the program again quickly and at reasonable cost. As a result, the DOE's past decisions will continue to have serious ramifications as the department tries to figure out how to honor its bilateral commitment with Russia and carry out the important mission of reducing the dangers posed by this stockpile of unneeded weapons-usable plutonium.

The DOE is not solely to blame for the mess the MOX program is in. The Nuclear Regulatory Commission also played a major role in enabling the MFFF's management problems to fester.

NRC Construction Authorization of the MFFF

A big part of the reason why the U.S. MOX program has fallen short of the safeguards and security goals originally specified by the National Academy of Sciences can be found in the way the MFFF was originally designed and licensed.

In 1999, the DOE awarded the contract for construction and operation of the MFFF to Duke Cogema Stone and Webster (DCS). As a DOE-owned facility at a DOE site, the MFFF ordinarily would be exempt from licensing by the NRC, the independent agency that oversees the safety and security of the U.S. civilian nuclear power sector. However, in the FY 1999 Strom Thurmond National Defense Authorization Act (coincidentally named for the South Carolina senator who was a major MOX booster), Congress gave the NRC the authority to license and regulate the facility. Granting oversight to the NRC was an important symbolic statement—especially internationally—that the MFFF was not a military facility. Moreover, the NRC's statutory requirements for providing public opportunities for hearings, as well as its own policies on providing the public with access to meetings and information, increased somewhat the level of transparency relative to facilities solely under DOE oversight.

However, NRC authority over MFFF licensing presented many problems of its own. The NRC had not had experience for decades in regulating plutonium fuel cycle facilities, and the level of staff knowledge in the relevant areas of expertise was relatively low. And because the plant would be a DOE facility on a DOE site, the DOE's own safety and security directives and orders would continue to apply unless it waived them. This resulted in an overlap of regulatory authority between the DOE and the NRC that caused inconsistencies and occasional conflicts, particularly in the areas of security and information protection. For instance, the DOE uses its own protective forces at SRS, but it wasn't clear how they would be coordinated with the protective force that NRC's own regulations required at the MFFF. That conflict was particularly problematic since the two agencies did not use the same Design Basis Threat (DBT), the set of adversary characteristics used to develop security plans. Also, the NRC and the DOE had different categorizations for sensitive information, and it wasn't clear how the different categories related to each other or how access to them would be established. The agencies recognized these issues and the potential problems of dual regulation as early as 1999 and proposed a Memorandum of Understanding to resolve any differences. The DOE and NRC staff worked for several years to develop such a document, but in 2003 the effort was suspended due to a lack of interest on the DOE's part, and the issues remained unresolved. The absence of a DOE–NRC Memorandum of Understanding would become increasingly problematic as development of the MFFF advanced.

The NRC's requirements for licensing fuel cycle facilities like the MFFF were contained in the Code of Federal Regulations as regulation 10 CFR Part 70, "Domestic Licensing of Special

Nuclear Material." Part 70 contains different procedures for uranium and plutonium fuel cycle facilities. Both types of facilities need to submit an application for possession and use of special nuclear material and an Environmental Report. For uranium plants, after nine months have elapsed and the NRC has issued a Final Environmental Impact Statement designating issuance of a license as the preferred alternative (in accordance with its NEPA review), an applicant may start construction (but not operation) before a Part 70 license is issued.

For a plutonium facility, on the other hand, construction itself may not begin until the NRC has determined that "the design bases of the principal systems, structures and components (SSCs) ... provide reasonable assurance of protection against natural phenomena and the consequences of potential accidents" (10 CFR §70.23(b)). As a result, plutonium facility applicants are required to submit, in addition to the license application, a summary description of the facility's "design bases" to the NRC for review.

This provision had its origin in the 1971 report of a task force convened by the Atomic Energy Commission (the NRC's predecessor) to examine the safety of plutonium processing and fuel fabrication facilities (AEC 1971). At the time, fuel cycle facilities were not required to be designed to withstand external hazards, such as earthquakes or tornadoes. The task force was concerned about the lack of protection for plutonium facilities—of which there were 11 at the time—and the risk of an accident that could disperse a respirable plutonium aerosol. The task force urged the AEC to conduct an "in-depth evaluation of those aspects of the application related to the site and the plant design bases" prior to construction approval (AEC 1971, 6). The task force recommended that the review include the design bases for structures, systems, and components relevant to safety and waste handling. It also said the review should include design provisions for security and nuclear material safeguards. However, the regulation later issued by the NRC referred only to review of the design bases of systems related to protection against "accidents" and not those related to security and safeguards.

In preparing to license the MFFF, the NRC staff issued a document called a "Standard Review Plan," outlining its approach for reviewing an application for a MOX fuel fabrication facility (NRC 2000). The Standard Review Plan interpreted the Part 70 pre-construction approval review for plutonium facilities and the subsequent operating license application review as two separate and sequential actions.[11] In particular, it did not require applicants to submit a complete license application in order for the NRC to grant construction approval. An applicant only had to provide the design-basis description and safety assessment in sufficient detail for the NRC to make a finding of "reasonable assurance." The applicant could then submit an operating license application at a later time. The operating license application would contain more detailed design information, as well as licensing documents that the NRC considered more operational in nature. In the latter category were the Physical Protection Plan (PPP) and the Fundamental Nuclear Material Control Plan (FNMCP), the documents needed for compliance with the NRC's security and material control and accounting (MC&A) requirements.

In February 2001 Duke Cogema Stone & Webster (DCS) submitted a "Construction Authorization Request," or CAR, along with an Environmental Report. The CAR did not contain detailed design information. Moreover, it contained virtually no design information about the physical protection systems and MC&A. The section on physical protection was a single

[11] A Standard Review Plan does not have the force of a regulation. It represents one method that the NRC staff considers acceptable for meeting the regulations. Therefore, its interpretation of the regulations is subject to challenge.

paragraph long, and the section on MC&A was less than one page long.

After receiving the CAR, in April 2001 the NRC issued a notice of opportunity for a hearing. In the notice, the NRC confirmed the applicant's approach and stated that only the CAR and NRC's construction approval requirements would be the subject of the hearing. The NRC would provide an opportunity later for a second hearing on an operating license after DCS submitted an operating license application.

This bifurcation of the MFFF licensing proceeding, which created two opportunities for public hearings, was completely opposite to the evolution of nuclear power reactor licensing to a one-step process. Before the 1980s, the original approach for licensing reactors was a two-step process, in which an applicant would first apply for a construction permit and then later for an operating license. But utilities complained that process gave public intervenors an opportunity to deny an operating license for a reactor that had already been constructed, threatening the loss of their capital investment. In the 1980s, Congress directed the NRC to develop a one-step licensing approach, whereby an applicant could get a combined license to construct and operate a nuclear plant. The NRC then developed its 10 CFR Part 52 regulations for "combined operating licenses," which the agency heralded as an effort to improve efficiency and regulatory predictability. Yet in this case, DCS, with the NRC's assent, sought to convert a one-hearing licensing process into a two-hearing one. One may speculate that DCS was anxious to get the project moving without having to develop a detailed design first and did not fully consider the potential ramifications further down the line.

CAR Contentions

In August 2001, the environmental group Georgians Against Nuclear Energy (GANE) filed a set of 13 contentions, which challenged the DCS CAR on security, safety and environmental grounds. Two contentions focused on the absence of detailed MC&A and physical protection design basis information in the CAR.

The first of GANE's contentions (Contention 1) stated that:

> The DCS Construction Authorization Request (CAR) does not contain detailed information on MFFF design features relevant to the ability of DCS to implement material control and accounting (MC&A) measures capable of meeting or exceeding … regulatory requirements … and there is no indication that MC&A considerations were taken into account in the MFFF design. As a result, the CAR does not provide a basis for NRC to 'establish that the applicant's design basis for MC&A and related commitments will lead to an FNMCP that will meet or exceed the regulatory acceptance criteria' … Failure to adequately consider MP&A issues during the MFFF design phase not only exhibits poor engineering practice but also greatly increases the probability that DCS will not be able to operate the MFFF in compliance with 10 CFR Part 74 without significant retrofitting (and may not be able to even with retrofitting), and thus that NRC ultimately will deny DCS a license to possess and use SNM at the MFFF … (GANE 2001)

GANE argued that new nuclear facilities should be designed to facilitate the effective application of both domestic material control and accounting and of international safeguards. An important aspect of this "safeguards by design" principle is that design information should be provided to licensing and safeguards authorities as early in the process as possible.

For example, in February 1992 the IAEA Board of Governors adopted a recommendation that design information on new nuclear facilities

should be supplied to the IAEA at least 180 days prior to commencement of construction (previously it was required only that such information be provided 180 days prior to commencement of operation). GANE contended that similarly detailed design information relevant to MC&A implementation should be provided to the NRC in advance of approving construction.

GANE pointed out that design flaws were partly responsible for the failure of the MC&A system at the Plutonium Fuel Production Facility in Tokaimura, Japan. During six years of operation (1988–1994), approximately 70 kilograms of plutonium accumulated on plant surfaces and process equipment, resulting in an unacceptably high value of "material unaccounted for." The plant was shut down, cleaned out, and retrofitted with additional systems to reduce holdup accumulation and nondestructive analysis measurement uncertainty. The total cost of the cleanup and retrofit was $100 million.

GANE's second contention was similar to the first, but dealt with the lack of a physical protection design basis in the CAR.

A third security-related contention challenged the absence of evaluation of sabotage impacts in the Environmental Report. The Environmental Report, as was common practice, only contained an evaluation of the consequences of severe accidents at the MFFF and judged that their likelihood was low. However, GANE argued that the impacts of sabotage attacks should also be evaluated. Such attacks could also cause severe consequences for public health and safety, yet they could not be dismissed as "low probability" according to the NRC's long-standing policy that it was not possible to quantitatively estimate the likelihood of terrorist attacks.

A fourth contention related to DCS's proposed designation of the "controlled area boundary" for the MFFF site. In Part 70, the NRC defined a zone around fuel cycle facilities, called the "controlled area," as an area to which the licensee can restrict access to anyone for any reason. The DCS application designated the controlled area boundary as identical to the boundary of the Savannah River Site itself, even though the MFFF site area would constitute only a tiny fraction of the SRS. Such a broad designation would enable DCS to consider all SRS workers to be MFFF employees for the purpose of meeting NRC safety regulations. Such a trick was useful for DCS because the standards for protection of plant workers were less stringent than protection of members of the public, and DCS could evaluate the impacts of a plutonium release accident on members of the public at a much greater distance from the MFFF than if it designated only the MFFF site as its controlled area. (There is a zone of several miles of forest between SRS facilities and the site boundary, whereas there is little buffer between the MFFF site and other active work areas in the SRS.)

The NRC staff itself challenged this designation, since DCS could not credibly claim that it had total control over the entire SRS site. But DCS had not changed its position at the time GANE filed its contention.

Separately from its contentions, GANE filed a motion to dismiss the MFFF licensing proceeding altogether, arguing that the two-step licensing approach for the MFFF violated NRC regulations.

DCS opposed all of GANE's contentions. It argued that the regulations simply did not require the MFFF Construction Authorization Request to include any information about physical protection or material control and accounting, because they only specified "accidents" and not sabotage or other deliberate acts. DCS committed only to providing detailed information at a later time, when it submitted the license application.

Since DCS was a DOE contractor, its position that there was no need to consider safeguards in plant design no doubt had the support of its sponsor. Yet only a few years later, the DOE instituted a program called "Safeguards by Design" in its Next Generation Safeguards Initiative.

DCS also argued that the contention should be rejected because it was willing to take the risk that

it might have to make significant retrofits after the MFFF was built if it could not meet MC&A and physical protection requirements. What DCS neglected to point out was that all MFFF construction costs would be paid by the DOE. Thus the risks of poor design would be borne by U.S. taxpayers, not by DCS or its parent companies. Again, since DCS was presumably following the DOE's direction, this means that the DOE was willing to gamble with taxpayers' money.

The NRC staff, for its part, also opposed admission of all of GANE's contentions. With regard to the MC&A and security contentions, it said that neither MC&A nor physical protection issues were relevant to the Construction Authorization Request proceeding. It didn't support GANE's challenge to the DCS controlled area boundary designation, even though that was a concern the NRC staff had itself raised. And with regard to the contention on the evaluation of sabotage impacts, the NRC staff filed what might qualify as one of the most tone-deaf legal pleadings in history. It argued that "under the long-established rule-of-reason line of NEPA decisions, federal agencies need only address reasonably foreseeable environmental impacts arising from a proposed action, and GANE does not establish that terrorist acts … fall within the realm of 'reasonably foreseeable' events (NRC 2001, 22). The date of the filing was September 12, 2001.

The September 11, 2001 attacks had a major impact on most NRC operations, as the agency scrambled to assess whether its security requirements were adequate and if not, what changes were needed. Ultimately, it upgraded security in a number of different respects, including issuing orders to all licensed power reactors and Category I fuel cycle facilities requiring them to be able to protect against a more stringent Design Basis Threat. These orders were known as "interim compensatory measures." Orders are distinct from regulations in that they are special requirements that the NRC issues to individual facilities.

However, the MFFF fell into a regulatory limbo. The NRC could issue orders only to facilities that already had licenses, not to a facility that was in the process of being licensed. In contrast, if the security regulations themselves were changed, then the NRC would have the option to decide whether to grandfather in a license applicant or require it to change its application. However, changes to the regulations require lengthy rulemaking proceedings, and would take years to adopt. (As of this writing, 13 years after 9/11, the NRC still has not revised the security rules for Category I fuel cycle facilities, although it has begun the process.) So although the NRC provided DCS with the post-9/11 interim compensatory measures for Category I facilities "for information purposes," the MOX plant license application was evaluated only against NRC's pre-9/11 security requirements. Only after the plant received its operating license would the NRC be able to issue the security orders to the plant, require DCS to incorporate them into its security plans, and assess whether it was in compliance with them (NRC 2010a, 13-2).

In December 2001, the Atomic Safety and Licensing Board (ASLB) issued a decision admitting eight of GANE's 13 contentions. Among the admitted contentions were the two that challenged the lack of consideration of MC&A and physical protection in the facility design. It also admitted the contention on the controlled area boundary designation.

MFFF Design Changes

In January 2002, the DOE announced its decision to cancel the immobilization program and redesign the MFFF to be able to accept some of the plutonium that would have been immobilized, e.g. the alternate feedstock (AFS). Although there were clear signs for months that such a decision was imminent, the NRC had no choice but continue to review the Construction Authorization Request and Environmental Report as originally

submitted until DCS formally notified it of the change, wasting a significant amount of staff time. The cancellation of immobilization resulted in profound changes to the plutonium disposition program and to the NRC's MFFF licensing. The MFFF design had to be modified to accommodate the additional process area and support equipment for the AFS lines, which resulted in an expansion of the building's length and height. But the impact was not only on the design; adjustments needed to be made to the preliminary site preparation that had already taken place, including the repositioning of support buildings and transmission lines. The operational area of the MFFF nearly tripled, from 15 acres to 41 acres. As a result, the combined land requirements for the MFFF and PDCF were greater than the original requirements for the original dual-track program, which also included a new plutonium immobilization plant. DCS needed to make significant revisions to both the Construction Authorization Request and Environmental Report to account for the design changes, causing a delay of about a year in NRC's safety and environmental review.

Moreover, DCS estimated that the additional transuranic waste that would be generated at the MFFF would increase by about a factor of seven, because of the additional quantities of americium in the AFS. Partly to accommodate this increase, the DOE decided to build a separate building called the Waste Solidification Building (WSB) for the processing of transuranic waste from both the MFFF and the PDCF. The WSB would be built by the DOE outside of the MOX site and hence would not be subject to NRC licensing. However, since there would be additional environmental impacts associated with construction of a new facility, this also necessitated a change in the Environmental Report and in the NRC's environmental impact statement, which were required to analyze all the impacts of the program, not just those of NRC-licensed facilities.

Construction Authorization

In May 2002, DCS proposed a settlement agreement to resolve contentions 1 and 2. It offered to provide a supplement to the Construction Authorization Request with the design bases for MC&A and physical protection, and allow GANE to evaluate them and file new objections if necessary. DCS emphasized that the contentions pertained to the absence of such information, not to the adequacy of such information. It also did not concede that it was required to provide the additional design bases (DCS 2003).

GANE did not accept the design bases as sufficient to address its concerns, and rejected DCS's attempt at a settlement. DCS then amended the Construction Authorization Request in October 2002 to include the design bases for MC&A and physical protection that it had developed. In May 2003, it filed for a summary disposition on the two contentions, arguing that because the Construction Authorization Request now contained these design bases, the contentions were now moot. (Summary disposition is a ruling that there are no genuine issues in dispute between the two parties.)

Finally, in May 2004, the ASLB granted the DCS motion for summary disposition of contentions 1 and 2, accepting the argument that the contentions were moot. The ASLB essentially ruled that it did not matter whether the design bases that DCS had attached to the Construction Authorization Request were in any way adequate; all that mattered was that there was now something there (ASLB 2004). The ASLB ruling also upheld the applicability of the pre-9/11 Design Basis Threat (DBT) in developing the physical protection design bases, although it pointed out that DCS said that it had taken the post-9/11 DBT, which was provided to it for information purposes, into account in the design on a voluntary basis (ASLB 2004).

The contention related to the controlled area boundary designation was still in play, and

the parties continued to prepare for a hearing. However, in November 2003 the DOE suddenly informed DCS that it could not consider the SRS site boundary as the controlled area boundary and instead would have to reduce it to what was designated as the "restricted area boundary" that surrounded certain buildings on the MFFF site. This would shrink the controlled area from over 777 square kilometers to 0.06 square kilometers. Such a change—which the NRC called the "second major change" in the plutonium disposition program (NRC 2006)—would have a significant impact on both the DCS safety analysis and on its environmental report. The NRC staff were about to release their Final Environmental Impact Statement, which had already been delayed because of the "first major change" related to cancellation of the immobilization program, but this change in the controlled area boundary forced them to revise it once again (NRC 2006). GANE withdrew its contention because the dispute was resolved in its favor. Meanwhile, DCS and the DOE and DCS apparently continued to argue over the controlled area boundary designation, and in April 2004 DCS informed the NRC that NNSA had given permission for DCS to consider the entire 0.17 square kilometer MFFF site as the controlled area (NRC 2006). Partly because of all the back and forth, the NRC did not publish the Final Environmental Impact Statement until January 2005.

With all legal objections removed and the Final Environmental Impact Statement issued, the NRC granted DCS authorization to begin construction in March 2005. However, DCS did not actually start construction until more than two years later. Part of the reason, according to the DOE, was the U.S. government's continuing reluctance to proceed in the absence of a liability agreement with Russia that would shield any U.S. contractors that might provide assistance to the Russian program. Soon after the PMDA was signed in 2000, Russia balked at a liability agreement, modeled after provisions in the Cooperative Threat Reduction agreement, that would hold the U.S. harmless for any damages resulting from accidents or sabotage at Russian plutonium disposition facilities. However, Undersecretary of State John Bolton reportedly did not want a weaker agreement (Baker and Linzer 2005).

The issue took years to resolve, and an agreement was not signed until September 2006. But by then, Congress, which was dealing with a revolt against MOX spending led by Congressman David Hobson (R-OH), had imposed a prohibition on funding construction of the MFFF until August 1, 2007. On August 1, 2007, after expiration of the Congressional prohibition on MFFF construction, groundbreaking finally began at SRS.

The DOE began construction without placing the facility on the IAEA eligible facilities list for safeguards or involving the IAEA in any other way, in spite of its commitment in the Record of Decision on the 1999 Surplus Plutonium Disposition Environmental Impact Statement to apply IAEA safeguards to surplus plutonium "as soon as it is practical." Because of the DOE's refusal to honor this commitment, the IAEA did not have the opportunity to carry out design verification on the facility.

According to the DOE, at the time the plant was on schedule to begin operation in 2016 and produce one metric ton (MT) of MOX fuel in 2017. Yet the MOX program's difficulties were just beginning.

Two-Step Licensing and "Design-Build"

And as far as the larger problem that GANE highlighted: the two-step approach that allowed DCS to avoid addressing security and safeguards in the plant design? The NRC commissioners rejected GANE's petition to suspend licensing (NRC 2002b). The commissioners said that the regulations did not require that the NRC only have one hearing for a MOX fuel fabrication plant or that it need have a complete application in hand before making a construction authorization

decision. It said that the Atomic Energy Act gave the commission broad power to organize its licensing process "efficiently."

In practice, however, the two-step process turned out to be anything but efficient. As of this writing (November 2014), the NRC still has not granted an operating license to the MFFF, in part because of legal proceedings on both steps that combined have lasted well over a decade. And NRC's two-step process enabled the DOE/DCS to apply to the MFFF a practice for which it had been roundly condemned: the so-called "design-build" (or more accurately "design-build-design") approach. In design-build, facility construction begins before its design is fully fleshed out, and design changes are made along the way. In April 2006, the U.S. Government Accountability Office (GAO) criticized design-build in a report on the troubled Hanford Waste Treatment Plant, which argued that the approach had contributed to the facility's substantial delays and cost overruns. The GAO pointed out that such an approach was high-risk and inconsistent with the practice in the commercial nuclear industry, which set a goal that the detailed design of first-of-a-kind plants should be 90 percent complete before the start of construction.

And it wasn't just the GAO that found problems. A DOE Inspector General report released in May 2014 revealed that in July 2006, both external and internal reviewers expressed concern that the MFFF facility design was incomplete and that the project managers planned to conduct design reviews "in stages," raising the possibility that the project would also fall into the "design-build-design" mode (DOE 2014a, 3). Nevertheless, the DOE ignored this warning as it proceeded with the MFFF project, and when it began construction the design (and associated cost and schedule estimates) were woefully incomplete. According to a 2014 GAO report, the DOE now estimates that the overall design was less than 60 percent complete in April 2007 (GAO 2014). When the NRC gave DCS authorization to construct the facility in 2005, the design was likely even less mature.

Because the NRC staff had insufficient information to make conclusions about the safety and security of the design at that early stage, it made the wrong call when it authorized construction of the MFFF. As a result, the design itself became an obstacle to implementation of NRC's material control and accounting regulations at the MFFF, as discussed in the next section.

Material Protection, Control and Accounting in the U.S. MOX Program

The lack of attention to material protection, control and accounting (MC&A) issues shown by DCS, the DOE, and the NRC during the Construction Authorization Request hearing was especially troubling in view of the National Academy of Sciences' key recommendation that the "stored weapons standard" be applied to the entire plutonium disposition process to avoid increasing the short-term risks of diversion or theft. While the concerns of most observers focused on the risks of the Russian program (notwithstanding the 1993 World Trade Center bombing, few in 1994 were worried about the subnational threat to U.S. nuclear facilities), the NAS had the foresight to recommend that the stored weapons standard be applied globally. A chief consideration was the need for the U.S. to set an example; after all, if the NAS vision of a program with stringent bilateral and international monitoring were to come to fruition, the U.S. could not do less than what the Russians would be obligated to do.

Twenty years later, the picture is far different. The image of U.S. domestic invulnerability has been shattered by the 9/11 attacks, the rise of al Qaeda and other sophisticated, well-funded terrorist groups, and the ever-present risk of well-armed domestic extremists. Subsequently, two displays of rank incompetence, widely reported in the press, have called into question the ability of the U.S. government to account for and protect its most valuable assets. In 2007, the U.S. Air Force failed to properly account for the location of six nuclear-armed missiles, which were unintentionally transported across the country on the wing of a B-52 bomber. In 2012, DOE contractors failed to prevent three unarmed protesters from penetrating the protected area of the Y-12 HEU processing facility in Oak Ridge, Tennessee.

Today, the threat of theft of U.S. nuclear weapons materials must be taken seriously; the NAS recommendation for a "stored weapons standard" has stood the test of time. But instead of following this recommendation, the U.S. has gone in the other direction, actively weakening (or interpreting as loosely as possible) physical protection and material control and accounting requirements for several stages of the MOX program. The burden of meeting the existing requirements, which themselves fell far short of the stored weapons standard, proved too onerous for the program's contractors. Experiencing massive cost overruns and delays, the contractors sought to cut corners in areas that were low priorities for them, like security and MC&A. Even worse, some of the legal precedents and measures for regulatory "relief" from security requirements that have come out of MOX licensing are being applied more broadly. The outcome is that the U.S. plutonium disposition program is helping to weaken domestic and international standards for securing nuclear materials rather than strengthening them, as the NAS had envisioned.

To be sure, the DOE never intended to apply the stored weapons standard in a literal sense,

despite its commitment in the 2000 Record of Decision on the Surplus Plutonium Disposition EIS to meeting the standard for materials in storage (but not in transport or during the disposition process itself). In fact, the stored weapons standard, taken literally, might appear to conflict with the DOE's own set of procedures governing the protection, control and accounting of weapons-usable materials, which is known as "graded safeguards." Graded safeguards adjusts the security and accounting measures to be applied to special nuclear materials in various quantities and forms according to their "attractiveness" for use in a nuclear explosive device (Figure 2). The highest security measures are applied to Attractiveness Level A materials, which include assembled weapons and test devices. For each category of material (e.g. each column in Figure 2), less stringent security would be applied as the attractiveness level decreases to B, including weapon pits and pure metals; C, "high-grade" materials, including compounds like oxides, and D, called "low-grade" material (DOE 2011).

As complex as the graded safeguards table in Figure 2 may appear, it doesn't contain all the information necessary to determine attractiveness levels. The DOE also has a separate "decision tree" with additional criteria (Figure 3). For instance, according to Figure 3, a solid material with less than 10 weight-percent plutonium would be considered Attractiveness Level D, but this cannot be derived from Figure 2. This is an important threshold for the MOX program, because fresh MOX light-water reactor fuel assemblies with weapons-grade plutonium contain less than 10 percent plutonium and hence would be Attractiveness Level D. Since there is no Category I quantity of Level D material, this means that the highest level of security the DOE would apply to fresh MOX fuel would be Category II. (As discussed below, NRC security requirements, which are different, would also be applicable.)

When considering the weight percent (percent by weight) of plutonium diluted in a particular matrix, it is important to consider whether there is a means of readily separating the matrix from the plutonium. In that case, dilution would be ineffective as a means of reducing attractiveness. As an extreme (but apparently real-world) example, if one diluted plutonium metal in the form of ball bearings with magnetic steel ball bearings, separation could be easily accomplished.[12]

Under the tightest interpretation of the stored weapons standard, Attractiveness Level A security would apply to all plutonium in the disposition process until the final state, or spent fuel standard, were achieved. This interpretation would be inconsistent with graded safeguards, which does not even call for protecting weapon pits as strictly as intact weapons, much less plutonium oxide or unirradiated MOX fuel assemblies. However, some analysts have pointed out that the NAS definition was very general and not inconsistent with graded safeguards (Bunn 1998). And the qualifiers "approximate" and "as closely as practicable" provide wide latitude for interpretation. Nonetheless, it is hard to imagine that the NAS committee would have been pleased with the degree to which security measures have been watered down in the MOX program.

MOX Fuel Security Exemptions

A clear example of how the MOX program has weakened security is the exemption from a number of physical protection requirements that the NRC granted to Duke Energy for storage of a Category I quantity of plutonium at the Catawba nuclear power plant in South Carolina. Catawba was one of the two plants where Duke Energy planned to use the MOX fuel produced at the MFFF, before Duke withdrew them from the program in 2009.

In February 2003, Duke Energy, a member of the DCS consortium, submitted a license amendment request to the NRC to allow the use of four MOX lead test assemblies at Catawba. In order to receive the four lead test assemblies, containing a total of 80 kg of plutonium, Duke needed to comply

[12] One should keep in mind, however, that "readily separable" is a subjective concept that depends to some extent on the capabilities of the group carrying out the separation.

with NRC security regulations governing the storage of a Category I quantity (2 kg or greater) of plutonium.

Catawba, as a nuclear power reactor, already had to meet NRC's requirements to be protected against the design basis threat (DBT) of radiological sabotage. To protect against the radiological sabotage DBT, NRC's regulations at the time include requirements for an on-site armed response force; a liaison with local law enforcement; two physical barriers around vital equipment with intrusion detection and assessment capability; access controls for vehicles and individuals; and unescorted access authorization procedures (primarily criminal background and credit checks). A post-9/11 requirement for triennial NRC-conducted "force-on-force" inspections was not yet in effect.

However, in order to receive the shipment of lead test assemblies, Duke would have had to significantly upgrade the security at Catawba to be able to protect the plutonium from the NRC's Category I theft DBT, which represented a more capable adversary than the radiological sabotage DBT. The additional requirements included detection and monitoring systems for unauthorized material movements; designation of material access areas for storage of plutonium, protected by an additional physical barrier; a dedicated "tactical response team," with at least five members with special weaponry and training in addition to the normal complement of armed responders; at least one NRC-observed force-on-force exercise per year; at least two armed guards posted at each material access area control point; entry and exit searches at material access area control points; and NRC top secret clearances for sensitive positions such as the security force and all individuals with unescorted access to material access areas or vital areas. These measures would have been quite cumbersome for Duke to enact: obtaining the clearances alone could have taken years, given that commercial nuclear power reactor personnel did not typically have them. Even so, the measures would not have cost the utility anything, since the DOE was committed to paying all incremental costs associated with the MOX program.

In September 2003, Duke requested an exemption from many of the requirements, including the annual force-on-force inspection, the tactical response team, and top secret clearances. Duke asserted that it did not need these measures to provide high assurance that it could protect the MOX LTAs from the Category I theft DBT. However, without the force-on-force requirements, Duke would not have to demonstrate its capability with performance testing. And without obtaining the necessary clearances, Duke personnel would not even know what the classified Category I DBT contained. Duke also provided a revised security plan describing a few additional "incremental" security measures for unirradiated MOX fuel assemblies that it would apply in lieu of the Category I requirements (Lyman 2005).

Unlike the DOE's graded safeguards, NRC's security categorization of special nuclear materials was based solely on the quantity of SNM contained in an item, and did not take into account the attractiveness of the material. For example, the rules required that the highest level of security, Category I, be applied to any (unirradiated) item that contained more than 2 kilograms of plutonium, even if it were diluted to a low concentration in a non-fissile matrix. But in its exemption request, Duke argued that attractiveness should be taken into account, since "the underlying rationale for imposing [Category I] regulatory requirements does not apply to … fuel pellets sealed inside fuel rods which are part of large, heavy fuel assemblies to be loaded into a reactor" (NRC 2004a).

For its part, the NRC staff agreed, stating that "…the staff's assessment is that the MOX material, while meeting the criteria of a formula quantity, is not attractive to potential adversaries from a proliferation standpoint due to its low plutonium concentration, composition and form." The staff based this conclusion on its belief that "a large quantity of MOX fuel and an elaborate extraction process would be required to accumulate enough material to fabricate an improvised nuclear device or weapon." The NRC staff also pointed to the fact that under the DOE material attractiveness categorization, the MOX lead test assemblies would represent a Category II quantity of Attractiveness

Level D material, implying that Category I protection was not necessary (NRC 2004a).

However, the difference between Category I and Category II security in the DOE's internal directives is not nearly as great as the difference in NRC's regulations. The DOE states that for both categories "protection measures must address physical protection strategies of denial and containment as well as recapture, recovery and/or pursuit" (DOE 2010a). But for NRC, the security organization at Category II facilities does not have to protect against the DBT for theft, unlike at Category I facilities. It only has to detect and assess thefts and notify "appropriate response forces," presumably local law enforcement and the FBI, to facilitate recovery of stolen special nuclear materials.

The Blue Ridge Environmental Defense League (BREDL) filed a petition challenging the exemption request, arguing that Duke had not shown that the substitute security measures it proposed could protect against the Category I DBT (Lyman 2005). BREDL contended that Duke's plan would burden the existing security forces, whose main responsibility was to protect the plant from radiological sabotage, with the additional duty of protecting the fresh MOX fuel from theft. BREDL devised scenarios in which adversaries could exploit this weakness and successfully steal fresh MOX fuel from a commercial power reactor site (Lyman 2005).

After a long and complex hearing, the ASLB approved the security exemptions, but also imposed four additional security conditions. Notably, the ASLB required that "prior to receipt of the MOX fuel at Catawba, Duke must demonstrate its ability to counter an attempt at theft of the MOX fuel material by undertaking tabletop and force-on-force exercises." The ASLB also rejected arguments that MOX fuel assemblies would not be attractive to any terrorist group, and accepted BREDL's view that "as a practical matter, attractiveness would be related to the experience and abilities of those in whose eyes any such 'attractiveness' is measured" (ASLB 2005).

Soon afterward, the NRC decided to review the ASLB's decision, even though no party in the case had appealed. On June 20, 2005, it issued an order overturning the four additional license conditions imposed by the ASLB, saying that "we find the Board's generalized assumptions about the relatively strong attractiveness of the MOX fuel as a target in contradiction to the weight of the evidence established in the record demonstrating otherwise" (NRC 2005). The bizarre order served no purpose other than to discredit the ASLB's decision, since the lead test assemblies had arrived at Catawba nearly two months earlier—presumably after Duke had met the ASLB's conditions—and had already been loaded into the reactor.

Subsequently, in a 2009 revision of its physical protection rules, the NRC extended the scope of this ruling by issuing a blanket exemption for MOX fuel with plutonium concentrations below 20 percent from Category I security requirements when stored at commercial power reactors. The rule did not explain the rationale for this numerical threshold, which was twice as great as the DOE Attractiveness Level D threshold that the NRC staff had invoked in the Catawba hearing.

And now (2014), the NRC is pursuing an even broader regulation that would incorporate a graded safeguards approach for physical protection based on material attractiveness considerations. This would reclassify MOX fuel and other mixtures with plutonium concentrations below 20 percent by weight so that they would no longer be subject to security and MC&A requirements comparable to Category I when stored or used at any type of facility, or when being transported (NRC 2014b). This rulemaking was initiated at least in part at the request of the Nuclear Energy Institute, the policy and chief lobbying organization for the nuclear industry, which had organized a fuel cycle facility working group to press the NRC on this issue. Nuclear Energy Institute's members include parties with an interest in the MOX program such as the Tennessee Valley Authority and the French multinational nuclear company AREVA (Lyman 2011).

Making MOX fuel transportation "more affordable" was a key consideration for these stakeholders in supporting a relaxation of the NRC's rules (NRC 2014b, 53). A memorandum from the Tennessee Valley Authority released under the Freedom of Information Act indicates that the expectation is that the new approach would eliminate the requirement for fuel to be transported by Safe Secure Trailers (SSTs) built to DOE specifications for transport of nuclear weapons and related materials, instead allowing the use of ordinary commercial trucks, as is done in France (Lyman 2011).

The DOE adopted a policy early on—consistent with its partial commitment to the stored weapons standard—that plutonium oxide and MOX fuel assemblies would be transported by the DOE Office of Secure Transportation and would use the SSTs or the more modern SGTs (Safeguards Transporters). In addition, the NRC would also have jurisdiction over regulating these shipments, and the Office of Secure Transportation transport systems are the only ones that meet the NRC's security requirements for transport of Category I special nuclear materials (Yapuncich et al. 2010).

However, reliance on the SSTs/SGTs for shipment would be cumbersome for utilities receiving MOX fuel. For instance, SSTs have classified features, and individuals must have security clearances to be able to enter them. Thus although the NRC eliminated the security clearance requirement for personnel at commercial power reactors using MOX fuel, they would still be required for personnel involved in unloading the vehicles.

Also, there is a problem that has been known since the 1990s regarding the capacity of the SSTs/SGTs to carry MOX fuel packages. At the time, there was only one U.S. design for MOX fuel transport that had been certified, the MO-1, which carried two pressurized water reactor assemblies. A typical 18-month cycle pressurized water reactor reload at 40 percent MOX would require around 32 assemblies, or 16 SST shipments. According to a 1998 Sandia National Laboratories report, only 1 MO-1 can fit into an SST because of both weight and size constraints, and not all SSTs can even carry one (Didlake 1998, 12). The report also said that "it appears" that the newer SGTs could not carry the MO-1 at all. (The MO-1 subsequently lost its NRC certification for MOX fuel transport.) Thus the fresh MOX fuel shipment requirements could be very high unless new, higher capacity MOX fuel packages could be licensed, or if the requirement that SSTs be used were relaxed.

DOE's choice apparently has been to relax the SST requirement. A new fresh MOX fuel package was certified for pressurized water reactor fuel in 2005 that could hold three pressurized water reactor assemblies, but the package is too short to hold boiling water reactor assemblies (as would be needed for the TVA Browns Ferry reactors, for example), and the pressurized water reactor assembly design has changed since the package was licensed. In 2012, AREVA notified the NRC that it was planning to design two new packages, but there has been no apparent interaction with the NRC on this effort since that time. (A 2013 scheduled meeting was cancelled.) Meanwhile, the 2012 draft SPD SEIS stated that, although the DOE's Secure Transportation Asset (STA) program would continue to be responsible for MOX shipments, "DOE's Office of Secure Transportation has determined that contractor-provided transportation configuration for mixed oxide fuel assemblies can be conducted under STA using escorted, commercial trucks" (DOE 2012a, E-2, fn.2). NRC Category I requirements would also have to be waived in order for this option to be implemented.

In summary, through its interactions with the NRC on the MOX program, the DOE has helped to drive an effort to significantly weaken the NRC's security requirements for plutonium and other weapons-usable materials. NRC's proposed reductions appear to go even beyond the DOE's graded safeguards standards. While the idea of material attractiveness may make sense under some circumstances, it is important to realize that attractiveness is in the eye of the beholder: that is, the concept is only meaningful in the context of the capabilities of the assumed adversary. Certain adversaries may be able to steal a MOX fuel

assembly and recover the plutonium it contains with little more difficulty than if the material were separated plutonium.

In any event, the plutonium disposition program, which has a strong symbolic component, is the wrong place to experiment with weakening security on nuclear materials. The message that the U.S. actions are signaling to Russia and the whole international community—namely, that the security risks of separated plutonium can be significantly reduced just by diluting it with uranium to below 20 percent—is poorly justified, dangerous, and inconsistent with the original purpose of the program.

Physical Protection and Material Control and Accounting Problems with the MFFF Operating License Application

In November 2006, DCS—which at the time was in the process of changing its name to Shaw AREVA MOX Services LLC—finally submitted to the NRC an operating license application, a physical protection plan (PPP) and a Fundamental Nuclear Material Control Plan (FNMCP).

In 2007, following the NRC's issuance of a notice of opportunity for a hearing on the MFFF license application (LA), the non-profit groups Nuclear Watch South (formerly GANE), Blue Ridge Environmental Defense League (BREDL), and Nuclear Information and Resource Service filed a set of contentions on safety and environmental issues.

Although the petitioners continued to have concerns about material protection, control and accounting at the facility their resources to prepare additional contentions were limited. Given the outcome of the hearing on the Construction Authorization Request for the MFFF, they did not request access to the Physical Protection Plan (PPP) or the Fundamental Nuclear Material Control Plan (FNMCP) in preparing their contentions. The PPP was classified as Secret. Even though some of the petitioners had security clearances, the NRC also would have had to determine that they had a "need to know" in order to gain access to the PPP. The FNMCP was considered to have sensitive unclassified information, so the petitioners would have had to sign a nondisclosure agreement for the protection of sensitive information to gain access to it. In either case, it would have been a significant burden for the intervenors to seek and obtain the necessary approvals in advance. Moreover, document management becomes much more challenging when classified information is involved, and innocent mistakes could result in civil or criminal penalties. But if the petitioners had requested and obtained those documents at that stage, they would have learned that their concerns during the Construction Authorization Request hearing had been validated: The MFFF design was incompatible with some of the NRC's MC&A requirements.

On June 28, 2008, the petitioners were granted a hearing by the NRC Atomic Safety and Licensing Board (ASLB). The main safety contention focused on Shaw AREVA's failure to address the safety issues associated with the protracted on-site storage of liquid radioactive waste containing high levels of alpha emitters in the event that transfer of the waste to the Waste Solidification Building were interrupted. And at the time, design work on the WSB was already delayed.

The most remarkable thing about the June 28 decision was the "concurring opinion" of the chair of the ASLB panel, Judge Michael Farrar. Judge Farrar heavily criticized the NRC staff's actions during the MOX proceeding, and wrote that "this proceeding has illustrated how the adjudicatory system established by the Commission can become contorted so as to place artificial—even unfair—barriers in the way of those citizens, organizations or governments genuinely seeking to participate in a constructive manner" (ASLB 2008). Judge Farrar was irked in particular by what he perceived as a deficient safety culture by the NRC staff in their filings and arguments. For instance, the staff had revealed that they were planning to issue an operating license for the MFFF before confirming that it had been constructed in accordance with the

approved design, which Judge Farrar called "an obviously unauthorized shortcut" (ASLB 2008).

Ultimately, Shaw AREVA sought to resolve the issues brought forth in the new contention without having to go through a hearing. It developed a plan to deal with the prolonged storage of high-alpha waste, which necessitated additional NRC staff review. The intervenors, again short of resources to retain a chemical safety expert, subsequently withdrew the contention.

However, a new issue came to the attention of the intervenors during that time, related to Shaw AREVA's proposed compliance with certain aspects of NRC's MC&A regulations in 10 CFR Part 74, as outlined in the FNMCP.

MATERIAL CONTROL AND ACCOUNTING (MC&A) AT THE MFFF

NRC's MC&A rules for facilities possessing a Category I quantity of special nuclear material (e.g. 2 kilograms or more of plutonium) include requirements for periodic physical inventories and for regular monitoring of items in storage and materials in process.

Physical inventory entails a quantitative measurement of all SNM in the plant with the objective of ensuring that all material is accounted for (within acceptable limits of measurement error), and therefore that no theft has occurred. However, physical inventory can be time-consuming and disrupt plant operations.

Prior to 1987, the MC&A regulations for Category I facilities required physical inventories every two months. In the early 1980s, the NRC raised concerns about the usefulness of physical inventories in providing timely detection of diversion of significant quantities of SNM. In 1984, the NRC pointed out that because it took about a month after initiating a physical inventory until inventory differences could be analyzed, it could be as long as 90 days before a diversion could be detected. The NRC further indicated that the usefulness of physical inventories was limited by the "difficulty in conclusively resolving large inventory differences" (NRC 1984). That is, significant amounts of SNM were often unaccounted for after physical inventories, because of measurement errors, poor accounting of material in waste streams and scrap, and the accumulation of material in process areas and piping from which it could not be easily recovered and accurately measured ("residual holdup"). A large value for "material unaccounted for" could trigger an alarm and a halt in operations until it was resolved.

To address this problem, in 1987 the NRC increased the required time between physical inventories from two months to six months (after a probationary period during plant start-up), in exchange for new requirements for monitoring of SNM in-process and SNM items in storage. These additional requirements for process and item monitoring were intended to provide near-real-time information that would improve the capability to detect abrupt losses of SNM from process equipment or storage areas, as well as help to resolve MC&A alarms quickly.

With regard to item monitoring, the 1987 rule (10 CFR §74.55) required that licensees "shall verify, on a statistical sampling basis, the presence and integrity of SSNM [strategic special nuclear materials] items," with the goal of detecting items losses of five "formula kilograms" (2 kilograms of plutonium) within specified time periods with a 99 percent power of detection. The time periods varied from three working days to 60 calendar days, depending on the nature of the item, and the storage area location. For example, SNM items stored in a "vault," a robust structure with specific regulatory requirements, would not have to be checked as frequently as items that were in less secure areas.

The intended purpose of the item monitoring provision was to help provide assurance that items have not been stolen or tampered with between the semiannual physical inventories. The plain-language understanding of the concept of verifying the presence and integrity of SSNM items on a statistical sampling basis entails a procedure where a random sample of items would be physically located, their identities checked, and their seals and overall condition inspected for potential tampering.

For groups of identical items each containing a quantity of strategic special nuclear materials comparable to a formula quantity, the statistically significant sample size would be so large that essentially all items would have to be physically located and inspected in each item monitoring period. These checks would not generally require remeasurement of the item contents and hence would not be as arduous as a full physical inventory. Nevertheless, for storage areas with large numbers of items, carrying out the required procedures at the specified frequency could be burdensome.

If the intervenors had obtained access to the 2006 FNMCP, they would have learned that Shaw AREVA was having difficulty meeting the required item monitoring timelines. The document did not demonstrate how the operator would meet NRC's regulations by conducting the required item monitoring checks within 30 or 60 days. Instead, Shaw AREVA proposed to conduct checks within intervals as long as 180 days. Given that this was the same duration as the period between physical inventories, it would have defeated the purpose of the item monitoring checks to provide assurances in between inventories. Shaw AREVA justified not complying with the regulation by claiming that "covert insider theft or diversion of PuO_2 from this hardened and normally inaccessible (by humans) location is not deemed as a credible scenario" (NWS 2013, 8).

Even the NRC staff, which had shown so little interest in MC&A during the construction authorization stage, found this proposal too much to swallow and questioned the 180-day schedule. An application could not simply choose to ignore a regulatory requirement. Applicants can, however, apply for exemptions from regulations, and the NRC can grant such exemptions if it determines that they are "authorized by law" and meet a number of additional criteria. Ultimately, in December 2009, Shaw AREVA decided to solve the problem by filing an exemption request, not only from the required timelines for item monitoring but also from certain requirements for process monitoring (NRC 2010b, 9). With regard to item monitoring, Shaw AREVA requested that the required time period be extended from 30 days to 180 days for certain items and from 60 days to 180 days for other items (NWS 2013, 8–9).

Shaw AREVA stated that it needed the exemption because it could not satisfy the regulatory time limits "due to the size of the MFFF's four storage areas, inaccessibility, and the time it takes for the automated equipment to perform the item monitoring …" (NWS 2013, 9). Put another way, it could not meet the regulations because they were incompatible with fundamental design features of the facility. Yet during the Construction Authorization Request phase, in its 2002 draft Safety Evaluation Report, the NRC staff had concluded that

> the applicant provided adequate commitments and goals for the design basis as it applies to material control and accounting (MC&A), and that these commitments and goals should result in an adequate MC&A program and an acceptable FNMC Plan that will meet or exceed the regulatory acceptance criteria … As a result, the staff determined that the applicant meets the requirements in the area of MC&A to approve construction of the facility under 10 CFR Part 70. (NRC 2002a, 13.2-2)

Clearly the NRC was wrong here in 2002, given Shaw AREVA's subsequent (2009) need for an exemption in order to meet the item monitoring requirements.

The NRC staff had missed early warning signs that DCS/Shaw AREVA had a problem. In the preliminary program abstract for a talk at the 2002 Institute of Nuclear Materials Management (INMM) conference, entitled "Implementation of NRC MC&A Reform Amendment to the MOX Fuel Fabrication Facility," Kenneth Bristol, an employee of Nuclear Fuel Services who was on loan to DCS, wrote that

> the MFFF design is for a highly automated, computer controlled facility with the SSNM

> processed and stored within containment. In contrast, the two uranium licensees [that currently meet the regulations] are not highly automated and store material in walk in vaults. Features of the … rule, including the process monitoring and item monitoring requirements, were influenced by the physical layouts and the operations of the two uranium licensees. This has resulted in some challenges in the development of a MC&A program for the MFFF. (INMM 2002)

Unfortunately, Bristol's talk was cancelled and he never submitted a final paper for the proceedings. If he had, perhaps the NRC would have become aware of and paid more attention to the "challenges" in MC&A program development before it allowed construction to proceed.

The intervenors in the MFFF operating license proceeding submitted a new contention in early 2010 opposing Shaw AREVA's exemption from the item monitoring requirements. (They did not have the time or resources to also challenge the requested exemptions from process monitoring requirements.)

In response, Shaw AREVA withdrew the request and said it had determined that it didn't need the exemption after all. In May 2010 it submitted a revised FNMCP that proposed a new approach to meeting the regulations.

This new approach would rely on the automated inventory management and process control systems at the plant to meet the regulatory requirements for "verifying the presence and integrity" of special nuclear material items. The MFFF was designed for extensive use of automated process controls. A system called the Manufacturing and Management Information System (MMIS) would be used to monitor and record the locations and movements of individual items throughout the facility. Shaw AREVA called the data stored in the MMIS the "book inventory," because it represented where all material is supposed to be. At any time, operators could use the MMIS to generate a "Perpetual Inventory Report," providing a snapshot of the book inventory. Another system, a network of computers called Programmable Logic Controllers (PLCs), would be used to actually control the item movements. The PLCs are described in general terms in the Construction Authorization Request, which says that each process unit "is controlled by one or several PLCs associated with a monitoring workstation … .All units are operated in an automatic mode. The operator may also intercede via a manual mode in which the interlocks are active in case of trouble in the automatic mode or for maintenance operations." (DCS 2002, 11.3-40)

Shaw AREVA proposed to "verify" the presence of all SNM items every day by comparing the data in the Perpetual Inventory Report with the data stored in the PLCs. Shaw AREVA maintained that the data within the PLCs represented the actual locations of all SNM items within the facility, so that a comparison of the expected locations of items (the Perpetual Inventory Report) with their actual locations (PLC data) would serve to verify the presence of the items (ASLB 2014, 20). Shaw AREVA asserted that this procedure would verify the presence of 100 percent of the items every day, therefore exceeding the regulatory requirement of 99 percent verification within three to 60 days.

In other words, Shaw AREVA proposed to rely entirely on the data within computer systems to "verify" the presence of SNM items. It would not perform actual physical verifications in the traditional manner, by selecting items to verify, removing them from storage, and inspecting them to ensure that they are indeed the correct items. Fundamentally, the approach assumes that the data stored in the PLCs is a 100 percent accurate representation of the actual locations of items, and that the data in the MMIS is a 100 percent accurate representation of the book inventory. And it assumes that the two systems (and their operators) are completely independent, so that a comparison of the data sets will provide meaningful verification.

But, of course, no set of computer data can be relied on to be 100 percent accurate at all times. Software and hardware glitches do occur. (Siemens, a major manufacturer of PLCs, lists "difficulty in finding errors" as one of the disadvantages of PLC control systems.) However, the larger concern is the

potential for deliberate corruption of the data in order to facilitate undetected diversions of material. If PLC data were altered to indicate that a particular item had not been moved from a storage location when in fact it was no longer there, or if the identities of two items were switched in the system, a theft could remain undetected until plant operators needed physical access to the item, which could be a matter of weeks or longer. Although the normal operation of the processes is automatic, the PLCs are given instructions by operators in various control rooms, and the PLCs can also be operated manually. Shaw AREVA maintained that any attempt to falsify data or circumvent procedures to compromise the integrity of the MMIS/PLC verification, including collusion between operators, would be deterred or detected by physical protection features.

NRC's item monitoring regulations do not require only verification of the physical presence of items, but also verification of their integrity: that is, an inspection to ensure that items have not been tampered with. Shaw AREVA understood that the computer-based verification concept could not achieve this, so it proposed a separate approach to verifying item integrity by establishing what it called "containment boundaries." Containment boundaries would be designated at item storage areas, and entry points at the boundaries would be sealed. Plant staff would inspect the boundary seals every day to ensure they had not been breached. The applicant argued that if the boundary of a storage area had not been breached, then one could conclude that all items within the boundary were intact. But there were problems with this concept too. For one thing, if the boundary were found to be breached, it would trigger an alarm that would likely require an inventory of the entire storage area to resolve.[13] This would contravene one of the main objectives of an MC&A system: to localize material losses in time and space.

[13] Resolution of an alarm means that if SNM appears to go missing, the operator needs to determine whether the material has actually been stolen or if there is another explanation.

Based on these issues, the intervenors then filed three new contentions challenging the revised FNMCP. The first, Contention 9, challenged the MMIS/PLC data comparison approach for item monitoring.

The issues raised by the applicant's original exemption request raised other questions. For example, the NRC also required fuel cycle facilities to have a plan to resolve MC&A alarms. Although time is critical in such a situation—after all, a knowledgeable adversary may be able to build a crude nuclear bomb in as little as a matter of days once it acquires sufficient material—NRC regulations do not specify a set time period to resolve alarms. NRC's guidance specifies that such alarms should be resolved "normally" within three days. However, since Shaw AREVA had said that it would take up to 180 days to physically verify all items in certain storage areas, it seemed improbable that an alarm could be resolved in only three days if it necessitated taking an inventory of one of those areas. Contention 10 challenged the applicant's ability to comply with its alarm resolution commitments.

A related provision requires applicants to "provide an ability to rapidly assess the validity of alleged thefts" (10 CFR §74.57(e)). Such a capability is critical to a good MC&A program. A mere allegation of theft of special nuclear material can be an effective terror instrument if its credibility cannot be swiftly disproven. if someone called in a claim that terrorists had built a nuclear device with plutonium stolen from the MFFF and threatened to detonate the bomb in New York City if their demands were not met in 24 hours, officials would want to know as soon as possible if the material were indeed missing. NRC's guidance defines "rapid assessment" as a capability to locate any specific item stored in a vault within 8 hours, and to verify the presence of all items in a vault within 72 hours. But again, given the length of time necessary to check all SNM items in certain storage areas at the MFFF, it was unclear Shaw AREVA could meet those timelines. (And if assessment of the threat required a partial or full physical inventory, the task could take far longer.) Contention 11 challenged the

applicant's ability to meet its regulatory commitment to rapidly assess the validity of alleged thefts.

The NRC staff accepted Shaw AREVA's revised FNMCP and MC&A approach in its Final Safety Evaluation Report, and sided with the applicant in opposing the new contentions. However, neither Shaw AREVA nor the NRC staff opposed the contentions on their merits, and focused instead on a procedural technicality: whether they had been filed soon enough. (Shaw AREVA argued that the contentions were more than three years too late, as the intervenors could have known about the item monitoring problem back in 2006 if they had requested access to the FNMCP when it was first submitted. The NRC staff, on the other hand, said the contentions were 10 days late.) But on April 1, 2011, the Atomic Safety and Licensing Board admitted the three contentions. Although it was a 2-1 vote, the dissenting judge, Lawrence McDade, did not challenge their merits, but accepted the applicant's argument that they were too late. However, the judges agreed that the three contentions raised "significant public safety and national security issues" and even if they had been untimely, the ASLB would itself have referred the issue to the NRC commissioners for review—an unusual occurrence.

The first hearing, which was closed to the public, took place in March 2012. Shaw AREVA's position on Contention 9, as characterized by the ASLB, can be summarized as

> By relying on the data in the MMIS and the PLCs, rather than conducting actual physical retrieval and inspection of items to achieve the required statistical sampling, Applicant will satisfy the NRC's requirements for item monitoring. (ASLB 2014, 30)

As for concerns that the data itself could be manipulated or the automated systems bypassed, Shaw AREVA argued that the "robust" physical protection measures in the facility would effectively prevent such unauthorized activities.

The intervenors maintained that "verification of presence and integrity" required sampling, physically locating and inspecting items, as facilities had implemented the rule in the past. The intervenors pointed out that there was no quantitative basis for the applicant's underlying assumption that the data within the MMIS and PLC systems would be 100 percent accurate. At a minimum, they asserted, the applicant should be required to provide a plan to verify that the data in the MMIS and PLCs was indeed accurate, and that the data in the PLCs was a perfect representation of the location of all items in the plant. The intervenors provided evidence, culled from the applicant's internal e-mails and other company documents that were obtained under discovery, that

> members of [the] Applicant's own staff believed that to provide the required assurance that the MMIS and PLC data represent 'an accurate reflection of the location of the items,' it would be necessary to periodically physically validate the data provided by the system. This would entail comparing the data with the actual presence and integrity of items in the storage areas at the plant as verified through direct inspection. (ASLB 2014, 26, fn. 101; 27–28)

However, the FNMCP contained no plan for validation of the computer system data, and Shaw AREVA maintained that it did not need to produce one until the facility was nearing startup. The applicant relied on similar arguments in its position on Contention 11. It asserted that it could use the MMIS and PLC data to meet the timelines for locating items to rapidly assess alleged thefts; that is, it was sufficient simply to rely on the computer data to verify that an item was in the right place.

In response, the intervenors postulated a scenario where the theft allegation included a claim that the adversary had tampered with the computer data to cover up the theft. Such a claim would call into question the applicant's validation approach using the MMIS and PLC data unless it could be

disproven. The plant operator would either have to prove that the computer systems had not been compromised or it would have to verify that no material in fact had been stolen by conducting a physical inventory. Both of those pathways would be time-consuming, but the applicant had not shown it could complete either of them within the time commitments (NWS 2013, 38).

This question was only one aspect of the larger issue of cybersecurity that came up repeatedly during the proceeding. The nuclear industry, like other sectors of the economy, has been too slow in dealing with rapidly evolving cyberthreats. While the NRC has issued regulations specifying how nuclear power plants should be protected against cyberattacks, it has not yet issued such rules for fuel cycle facilities like the MFFF. Therefore, the NRC has no standards for the procedures to protect the computer systems that Shaw AREVA proposed to monitor items and other crucial MC&A and physical protection functions. Because the NRC had no requirements, the intervenors could not raise issues related to those procedures. In effect, the applicant was proposing a system for item monitoring much more vulnerable to cyberattack than a system involving direct physical inspection, but the NRC had no cybersecurity standards in place to provide confidence that the systems would be adequately protected.

This is not to say the facility would be completely defenseless in the face of cyberattack. As a DOE-owned facility, the MFFF was obligated to meet the DOE's cybersecurity standards. However, the NRC had no authority to review the DOE standards and simply had to assume that they were adequate. This was another area that could have benefited from a DOE-NRC memorandum of understanding, but the agencies had not concluded one.

The ASLB did not render a quick judgment after the March 2012 hearing. In a June 2012 order that reflected the arguments of the intervenors, the judges requested that the applicant provide a substantial amount of additional information "relating to system data verification and reliability" (ASLB 2014, 10). In the order, the ASLB stated that "the method Applicant intends to use to verify the accuracy of the MMIS and PLC data was not evident," and asked the applicant to provide a document "setting forth the approach to and criteria underlying its planned process for verifying the accuracy of the data generated by the PLCs and MMIS throughout the life of the MOX facility" (ASLB 2014, 61).

This request was a partial victory for the intervenors, as the ASLB appeared to agree that the applicant's plan was insufficient without an additional procedure for validating the MMIS and PLC data. However, the intervenors didn't concede that such a procedure could fix the plan's problems.

In the June 2012 order, the ASLB also expressed its concern "about Applicant's ability to assess an alarm within the timelines," and asked the applicant to provide a "contingency plan … for assessing, within the 8 and 72-hour timeframes … an external alarm that includes an assertion that an external entity compromised the MMIS and PLC systems remotely and maliciously changed their respective data" (ASLB 2014, 94, fn.397). Again, this was a victory for the intervenors.

In October 2012, the applicant complied with the ASLB's order by providing a procedure for validating the MMIS and PLC data. It also provided a list of additional steps it would take in order to assess an allegation that the MMIS or PLCs were compromised, although it did not commit to completing those steps within eight or even 72 hours, and maintained that it was under no obligation to do so (ASLB 2014, 94–95).
It appears that the ASLB may well have denied the operating license if it had issued a decision without supplementing the hearing record with the additional information. However, it gave Shaw AREVA ample opportunity to address its concerns before that point was reached. The ASLB then scheduled a second evidentiary hearing for May 2013 to address the new information provided by the applicant. By the time the hearing convened, one of the three judges, Judge Lawrence McDade, had withdrawn and was replaced by Judge Paul Abramson. In February 2014, the ASLB issued a split decision in the case. Judge Abramson and

Judge Nicholas Trikouros ruled in favor of the applicant, while Judge Farrar issued a dissent.

Judges Abramson and Trikouros accepted the applicant's computer-based item monitoring plan. They ruled that the NRC's item monitoring regulations were "performance-based" and did not require physical inspection of items. To them, the fact that the regulations were written at a time when item monitoring by necessity involved pulling cans and checking labels was irrelevant and did not exclude the use of new technologies. However, they agreed with the intervenors that "consideration of the quantitative accuracy of the MMIS/PLC computer systems data must be considered in determining whether or not requirements … are satisfied by Applicant's plans" (ASLB 2014, 52). Nonetheless, the two judges in the majority accepted the additional procedures that the applicant had provided to verify the MMIS/PLC data as providing "reasonable assurance" (ASLB 2014, 59).

On the cybersecurity question, Judges Abramson and Trikouros pointed out that Shaw AREVA had committed to meeting the DOE's cybersecurity standards, and said that the question whether the NRC may license the MFFF without having its own cybersecurity standards for fuel cycle facilities "is beyond the scope of the proceeding" (ASLB 2014, 68–70). With regard to Contention 11, they said that "NRC regulations do not require the applicant to show the ability to rapidly assess the validity of alleged thefts in every conceivable theft scenario,"—that is, even if there were an allegation of data tampering—but also said they were satisfied that the applicant would take "whatever actions are appropriate and necessary to evaluate the theft as it is alleged." It also concluded that the applicant had the capability to meet the 8- and 72-hour timeline requirements, glossing over the applicant's own refusal to commit to resolving allegations of compromised data within those timelines (ASLB 2014, 92–96).

Judge Farrar's dissent focused primarily on cybersecurity. He pointed out that Shaw AREVA "does not have a cyber-security system in place …" yet it argues that "cyber-security measures can eventually be counted on to assure the non-corruption of those data systems." His response:

> We don't know that. Perhaps there will come a time when it will be known. But … one could justifiably conclude that the Applicant … is entitled at this stage to, at most, a Scottish verdict of 'not proven.' (ASLB 2014, 103)

Judge Farrar objected to the characterization of the cybersecurity matter as a mere "post-licensing compliance item," arguing that the adequacy of the MC&A system was "so fundamental … it deserves to be resolved—along with its cyber-security underpinnings—*prior* to the grant of a license." He did not agree that the lack of NRC cybersecurity regulations for fuel cycle facilities meant cybersecurity issues were outside of the scope of the hearing, since the applicant itself had taken credit for its cybersecurity program in defending the integrity of the MFFF's computer data. And he pointed out that although the DOE was a federal agency, it "stands in the shoes of a mere Applicant here" and thus its own cybersecurity standards would remain subject to NRC scrutiny, "absent a … Memorandum of Understanding or similar agreement with DOE expressing a willingness by [NRC] to accept DOE's work without review" (ASLB 2014, 105).

Judge Farrar concluded that "whether and how all the facility's infrastructure and security will come together to guard its raw materials against diversion is to this day an open issue, and today's decision should not be taken as affording any assurances in that regard" (ASLB 2014, 110).

Based on the split decision, the intervenors filed an appeal to the NRC commissioners, who act as an appellate court with regard to ASLB decisions. As of this writing (December 2014), the Commission has not issued its decision.

PHYSICAL PROTECTION

Shaw AREVA's material control and accounting (MC&A) plan took a great deal of credit for the

physical protection system at the MFFF to protect against unauthorized access to nuclear materials and computer data. But were the MFFF's physical protection measures themselves adequate? There is little that can be said publicly about this, but there are a few open-source clues that shed a little light on the security approach for the MFFF.

One of the overarching questions about security at the MFFF is what the applicable security requirements are. The NRC has said that the MFFF security plan will meet the criteria for both the NRC's and the DOE's design basis threat (DBT). But verifying this might cause problems because the NRC and the DOE design basis threats are different. In particular, according to a 2007 analysis by the Government Accountability Office, "the DOE Category I DBT is based on a broader view of the domestic threat to nuclear facilities than the NRC DBT" (GAO 2007). It is unclear how defense against both DBTs would be established and demonstrated.[14] The GAO has pointed out that the DOE and the NRC have not fully cooperated on sharing of classified information related to potential misuse of Category I materials. And as of this writing, the NRC and DOE still have yet to conclude a Memorandum of Understanding that would address the coordination of the two agencies with regard to physical protection at the MFFF.

Compounding confusion over the applicable security requirements, Shaw AREVA, in submitting its Physical Protection Plan to the NRC, "requested the use of alternate methods for numerous areas of the MFFF" (NRC 2010a, 13-2). The NRC's rules allow applicants to implement alternatives to its prescriptive security requirements if it concludes that the overall level of security performance is not reduced. For the MFFF, Shaw AREVA referenced a 2008 "Final Design Vulnerability Assessment Study" and a "Penetration Delay Analysis" of the MFFF barriers to justify its request for alternative measures. (Of course, the reference to a "final design" does not provide confidence, given how immature the design actually was at the time.)

The NRC approved the alternative measures that DCS/Shaw AREVA proposed in its 2010 Final Safety Evaluation Report, but neither the measures, nor their justifications, are public. However, it is public knowledge that the NRC assessed them against standards that predate the 9/11 attacks, and the NRC will grant an operating license to Shaw AREVA before it meets the post-9/11 requirements. Thus there is good reason to question the adequacy of the security regime for the MFFF in today's threat environment, whether or not alternate measures are used.

In March 2010, the NRC staff sent Shaw AREVA a set of questions called a "request for additional information," on its Physical Protection Plan. The questions are public. From this document, a number of facts, as of that date, can be gleaned (NRC 2010c):

- No Memorandum of Understanding between Shaw AREVA and the Savannah River Site regarding supplemental security response had been established.
- There were no contingency plans in the event that SRS protective force personnel were unavailable.
- One of the "alternate measures" that the Physical Protection Plan puts forward appears to be in lieu of the NRC's requirement for a 5-person minimum tactical response team (as Duke Energy also requested at Catawba).
- The Physical Protection Plan did not accurately describe the NRC Design Basis Threat.
- The MFFF final design vulnerability assessment in 2008 was performed using

[14] It is important to note that the DOE's security requirements themselves are moving targets. The DOE DBT was upgraded in 2003 and again in 2005. However, in 2008, in response to concerns about the security costs, DOE introduced a "graded security policy" that halted efforts to implement the 2005 DBT. Today, it is not publicly known whether the security standards that were used to assess the MFFF design are still applicable, and whether GAO's 2007 conclusion about the relationship between the DOE and NRC's security standards are still valid.

the DOE DBT, not the NRC DBT (and see footnote 14).

Another security feature that can be discerned from the MFFF license application and other public documents is a structure called a "gabion wall" surrounding the MFFF MOX Fuel Fabrication Building (Shaw AREVA 2006, 1-3). According to the license application, the exterior of the building (walls and roof) in surrounded by another reinforced concrete wall 3 feet away and attached to it with beams. The space in between the two walls is filled with "gabion stone." Although the type of gabion stone is not specified in the public documents, gabion stone is typically composed of small rocks or soil. The gabion wall is an ancient technology that has both civilian and military uses. According to Wikipedia, "Today, gabions are often used to protect forward operating bases against explosive, fragmentary, indirect fires such as mortar or artillery fire" (Wikipedia 2014). NRC's security regulations make no mention of gabion walls.

The End of MOX and the Promise of Alternatives

Although it is a near certainty that the NRC will issue an operating license for the MFFF, it is far from certain that the MFFF will ever operate. Not long after the ASLB issued its initial decision granting the license, the DOE released its FY 2015 budget request, which stated that "as part of an ongoing analysis of options to dispose of U.S. surplus plutonium, it has become apparent that the Mixed Oxide (MOX) Fuel Fabrication Facility will be significantly more expensive than anticipated, and therefore, the Budget Request places the MOX Facility in cold stand-by while the Department evaluates plutonium disposition options" (DOE 2014c, 10).

Putting the MFFF project into cold standby, however, is more difficult than it sounds. The states of South Carolina and Georgia and their Congressional delegations are determined to keep construction going and avoid layoffs. An attempt by the DOE to initiate cold standby in spring 2014 ran into trouble when the state of South Carolina sued, claiming that the DOE could not legally divert funds appropriated for construction in FY 2014 to other uses. The state dropped the lawsuit when DOE announced it would continue construction until the end of the fiscal year. Meanwhile, both the House and Senate Armed Services committees passed authorizing bills for FY 2015 that prohibited the DOE from spending money on standby activities, and if a Continuing Resolution for FY 2015 appropriations is passed, as seems likely, another year of construction funding (that DOE cannot refuse) will be provided.

Accordingly, Shaw AREVA continues construction on the MFFF, including installation of process piping, gloveboxes, ventilation systems and electrical equipment (NRC 2014a). This is a wasteful endeavor, because as more equipment specific to the MOX fabrication process is installed, the cost and difficulty of later repurposing the facility for other uses, such as non-MOX disposition alternatives, will increase. As MOX supporters likely know, continued expenditure of funds to construct a facility that the DOE no longer wants to finish will make it harder politically for the DOE to justify cancelling the project and selecting an alternative, regardless of the potential cost savings.

This is unfortunate, but it is typical of the way the disposition program has been managed from the outset. At numerous junctures, the DOE and Congress pressed on with the program without resolving important questions, only to have to backtrack later. This shortsighted planning contributed in no small part to the costs and delays experienced by the program. The current situation presents perhaps the best opportunity to finally get the program back on track, and it would be a shame if this opportunity were also missed.

It is clear that any credible alternative path forward will have to be far less expensive and less risky than the current MOX program. At the outset of the plutonium disposition program, analyses showed that immobilization approaches would generally be cheaper, quicker to implement and less complex than the MOX route. This comparison was most

most straightforward for the option of homogenous immobilization at the Defense Waste Processing Facility at SRS, which was ruled out early in the decision process. However, it still held true for options like can-in-canister, where a separate immobilization facility was needed, because the immobilization process would be less involved than MOX fabrication.

First of all, unlike the MOX plant, an immobilization plant would likely require only a small aqueous processing capability (or even none at all). The feedstock purity requirements for producing immobilized plutonium waste forms of satisfactory quality would be far less exacting than the feedstock requirements for fabricating MOX fuel for use in reactors. The bulk of the excess plutonium inventory has impurity levels well within the acceptance specifications for the immobilization plant that had been proposed; dry blending strategies would be used to dilute the impurities in most of the remaining materials.

The fact that the immobilization plant wouldn't need an extensive aqueous processing capability gives it a number of advantages over the MFFF. First, the facility would not need the expanded footprint or the equipment associated with the aqueous polishing and AFS alternate feedstock process areas. Second, it would not need storage and treatment for liquid "high-alpha" radioactive waste. Thus, the DOE would not need to finish and operate the Waste Solidification Building, nor deal with the disposition of the additional volume of waste generated. Third, eliminating aqueous processing would significantly reduce cost: The DOE has estimated the capital cost of the aqueous processing lines alone to be approximately a third of the capital cost of the entire MOX project (DOE 2014c, C-E-10).

Even the more elaborate process of can-in-canister immobilization would require fewer steps than the process to transform purified plutonium oxide into MOX fuel pellets, because of the additional steps needed to meet the tight tolerances for MOX pellet size and shape. For the baseline approach, which would use a cold press and sinter process similar to MOX fuel pellet production, the finished product also would not have to be ground like MOX pellets, thereby avoiding the generation of plutonium-laden scrap materials that present challenges both for waste management and material control and accounting. Moreover, the process pressures and temperatures needed for the ceramic immobilization process would be less demanding than the equivalent process for fabricating MOX pellets, resulting in less equipment wear (Brummond, Armantrout, and Maddux 1998). Lower pressures and temperatures would also be associated with lower risks for certain accident scenarios.

One alternative to the immobilization baseline could in principle simplify the process even further: the use of hot isostatic pressing or hot uniaxial pressing instead of cold press and sinter. In these processes, the precursor powders are pressed and solidified in one step, eliminating the need for a separate sintering step. (The DOE considered these processes for ceramic immobilization before choosing cold press and sinter, which had yielded good results in testing.)

Finally, at the end of the production process for either the immobilization plant or the MOX plant, the plutonium-containing items (cans in the former case, MOX fuel assemblies in the latter) must be transported elsewhere and undergo another step before disposition is complete and the spent fuel standard is achieved. For immobilization, this would entail shipment only within the Savannah River Site itself to the Defense Waste Processing Facility, where the can-in-canister assemblies would be filled with radioactive glass, and stored on site. In contrast, MOX fuel assemblies would have to be transported off-site—perhaps even to different states—to the commercial reactors that had agreed to accept the fuel, where they would be stored until they could be loaded into the reactor cores and irradiated for a certain number of cycles. Assuming the DOE were able to identify reactors willing to accept the MOX fuel, plant owners would need to obtain license amendments from the NRC, make physical modifications to their reactors to accept the new fuel, and upgrade security (although not all the way to Category I as discussed

above). They might also need to adjust operating cycles and spent fuel storage procedures. Thus compared to the immobilization approach, the final step in the MOX approach would present many more safety, security and operational challenges.

Today the considerations are somewhat different. The early analyses that indicated immobilization had cost and schedule advantages compared to the MOX program must be viewed in the context of the DOE's dismal performance over the last 20 years. The DOE's cost and schedule estimates based on paper studies, incomplete designs and unrealistic timelines for resolving technical issues have been thoroughly discredited. For an option to be acceptable to Congress, any non-reactor alternative should be clearly and significantly cheaper going forward and have a more certain success path than the MOX program.

An alternative which would be clearly cheaper is downblending and disposal of plutonium in the Waste Isolation Pilot Plant (WIPP) in New Mexico. WIPP is the only licensed deep geologic repository for radioactive waste in the United States, and it has been already used to dispose of an appreciable quantity (several metric tons) of excess plutonium underground. This gives options that utilize WIPP for ultimate disposal an advantage over those that had counted on Yucca Mountain being available sometime in the next few decades. However, WIPP has been shut down since a February 14, 2014 accident that resulted in plutonium contamination of the repository as well as a release to the environment. Although DOE remains optimistic that WIPP will resume operations within a few years, its predictions have low confidence because the root cause of the accident is not yet understood. Therefore, the success path of this approach is far less certain today than it was before the accident.

Any new disposition alternative likely would have to leverage the DOE's existing infrastructure to the greatest extent possible, given the prohibitive capital cost of greenfield facilities. The DOE's infrastructure at SRS includes the K-Area Complex, H-Canyon/HB-Line, DWPF, and even the partially built MFFF and WSB. But the inherent advantage in using existing infrastructure would be diminished to the extent that significant upgrades are needed to maintain high levels of safety and security, or the extent to which the project extends the lives of facilities that were scheduled for shutdown.

Among the issues that need to be considered are these:

- The K-Area facilities would need significant upgrades of ventilation and other safety systems in order to handle a high plutonium throughput.
- H-Canyon is an aging Cold War-era facility that chalks up a steady stream of safety violations; it is currently slated to be shut down in 2019 (although SRS boosters continually search for new missions to justify extending its lifetime). In addition, H-Canyon/HB-Line are DOE Category II facilities, which limits the amount of plutonium and highly enriched uranium they may process at any one time to levels below what would be practical for the plutonium disposition mission. Addressing this issue would require upgrading H-Canyon/HB-Line to Category I security. (Extending the current practice of introducing waivers to allow Category II facilities to temporarily handle Category I quantities of special nuclear materials would probably be neither adequate nor efficient. In addition, HB-Line may already be operating on a waiver from some Category II requirements.) Even with the security constraint removed, the throughputs of H-Canyon/HB-Line are limited and disposition would be relatively slow.
- The Defense Waste Processing Facility is currently scheduled to complete its mission to vitrify the remaining SRS high-level radioactive wastes by FY 2040 (Chew and Hamm 2014, 26). If that date were postponed in order to accommodate a plutonium immobilization program it would interfere with SRS's long-term

cleanup plan of the HLW tank farms and extend the period of time in which the HLW would exist in a more vulnerable liquid state. On the other hand, the vitrification program has already experienced significant delays as the result of difficulties in pretreating the HLW to separate and concentrate the highly radioactive salt fraction, which includes most of the cesium-137 in the HLW. As a result, under the current schedule (which may well slip again) DWPF will not begin producing canisters with high levels of cesium-137 until 2018.

- DWPF is a Category III facility and is limited in the amounts and types of plutonium that it can receive. Under the baseline can-in-canister program, each can would contain less than 10 weight-percent plutonium and would be Attractiveness level D when transferred to DWPF. However, a fully loaded canister with 28 kg of plutonium would be a Category II item, and SRS would have to address this issue by requiring either security upgrades, temporary compensatory measures, or numerous variances.
- The Waste Solidification Building could be repurposed for use as a plutonium immobilization facility. However, it has minimal security as currently designed and would require substantial upgrades in order to process Category I quantities of plutonium.

Nuclear Material Security and the Spent Fuel Standard

As the the DOE analyzes the alternatives to MOX, it should also reevaluate the original assumptions from the mid-1990s underlying its requirements for plutonium disposition, given the major global political and economic shifts that have occurred. A critical consideration is whether it is still appropriate to meet the spent fuel standard as originally defined by the National Academy of Sciences in 1994, interpreted by the DOE and incorporated into the 2000 Plutonium Management and Disposition Agreement with Russia. There are two aspects of this question. The first is whether there are ways of disposing of plutonium that would achieve the underlying objectives of the spent fuel standard without meeting the entire checklist of prescriptive criteria. The second is whether the spent fuel standard itself, with its dual goals of significantly reducing the risk of subnational theft and the risk of rearmament, is still the right standard.

Harvard professor Matthew Bunn, who served as the study director for the NAS plutonium disposition reports, recently expressed his view on this question, considering that the "loose nukes" problem was much more severe in 1994, and that the possibility that Russia would collapse was less of a concern today than when the studies were performed (Bunn 2014). Moreover, the plutonium stocks that have been designated for disposition are some of the best-secured materials in either the U.S. or Russia, so they do not present an urgent security problem. Professor Bunn also said that at the time of the NAS study, it seemed like deep bilateral nuclear arms reductions with far-reaching transparency and verification measures were a possibility in the near future. Also, the NAS estimated the cost of a disposition program to achieve the spent fuel standard to be around $1 billion (in 2014 dollars), which has proven to be too low by a considerable factor. Professor Bunn said that governments should take a "risk-informed" approach to the spent fuel standard, and that if alternatives exist that are significantly cheaper and "could achieve a substantial portion of the disposition effort's objectives" that they might be worth pursuing. He concluded that "meeting 100 percent of the spent fuel standard" is not essential if the additional risk was insignificant (Bunn 2014).

Such an approach would increase the range of potential alternatives to MOX and is well worth considering. In order to figure out how to move away from the spent fuel standard, it's necessary to understand the spent fuel standard in more detail.

As defined by the NAS, meeting the spent fuel standard meant that excess plutonium would be rendered "roughly as inaccessible for weapons use as the much larger and growing stock of plutonium in civilian spent fuel" (NAS 1994). The National Academy emphasized that the spent fuel standard was rooted in the intrinsic physical properties of the items containing plutonium, and not in extrinsic ones such as security and institutional controls.

The chief material properties relevant to the comparative inaccessibility of disposition forms and civilian spent fuel are the mass and bulk of the item, the plutonium dilution, and the "self-

protection"—that is, the intensity of external radiation from the fission products in spent fuel, primarily cesium-137. The NAS regarded the isotopic composition of the plutonium after disposition as a much less important characteristic. This was the right call, given that irradiation to alter the plutonium's isotopic composition from weapons-grade to reactor-grade would have no significant impact on the ability of the U.S. and Russia to utilize the material for weapons, nor on the ability of terrorists to build a crude nuclear device. (Immobilization would not change the isotopic composition of the plutonium from weapons-grade unless it could be blended with a significant amount of separated reactor-grade plutonium—more than the U.S. has available.) Consequently, the NAS judged that both spent light-water reactor MOX fuel, and plutonium homogenously immobilized in high-level waste canisters, met the spent fuel standard.

The presence of a substantial radiation barrier stands out as one of the defining characteristics of the spent fuel standard in the 1994 report. Such a barrier would preclude processing of the plutonium disposition forms in an unshielded glovebox operation that would be relatively cheap to do and difficult to detect. The prevailing view at that time was summed up in a statement from a 1998 report by DOE contractor Kaiser-Hill Company LLC: "it has been clearly shown that no material form containing plutonium is truly 'proliferation-proof'; experienced plutonium chemist [sic] have demonstrated they can recover plutonium from any form with the only issue being time and resources necessary to accomplish the end objective" (Kaiser-Hill 1998, 12).

This statement of course is also true for plutonium mixed with highly radioactive fission products; however, the NAS gave significant weight to the differences between a reprocessing facility needed to separate plutonium from self-protecting, highly radioactive spent fuel, and a chemical processing facility that could be used to separate plutonium from any material that was not highly radioactive.

The 2000 PMDA incorporated a definition of the radiation barrier for disposition based on U.S. and international standards: a dose rate of at least 1 Sievert per hour at 1 meter from the accessible surface at the centerline at 30 years after production. Under this criterion, disposition waste forms would remain self-protecting for 30 years.

In 2000, the NAS undertook a review of the spent fuel standard concept in part to address the concerns of critics who argued that the DOE's preferred immobilization alternative, "can-in-canister," did not meet the spent fuel standard. Analysts from Sandia National Laboratories had argued that it would be possible for thieves to rapidly disassemble the waste canisters with cutting tools or explosives to separate the plutonium-rich, portable and non-self-protecting cans from the self-protecting glass matrix (NAS 2000).

In its review, the NAS judged that the most important barriers to subnational groups or to proliferant states were the low concentration of plutonium in an individual item (e.g. a spent fuel assembly or canister of immobilized plutonium), the difficulty of partly separating plutonium on site from bulk materials (e.g. the radioactive glass filling the canisters in the can-in-canister option), the technical difficulty of dissolution and separation once the cans were acquired, and the quantity of material needed. In contrast to the 1994 study, this assessment by the NAS rated the radiation hazard as only moderately important, since the external radiation doses, even from relatively young spent fuel assemblies, would not be immediately disabling and might not be sufficient to deter suicidal adversaries.

Even so, the NAS concluded in 2000 that additional research and testing were needed to determine whether the can-in-canister approach met the spent fuel standard. The report was a blow to supporters of immobilization, given that the recommended testing would be costly and could delay implementation of the option. The testing was never done and the issue was left unresolved when the United States cancelled the immobilization program in 2002.

Meanwhile, as various interested parties were debating whether terrorists could blow up canisters filled with high-level radioactive waste and steal plutonium cans without killing themselves in the process, the DOE was disposing of several metric tons of excess plutonium through a pathway that the NAS had judged did not meet the spent fuel standard: direct disposal underground in WIPP without any added radiation barrier. The DOE had determined that this was permissible under its procedures because the plutonium was converted to a form that the DOE considered so unattractive that it could terminate safeguards on it (that is, it could remove the material from the inventory subject to its security and material accounting programs). This apparent inconsistency (and no one could ever accuse the DOE of acting with foolish consistency) stems from the fact that the relationship between the spent fuel standard and the attractiveness levels that determine DOE graded safeguards was never clearly defined. But the two standards have different purposes: while DOE safeguards are aimed at subnational threats, the spent fuel standard was also meant to address the risk of national reuse.

In 1998, the Rocky Flats Environmental Technology Site wanted to quickly get rid of about 3 metric tons of excess plutonium in the form of pyrochemical salts, incinerator ash, and other residues by shipping it to WIPP. Despite being called "residues," much of this material was rich in plutonium and fairly easy to process. DOE standards require that domestic safeguards—that is, physical protection and material control and accounting—be terminated on materials containing plutonium or other weapons-usable materials prior to their transfer to WIPP. WIPP is a "property protection area" with security standards even below those required for sites possessing a Category IV quantity of special nuclear materials (e.g. 1 gram for plutonium-239). Termination of safeguards on special nuclear materials, according to DOE guidance, generally requires the material to meet Attractiveness Level E criteria (see Figure 2). According to current guidance, a solid item containing plutonium would be considered Attractiveness Level E *either* if it contained less than 0.1 to 1 percent plutonium by weight, depending on the chemical nature of the matrix, *or* if it was "highly irradiated" to generate a self-protecting radiation barrier (see Figure 4).

However, the DOE may grant a variance from the established safeguards termination limits under certain circumstances. For instance, it may allow termination of safeguards on Attractiveness Level D material if a vulnerability assessment shows that addition of the material to the waste storage area would not significantly increase the risk of theft, diversion or sabotage of a Category II quantity of material, which is 16 kilograms of plutonium for Level D.

In order to send the material to WIPP under the DOE's guidelines, Rocky Flats had to convert much of it to Attractiveness Level D and conduct a vulnerability assessment to obtain approval to terminate safeguards. But given that this material was also included in the DOE's declaration of excess plutonium, the final waste form would in principle have to meet the spent fuel standard under the DOE's policy—which meant also surrounding it with a self-protecting radiation barrier.

Even if technically feasible, adding a radiation barrier was not compatible with WIPP disposal. Sending highly irradiated items to WIPP was not an option because of the strict limits on the amount of remote-handled waste and the maximum dose rate. (The WIPP Land Withdrawal Act limits the volume of transuranic waste to 175,600 cubic meters. Depending on its level of radioactivity, transuranic waste is classified as either contact-handled—that is, not too radioactive to be handled by personnel—or remote-handled, which is so intensely radioactive it can be manipulated only by mechanical equipment.[15] A separate 1988 agreement between the DOE and the state of New Mexico restricts the total volume of remote-handled transuranic waste to no more than 7,080 cubic meters.) Moreover, fission

[15] Contact-handled transuranic (CH-TRU) waste has a surface dose rate of less than 200 millirem per hour, whereas remote-handled transuranic (RH-TRU) waste has a surface dose rate between 200 millirem and 100 rem per hour and is too radioactive to be directly handled by personnel.

products from high-level waste could not have been used because WIPP was forbidden by law from accepting high-level waste.

Instead, Kaiser-Hill, the Rocky Flats contractor, argued that an alternative disposal scheme would justify a variance from termination of safeguards limits and provide a level of inaccessibility comparable to that of the spent fuel standard. It proposed combining residues or blending them down with "virgin material" to below 10 percent plutonium by weight (the attractiveness level D threshold) and packaging the material in pipe overpack containers. A pipe overpack container is a 208-liter (55-gallon) waste drum containing a piece of metal pipe filled with plutonium that has been diluted with other materials to below 10 weight-percent. The amount of fissile material that can be loaded in an individual waste drum is limited to prevent any criticality accidents. The plutonium limit for each 208-liter pipe overpack container is 200 plutonium-239 "fissile gram equivalents."

Kaiser-Hill argued that dilution of the plutonium and packaging in pipe overpack containers would render the material unattractive as a target for diversion or theft not because of the existence of a high radiation field, but because of the large number of drums that would have to be taken to acquire the same amount of plutonium (28 kilograms) as one high-level waste canister containing immobilized plutonium. It stated in its variance request that "to acquire a comparable quantity of material … will require that 127 to 160 drums weighing a total of 19,000 to 40,000 kg and having a volume of 26,400 to 33,300 liters, would have to be taken. "The logistics for successfully acquiring and handling this quantity of material to recover the plutonium are recognized as low risk" (Kaiser-Hill 1998, 15).

In 1998, the DOE approved Kaiser-Hill's safeguards termination limit variance request for some of the categories of material it wanted to ship to WIPP, but not for some others, including plutonium fluorides. The DOE said that "it was impractical to apply a variance to safeguards termination limits for plutonium fluoride residues due to the high plutonium concentration and the relative ease of recovering the plutonium from the residue matrix" and therefore it did not analyze an alternative to blend them down to less than 10 weight percent plutonium (DOE 2001). It decided instead to ship the fluorides to SRS for reprocessing.

The DOE subsequently changed its position. Kaiser- Hill's 1998 variance request had not given credit to any special properties of the "virgin" material that it proposed to use to dilute the plutonium residues. However, in 2001, the DOE issued an amended Record of Decision that stated that "the Rocky Flats Site has since developed a blending matrix of inert material that would result in a blended material from which plutonium recovery is difficult" (DOE 2001). The DOE credited the properties of this material, along with a few other conditions, in granting a safeguards variance for the plutonium fluorides and allowing them to be sent to WIPP as well, after blending them down to less than 10 weight percent plutonium.

This matrix material, called "stardust," is reportedly a mixture of cementing, gelling, thickening and foaming agents that was developed to "change the physical and chemical characteristics of the residues and make it more difficult and more complex to recover, concentrate and purify the plutonium" (Hayes and Nelson 2012). The composition of the material is classified.

More recently, stardust or a similar substance, referred to as "termination of safeguards" material, has also been used at the Savannah River Site to package non-pit plutonium materials for disposal as transuranic waste for disposal at WIPP, indicating that the DOE still believes the approach is adequately secure, even after the major changes to its security policies after 9/11. In fact, in the draft SPD SEIS states that "DOE believes that … the WIPP Alternative … provide(s) protection from theft, diversion, or future reuse in nuclear weapons akin to that afforded by the Spent Fuel Standard" (DOE 2012a, S-14).

The DOE's graded safeguards allows for tradeoffs between different attributes of a plutonium disposition form, since, for example, a reduction in attractiveness level can be achieved either through a

change in chemical form or through irradiation. If the spent fuel standard concept is to be consistent with this, it would need to have similar flexibility. For example, the standard could take into account that possibility that greater dilution or other measures could increase the time and resources needed for plutonium recovery, and therefore could compensate for a smaller or non-existent radiation barrier. This would deviate from the clear conclusion of the NAS in 1994 that "chemical barriers alone … cannot meet the spent fuel standard" (NAS 1994, 148). Therefore, the DOE needs to provide more justification for its conclusion about the WIPP alternative meeting the spent fuel standard. It could well be that for certain adversaries, some chemical barriers could provide obstacles comparable to a radiation barrier with regard to ease of theft and conversion time to weapons-usable material, but to demonstrate this would require detailed vulnerability analysis.

Disposal of the entire 40–50 MT inventory of excess plutonium in WIPP would be a significant change from the more limited proposal analyzed in the draft SPD SEIS. It would require increasing the amount of plutonium sent to WIPP by several times—and most of the plutonium currently buried there is diluted to a much lower concentration than 10 weight-percent. The assumptions that enabled the DOE to terminate safeguards on a relatively small number of 10 weight-percent plutonium drums sent to WIPP may not apply to a much larger quantity. For instance, Kaiser-Hill took credit in its variance proposal for the difficulty adversaries would have in identifying which transuranic waste drums contained residues with relatively high plutonium content. This advantage would diminish as the number of such drums increased.

Therefore, if the DOE decides to dispose of tens of tons of excess plutonium by downblending it and burying it in WIPP, it should more carefully analyze whether 10 weight-percent would still be the appropriate dilution factor to use for termination of safeguards. The DOE should not rely on administrative variances from established safeguards termination limits for this stockpile: That could undermine efforts to convince Russia and the international community that the WIPP burial option is secure, and would set a poor example. If there is a technical basis for giving such a great deal of credit to "stardust," then that should be incorporated into the safeguards standards. More generally, the DOE should strive to ensure that graded safeguards are applied on a more consistent footing. Its approach to making security determinations has too often appeared ad hoc, intended as a quick fix for a particular site's urgent nuclear material management problems.

There are other options that could be used in addition to or as an alternative to blending with termination-of-safeguards materials to further reduce accessibility. One option is greater dilution and encapsulation of the plutonium in a fixed, refractory matrix, as discussed below. Alternatively, the security classification of WIPP itself could be increased, and it could be placed on the IAEA eligible facilities list for international safeguards. The DOE should examine the costs and benefits of doing so.

However, although alternatives to the spent fuel standard such as downblending with stardust may present significant obstacles to subnational groups seeking plutonium, they would have little impact on the ease of national recovery and reuse of the plutonium. After all, the U.S. knows exactly what stardust is. Nevertheless, there are limits to how far the U.S. would go to recover plutonium from very unattractive materials. As a Los Alamos National Laboratory memo from 1996 proposing the introduction of safeguards termination limits said,

> It is recognized that given sufficient resources, time and volumes of SNM-bearing material, sufficient SNM can be recovered from the most refractory matrices to constitute a threat to national security. However, this proposal for derivation of safeguards termination limits is based on the premise that attractiveness of SNM-bearing materials must be directly related to difficulty of recovery and the assumptions that DOE does not have infinite resources to apply to recovery and

> the resources and technologies possessed by enemy states/groups do not exceed that of DOE. (LANL 1996)

A key question, as articulated by Matthew Bunn, is whether there are alternatives that are able to achieve a substantial portion of the objectives of plutonium disposition while costing a lot less than those that fully meet the spent fuel standard.

Geologic Barriers vs. Intrinsic Barriers

One way to compensate for the lack of a radiation barrier would be to provide a substantial geologic barrier in the near term for plutonium disposition waste forms.

Underlying the idea of the spent fuel standard is the assumption that once converted to a disposition form, excess plutonium would be treated similarly to existing stockpiles of spent fuel and high-level waste—it would be placed in interim storage pending development of a geologic repository like Yucca Mountain where such materials could be buried. However, if one option could lead to faster or more certain burial than others, this assumption would no longer be valid, because that option could take credit for a geologic barrier to accessibility. And the geologic barrier could be non-trivial with respect to both subnational and national threats.

The options for diversion or theft of a significant quantity of plutonium from a geologic repository are limited. During the so-called retrievability period before the repository is closed and sealed, subnational groups would either have to covertly smuggle waste drums through the limited number of access portals or overtly seize a repository for a considerable length of time. After closure, their only covert option would be to drill into a repository and remove a large volume of material undetected.

As an alternative to a mined geologic repository, deep boreholes are attractive because the potential for retrievability is even more limited. However, the tradeoff is that an increase in the difficulty of retrievability could have safety consequences should problems develop that require access to or removal of emplaced waste.

Another factor to consider is that the radiation barrier itself has been overrated as a self-protection measure. The 100 rem per hour at 3 feet dose rate (or 1 Sievert per hour at 1 meter for metric system users, which is not identical) that has defined "highly irradiated" material in domestic and international guidance, is a radiation level that could prove ultimately lethal after several hours of exposure (depending on the distance that the thieves were able to maintain and the shielding that they might use). However, most acute radiation effects at that level of exposure are delayed, and death would not occur for days to weeks afterward. If the thieves were prepared to die for their cause, as the 9/11 attacks illustrated, they would be willing to receive a lethal dose as long as they had enough time to complete their mission. In order for a radiation barrier to be a sufficient deterrent to theft, it would have to generate a dose rate high enough to immediately incapacitate a thief, a level probably one hundred times greater (Coates et al. 2005; Lyman and Kuperman 2002).

In 2011, the DOE acknowledged this issue by removing the specific dose rate limit from its security guidance. Instead, it now defines "highly irradiated" as the dose rate above which an adversary would be unlikely to complete all necessary tasks to acquire a target quantity of SNM (e.g. theft, transport, processing) before being incapacitated. By this criterion, even some commercial spent fuel may not be self-protecting. Also, the NRC is considering raising its own limit by a factor of 60, to 6000 rem/hour at 3 feet.

A detailed adversary task analysis would be required to determine the degree to which the geologic barrier provided by WIPP could compensate for the lack of a radiation barrier when compared to spent fuel sitting in interim storage for a hundred years or more, a possibility that now appears more likely since the Obama administration's decision in 2009 to no longer pursue the Yucca Mountain Project. However, as the National Academy of Sciences argued two decades ago, the introduction of a geologic barrier

would be necessary for the long-term security of disposition waste forms as radiation barriers declined with time (NAS 1994, 148). If substitution of a geologic barrier for a radiation barrier could provide adequate security in the long term, then logically it would also provide adequate security today. And given that the radiation barrier may be less effective than originally thought, the prospect of getting excess plutonium buried quickly without a radiation barrier may be a better alternative than irradiating it and leaving it above ground indefinitely. Assuming that WIPP will resume operations within the next few years, as the DOE anticipates, this possibility could be a big advantage for the WIPP option.

For national threats, in contrast, some argue that a geologic barrier can provide no real protection, as a nation could easily excavate the site and recover the material. This is the specter of the "plutonium mine." The counter-argument is that such activities would be easily detectable by minimally invasive safeguards techniques, such as acoustic monitors, radar and satellite surveillance (Lyman and Feiveson 1998). In fact, it would be easier for the IAEA to safeguard a single known geologic disposal site than to safeguard multiple interim surface sites storing large stocks of aging spent fuel, not to mention to detect clandestine plutonium production activities which could occur anywhere.

Non-Reactor Alternatives for Plutonium Disposition

In April 2014, DOE released the report of its internal Plutonium Disposition Working Group (PDWG), which it had convened a year earlier to evaluate alternatives to the program to convert excess weapons plutonium into MOX fuel for commercial power reactors (DOE 2014c). The report discussed three non-reactor disposition options for excess plutonium: immobilization with high-level waste, downblending and disposal, and disposal in deep boreholes.

However, the report's examination of the options fell short in a number of respects. With regard to immobilization, for example, the report considered only a couple of options and judged they had insurmountable problems. It did not attempt to come up with ideas about how to make immobilization work.

The DOE should consider a broader range of non- reactor alternatives in order to establish which are compatible with the capabilities of the existing infrastructures. Such additional options include:

Inhomogeneous, radiation barrier not readily separable

- Can-in-canister immobilization at DWPF

Homogenous, spent fuel standard

- Dissolution in H-Canyon/HB-Line and transfer to HLW tanks for vitrification (immobilization) in DWPF
- Direct injection into the DWPF melter
- "Melt and Dilute"

Inhomogeneous, radiation barrier readily separable

- "Third Way" (off-spec fabricate MOX assemblies for direct co-disposal with spent fuel)

Direct geological disposal, no radiation barrier

- Downblending (multiple options) and disposal at WIPP
- Immobilization and deep borehole disposal

It is beyond the scope of this report to examine all seven of these options in detail. We focus below on those three options that have been more extensively developed.

Can-in-Canister Immobilization at DWPF

The PDWG's analysis of immobilization began with the premise that can-in-canister immobilization could not be implemented at SRS because "since nearly half of SRS's HLW has already been remediated, there is not enough HLW remaining to dispose of 34 MT of surplus plutonium" (DOE 2014c). This meant that immobilization would have to be carried out at Hanford, which the report concluded was even more expensive than the MOX option and was not viable for other reasons. Thus the PDWG ruled out immobilization as a potential alternative.

But the statement that "half" of SRS's high-level waste has already been remediated is

misleading. While half of the total number of HLW canisters originally anticipated have been produced, the vast majority of these canisters contain "sludge-only" waste withlow levels of CS-137. While 44 percent of the sludge has been processed, 94 percent of the salt waste, which contains well over 60 megacuries of cesium-137, remains to be vitrified (SRS 2014, 5 and 37). The DOE plans to produce approximately 5,000 more canisters to vitrify this waste by 2039. (And even this date may slip, as the DOE is not providing enough funding to the salt waste processing project to meet its design throughput [SRS 2014, 18]). To dispose of 34 MT of plutonium using the baseline can-in-canister approach, in which each canister would contain approximately 28 kg of plutonium, about 1,215 canisters would be required, a number well within the remaining capacity of the facility. (A few hundred additional canisters also would need to be produced overall in order to accommodate the slightly reduced waste volume within those canisters containing the plutonium cans.)

In order to achieve the dose rate specified in the PMDA, it has been calculated that each canister would have to contain 10.8 kilocuries of cesium-137 at fabrication (Gray and McKibben 1999). Given the number of canisters that will have to be produced, that would require about 13 megacuries of cesium-137. Based on the remaining tank inventory, there is certainly sufficient cesium-137 to meet the standard, even after taking into account its radioactive decay over its half-life of 30 years.

Therefore, it is worthwhile to examine the possibility of building an immobilization facility at the SRS K-Area Complex that would be capable of disposing of the entire stockpile of surplus plutonium. There is no indication that DOE has ever done such analysis. In fact, DOE officials have repeatedly rejected consideration of that option. In 2007, DOE officials testified in Congress that the proposed K-Area Complex facility for vitrifying 13 MT could not be "scaled effectively" to handle a larger quantity of plutonium, and if a decision was made to immobilize the entire surplus plutonium inventory, an "entirely different facility" would have to utilize a ceramic immobilization process instead of glass, requiring an additional lengthy period of research, development and engineering (because, of course, DOE had terminated ceramic immobilization research in 2002). DOE argued this was because the vitrified plutonium would expose workers to unacceptably high doses of neutron radiation (DOE 2007a, 27).

The increased radiation dose that the DOE pointed to was a consequence of the presence of boron in the glass composition. As a result, the neutron dose resulting from (α,n) reactions is approximately eight times greater for vitrified glass than for ceramic. However, the DOE concluded elsewhere:

> Although the process material dose rate in the glass vitrification process after the glass frit blending step is approximately eight times higher than in the ceramic immobilization process, based on preliminary dose calculations, the predominant worker dose exposure is from the plutonium conversion operations in the front end of the immobilization process. There is little difference in overall dose exposure to all badged workers at the immobilization facility for both the glass and ceramic processes (DOE 1998a, 6-4).

In addition, the comparison document showed that substituting boron enriched in the isotope B^{10} would reduce the dose rate from the vitrified plutonium frit by a factor of two. At $3.50 per gram of enriched boron, it was estimated that the additional cost for immobilizing 50 metric tons of plutonium in glass would be $50 million—hardly a decisive factor in comparison to the cost of MOX plant.

In any event, the additional life cycle costs and risks of the MOX option, which would involve hazardous and waste-producing aqueous processing, more extensive transportation, and reactor irradiation, would most likely be far greater and harder to control than scaling up the throughput of a vitrification plant at K-Area Complex. In short, it appears that the DOE used every excuse it could

find to justify continuing the MOX program and not considering immobilization, despite its advantages.

With regard to timing, the DWPF is scheduled to produce up to 276 canisters per year; if that were the only factor, the entire disposition mission could take place in under five years. However, the rate-limiting step is can production. When the DOE analyzed the possibility of installing a vitrification line in the K-Area Complex, it developed a facility design utilizing 10 melters in parallel operation, with each melter vitrifying two batches a day (DOE 2007b). By also assuming that one melter would be out of service at any one time, and a facility would operate 60 percent of the time, it estimated that a throughput of 3,683 cans containing 2.2 MT of plutonium per year would be achievable. At this rate, it would take about 15 years to immobilize the 34 metric tons of plutonium in cans. That timing would mean the process would have to be up and running by about 2025 to avoid a delay in the DWPF schedule. In addition, under the current DWPF plan, the cesium-137 in the salt waste would not be vitrified at a uniform rate; the highest concentration wastes would be vitrified first.

However, this estimate was based on the vitrification of 21 metric tons of impure plutonium-containing bulk materials, which limited the amount of plutonium in each can to around 0.6 kg. This is well below the Attractiveness Level D threshold of 10 weight percent plutonium, which also happens to be the solubility limit of plutonium in the baseline glass composition. Thus for pure plutonium materials, this quantity could be increased. The safety assessment for the proposed vitrification plant assumed a bounding value of 0.95 kg of plutonium per can (DOE 2007b, 2-8). Therefore, at the same rate of can production, pure plutonium materials such as pits could be vitrified in the K-Area Complex at a rate of 3.3 metric tons per year, reducing the necessary time to complete the mission for 34 metric tons of both pure and impure plutonium to about 12 years.

Increasing the plutonium content of each can to nearly 1 kilogram would increase the total plutonium content of a fully loaded canister from 16 kilograms to almost 28 kilograms, which was the original baseline assumption for can-in-canister in the 1990s. However, 16 kilograms is the upper limit of the amount of Attractiveness Level D special nuclear material that the DWPF, a Category III facility, could accept. Therefore, DOE would have to address this issue in order to maximize the benefit of the increased plutonium throughput. The DOE could reduce the number of cans per canister, but that would increase the burden on DWPF operations.

The impact on the DWPF schedule depends on not only the attainable throughput of a full-scale vitrification plant in K-Area Complex but also how soon the facility could begin operation following a decision to proceed. When the smaller scale project was approved in 2006, officials anticipated being ready to start operations in 2012. But DOE's projections at that time were developed using the same flawed methodology that was used to grossly underestimate the cost and duration of the MOX plant construction.

In any event, it is not straightforward, using public information, to extrapolate from the 2006 K-Area Complex vitrification plant design to a larger-throughput facility. For one thing, in 2006, the DOE still planned to build a stand-alone Pit Disassembly and Conversion Facility for disassembling and oxidizing pits. Now, with the PDCF cancelled, the K-Area Complex is the most likely place for installation of a pit disassembly and conversion capability, which would compete for process space with a vitrification facility. There would be some overlap of capability because the vitrification facility design included direct metal oxidation furnace gloveboxes to convert non-pit metal to plutonium oxide. However, the 2006 study does not state how much process area would be required for the vitrification facility. An earlier study that developed a conceptual design for a greenfield plutonium vitrification plant with a throughput of 5 metric tons of plutonium per year— 50 percent larger than the throughput for the K-Area Complex facility—calculated that 58,400 square feet of new process area (excluding feed storage and preparation and analytical laboratory space) would be required (DOE 1998b, 2-5).

It is also not clear how much process area would be required for the pit disassembly and conversion project at K-Area Complex, which was sized for a plutonium throughput of 3.5 metric tons per year. DOE's plan states that the project "would not utilize all of the available space within the existing facility nor within the protected area" so that "opportunities for other DOE missions to take advantage of this existing infrastructure would be possible" (DOE 2012b, 54). It does not say how much space would be available. Of course, there are other options for pit disassembly and conversion operations, but none appear as practical as using the K-Area Complex. The DOE's 2014 PDWG study did not consider the possibility of an expanded immobilization facility in the K-Area Complex, but it did favorably evaluate the possibility of installing a facility there for producing metallic plutonium-based fuel for fast reactors. The study estimated that a facility with a throughput of up to 2 metric tons of plutonium a year was feasible and could be started up by about 2027 at a cost of $1.9 billion. The study says that 50,000 square feet of process area, with up to an additional 100,000 square feet of support area, could be made available within an adjacent to the K-reactor building. The study says the fuel fabrication facility would need about 80,000 square feet (but it isn't clear how much of that is process area).

The analysis is rather vague on where pit disassembly and preparation activities would be carried out. It assumes that they would be divided between the Los Alamos PF-4 facility and SRS's K-Area Complex. The latter would receive "select pits" that could be readily accepted and processed in the K-Area Complex metal fuel fabrication facility.

Can one make conclusions about the feasibility of a high-throughput vitrification facility in K-Area Complex from the PWDG analysis of a metal fuel fabrication facility? The immobilization process is similar to that of the fast reactor fuel fabrication process in terms of the number of steps required for processing both metals and oxides: essentially, plutonium feeds are prepared and then blended with other materials in a furnace. (While metal fuel fabrication would not require oxidation of metal feeds, it would require reduction of oxide feeds.) Vitrification for immobilization would require higher temperatures than metal fuel fabrication, placing more demands on the support systems. On the other hand, the cast metal fuel slugs would have to be trimmed, requiring an additional stage and the generation of another waste stream compared to vitrification. If one assumes that a 3.3 metric ton per year immobilization capability could also be launched by 2027, vitrification of 34 metric tons of plutonium could be completed by about 2038 and would not delay the schedule for DWPF operation and shutdown, although it might have an impact on the schedule for vitrifying high-cesium wastes. (Vitrification of the remaining 13 metric tons, including impure plutonium feeds, would take another 5 years or so, prolonging the operating lifetime of the DWPF by a few years.)

The partially built MFFF may also provide another opportunity to utilize existing infrastructure, but only if it can be used in a manner that would result in significant cost savings relative to its original purpose: producing MOX fuel. This in turn would depend on the extent to which the cost of the remaining construction and equipment procurement and installation could be reduced, and whether the operating cost could also be cut.

The MFFF's gloveboxes and process equipment dedicated to powder blending, cold press, and sintering could potentially be utilized for a ceramic immobilization process requiring similar steps. Operating costs could be reduced if the aqueous processing systems were not used, which might also allow the DOE to avoid completion and operation of the Waste Solidification Building.[16] However, unless the operating process area could be completely segregated from the rest of the facility, it is unlikely there would be a substantial cost

[16] The Waste Solidification Building was also intended to process certain wastes from the Pit Disassembly and Conversion Facility. It is not clear if the WSB would also be needed to handle wastes from pit disassembly and conversion activities carried out in other SRS facilities if the PDCF is not built.

savings. The PWDG analysis of the fast reactor option considered installation of a fast reactor fuel fabrication capability within the MFFF, but stated (without explanation) that use of the K-Area Complex was more "cost-effective" (DOE 2014c, B-54). It is also not clear that the existing equipment could be efficiently adapted for another process.

On the other hand, the DOE did identify an area of the MFFF where it could install furnaces and gloveboxes to carry out direct metal oxidation. One possibility is that a self-contained, separately ventilated process unit could be installed there to carry out some of the activities necessary for immobilization. Or perhaps this area could be adapted to function as the Pit Disassembly and Conversion Facility, which is a critical process necessary for all disposition options.

Homogeneous Immobilization at DWPF

The PDWG report also analyzed two options for homogenous immobilization at DWPF. First, it took another look at one of the very first immobilization ideas: simply blending the plutonium with high-level waste and glass forming materials and melting and vitrifying the mixture. H-Canyon/HB-Line would be used to dissolve plutonium (after any necessary disassembly and preparation) and pipe the solution to the high-level waste tanks, for eventual transfer to the DWPF melter.

The criticality concerns that led the DOE to reject the idea years ago have been largely analyzed and resolved for limited concentrations of fissile material. Recent work has established that DWPF glass can dissolve up to about 1 weight-percent plutonium without affecting the glass structure and durability, translating to 18 kg per canister. (The current legal limit of 897 grams per cubic meter of fissile material in the Yucca Mountain waste acceptance criteria is not technically justified, and is not relevant in any case given that DOE is no longer pursuing the Yucca Mountain Project.) (Ray, Marra, and Herman 2013). This is less than two-thirds the 28 kg per canister that would be achievable in the can-in-canister approach; it also would require some 1,900 DWPF canisters, about 700 more than can-in-canister. Still well within the expected production run of DWPF, this option could be implemented much sooner than can-in- canister, given that an immobilization facility would not be needed.

A major limiting factor, however, is the rate at which plutonium can be dissolved in H- Canyon/HB-Line given security constraints. The 2006 disposition options study evaluated the time it would take to dispose of 13 metric tons of non-pit plutonium through dissolution and transfer to waste. It considered two alternatives: maintaining H-Canyon/HB-Line as security Category II facilities or upgrading them to Category I. Without upgrading them, 3,013 cans containing Category I quantities of plutonium could not be shipped to H- Canyon/HB-Line directly; the plutonium would have to be repackaged into Category II quantities at the K-Area Complex first. In this case, the study found the facilities could process only about 700 kilograms a year of plutonium metals and oxides. If H-Canyon/HB-Line were upgraded to Category I, increasing operational flexibility, the rate could increase to about 870 kilograms per year. At that rate, it would take 40 years to dispose of 34 metric tons, and DWPF operation would have to be extended by fifteen years or more, even if the program started immediately.

The second option is an approach first proposed by scientists at Catholic University that would develop a method to inject plutonium directly into the canisters while they are filling with high-level waste glass (Lutze and Pegg 2013). The PWDG report argued that this approach raised numerous technical questions, including the impact of the injection stream on the glass pouring process. Also, this approach would entail the transfer of concentrated plutonium in Category I quantities to the DWPF, and thus would raise even more security issues than the can-in-canister approach, requiring significant compensatory measures, security upgrades or variances. Nevertheless, the option deserves more detailed study.

Downblending and Disposal: The WIPP Option

The plutonium disposition option that the PDWG identified as least expensive[17] was downblending and direct disposal in WIPP. (Actually, the report referred to WIPP only as a "reference case," but the notion that another, similar repository would be operational in the foreseeable future is not realistic.) This 2014 study was the first time that the DOE had publicly acknowledged that disposal of the entire 34 metric tons of surplus plutonium covered under the 2000 PMDA underground in WIPP was a viable option.

However, the PWDG report claimed that WIPP could only accept up to 13 metric tons of plutonium within its current unsubscribed capacity; therefore in order to dispose of all 34 metric tons, the WIPP Land Withdrawal Act would "likely" have to be amended to increase the capacity. If true, that obstacle could be a major stumbling block. The state of New Mexico and local environmental groups are unlikely to support any increase in the legal capacity limit, but their consent (or lack of opposition) would be essential for plutonium disposition in WIPP to be successful. Based strictly on the numbers, though, it is not clear why an increase in the statutory waste volume would be necessary to accommodate more than 13 metric tons of plutonium, although additional repository panels may have to be excavated.

In the *2013 Annual Transuranic Waste Inventory Report,* the total amount of transuranic waste in WIPP was reported at the end of 2012 as 85,200 cubic meters, and the inventory of transuranic waste that had yet to be disposed of was 66,200 cubic meters, for a total of about 151,400 cubic meters (DOE 2013). Considering the statutory volume limit of 175,600 cubic meters, this accounting leaves 24,600 cubic meters of unsubscribed capacity.

How much plutonium can be disposed of within this volume? Transuranic waste disposed of in WIPP is commonly packed into standard 208-liter (55-gallon) drums as pipe overpack containers. Thus, the available volume of 24,200 cubic meters could accommodate about 116,350 pipe overpack containers.

Each pipe overpack waste drum is limited to 200 plutonium-239 fissile gram equivalents. However, the DOE has developed a new packaging arrangement for transport and disposal utilizing "criticality control overpacks," which can carry almost double the amount: up to 380 plutonium-239 fissile gram equivalents per 208-liter waste drum. Moreover, the criticality control overpacks are lighter-weight than the pipe overpack containers, allowing more drums to be carried in a single shipment, reducing transport costs. The NRC, which licenses radioactive waste packages for transport, approved the criticality control overpacks in 2013.

If criticality control overpacks are used, 116,350 drums could be loaded with over 44 metric tons of plutonium. Moreover, 34 metric tons of plutonium so packaged would require only about 18,600 cubic meters of disposal volume. Thus by using criticality control overpacks, it would appear that WIPP can accommodate, without amending the volume limit in the Land Withdrawal Act, the entire 34 metric tons of excess plutonium covered by the U.S.-Russian plutonium disposition agreement, as well as a large fraction of the additional 13 metric tons of plutonium the DOE needs to disposition.

However, the total statutory volume is not the only consideration, which is presumably why the PDWG report only found room for an additional 13 metric tons of excess plutonium in WIPP.

The WIPP waste disposal area is laid out in a series of excavated "panels," each consisting of several rooms. Each panel has received a permit from the state of New Mexico to store a certain volume of both contact-handled and remote-handled transuranic waste. After each panel is filled, it is sealed off. Some panels were sealed with concrete explosion-isolation walls; others were sealed with steel bulkheads.

[17] At an estimated "to-go" life cycle cost of less than $9 billion, the WIPP option is far cheaper than the MOX "to-go" life cycle cost of over $25 billion.

The problem is that the panels that already have been closed off were not filled to their permitted capacities with either type of transuranic waste. Therefore, a considerable amount of permitted capacity is unused and unavailable. Since the sealed-off drifts cannot be reopened without great difficulty, this means that new panels would have to be permitted by the state and excavated. The state of New Mexico has already permitted two new panels but they have not yet been built; even so, the two new panels will not fully compensate for the amount of lost capacity. As of January 2014, only three panels had not been sealed (Hancock 2014). Consequently, acceptance of the entire surplus plutonium inventory in criticality control overpacks would probably require the issuance of permits for construction of new panels, even if it didn't require amending the Land Withdrawal Act to increase the total capacity. The need for additional permits would subject the plutonium disposition plan to additional public scrutiny. Moreover, expansion of the repository itself, although technically feasible, would move the active repository area closer to oil and gas wells in the vicinity.

The situation is even worse today because of the February 14, 2014 accident, in which a waste drum in Panel 7 overpressurized and released plutonium and americium into the repository, and then through unfiltered pathways into the atmosphere. As a result, not only are operations at WIPP suspended indefinitely, but the state of New Mexico is demanding that the DOE expedite the closure of both Panels 6 and 7, where more drums suspected of containing the same chemical mixture that may be responsible for the event are located. Panel 7 is only partially filled, so this would close off even more permitted capacity.

However, assuming that WIPP does eventually resume normal operations, there are options for further reducing the volume of transuranic waste containing the surplus plutonium inventory and thus conserving repository space.

One option, which was identified by the PDWG, would be to use a different type of container designated "9975," to ship and dispose of the downblended material. In this case, the study estimated that it would be technically feasible to load 1,000 plutonium-239 fissile gram equivalents in each 9975. (Typically, 9975s transport a single 3013 can, which contains up to 4.4 kg of plutonium.) The volume occupied by a 9975 is about 142 liters, or about two-thirds the volume of a criticality control overpack. Since, in addition, each 9975 could contain 2.6 times as much plutonium as the criticality control overpack, the transuranic waste volume corresponding to a given amount of plutonium would appear to be reduced by nearly a factor of 4. In other words, less than 5,000 cubic meters of space could accommodate 34 metric tons of plutonium. (Note: The PDWG report says the switch to 9975s would reduce the required volume by half to two-thirds).

The PDWG report cautions, though, that the option would result in a greater quantity of fissile material per shipment and hence trigger increased safeguards and security requirements both during transport and receipt at the repository, requiring $50-$100 million in capital investment, which would be offset by the reduction in the volume of waste to be transported.

The need to increase security may be explained this way. The number of criticality control overpacks in a shipment is limited by weight to 42 (3 fully loaded TRUPACT-II shipping containers). With 0.38 kg fissile gram equivalents of plutonium-239 in each container, the total is just below a Category II quantity of material, which is 16 kilograms for Attractiveness Level D. However, to take advantage of the higher plutonium disposition rate with the 9975 option, the amount of plutonium per shipment would be greater, necessitating Category II security.

There are other alternatives that the PDWG did not evaluate, however, that could reduce the waste volume and number of shipments needed without requiring security upgrades. The 2006 DOE plutonium disposition alternatives analysis evaluated an option in which plutonium would be diluted in concrete and poured into 208-liter drums, and then cured at room temperature. The safeguards termination limit is 1.0 weight-percent for plutonium "microencapsulated in refractory

compounds or in solid-dilution," that is, "vitrified, bituminized, cemented, or polymer-encapsulated materials" (Figure 4).[18] A 208-liter drum filled with about 140 liters of concrete (the optimal loading determined by the study) at a density of about 2.3 grams per cubic centimeter would weigh about 322 kilograms (excluding the weight of the empty drum). Therefore, the safeguards termination limit of 1 weight-percent would correspond to 3.2 kilograms of plutonium per drum.

However, this would exceed the criticality limit for this configuration. A 2002 Oak Ridge National Laboratory study calculated that the mass limit for plutonium fixed in concrete in a 208-liter drum would be 545 fissile gram equivalents (or 574 fissile gram equivalents for drums weighing slightly more overall than the current maximum of 455 kg or 1000 lbs) (Goluoglu and Hopper 2002). This is still an improvement of around 50 percent compared to the criticality control overpack limit. An additional advantage is that safeguards could be terminated on these packages (the plutonium concentration would be 0.18 percent, well under the limit) without the use of "stardust" and administrative variances from safeguards termination limits.

The 2006 DOE plutonium disposition alternatives analysis considered the use of the Waste Solidification Building for production of the concrete waste form for plutonium immobilization. One disadvantage of the process would be that aqueous dissolution of the plutonium feedstock would be necessary. Dissolution would be the rate-limiting step, and achieving a reasonable throughput would require multiple process lines. Another disadvantage is that it would require upgrading the security classification of the WSB to Category I, which the report describes as very expensive. However, construction of the WSB is currently suspended, so there is an opportunity for facility modification. Moreover, those additional security costs should be compared with the cost of having to increase security for shipments to WIPP and for WIPP itself.

An alternative would be to use K-Area Complex to stabilize plutonium in a grout matrix and pack the mixture in pipe overpack containers. In that case, security upgrades at SRS would not be necessary because K-Area Complex is already a Category I facility. But the advantages of this approach over simple downblending are not as clear. One advantage is that it may be used to terminate safeguards on the grouted plutonium in pipe overpack containers without the use of "stardust." A 12-inch pipe component, with a volume of 48,000 cubic centimeters, could be filled with up to 110 kilograms of cement. If 380 fissile gram equivalents of plutonium-239 were encapsulated in the cement, this would be well below the 1 percent limit.

In short, there are a range of options for utilizing WIPP that the DOE should consider. However, the prospects for any option involving WIPP—which had appeared to be the most promising alternative to MOX before the February 2014—accident, are now in doubt. Although DOE has downplayed the significance of the event and is promising to reopen the repository within several years, the accident revealed numerous shortcomings in WIPP operations that may not be simple to fix. Questions about the future availability of WIPP considerably diminish the most attractive aspect of the WIPP option for plutonium disposition: namely, that it is a proven path for getting excess plutonium out of above-ground storage and into a less accessible geologic repository in the near-term. However, if the DOE is right and the delay is only for a few years, it would not have a significant effect on the disposition schedule.

Perhaps the most troubling aspect is that the DOE has been unable to determine the root cause of the overpressure event. The most prominent theory is that a chemical reaction occurred between nitric acid and a wheat-based absorbent material ("kitty litter"), possibly catalyzed by lead

[18] This is comparable to the dilution of plutonium in a light-water reactor low-enriched uranium spent fuel assembly, and only about a third the concentration of plutonium in a spent weapons-grade MOX fuel assembly. Unlike spent fuel, however, this waste form would lack a radiation barrier.

contained in discarded work gloves. DOE claims there is only one other drum with this particular mix of constituents, emplaced in Panel 6 (Ponce 2014). However, such a reaction requires an ignition temperature of around 600°F and DOE has to date been unable to explain how such a high temperature could have occurred or to reproduce the reaction in a laboratory setting. Until the DOE fully understands the cause of the accident, it cannot provide assurance that similar accidents can be prevented in the future.

This incident also highlights the need for the DOE to provide complete transparency to state regulators and other stakeholders with regard to the contents of waste packages that are sent to WIPP. Lack of transparency could be a problem for the continued use of "stardust" materials for the downblending of excess plutonium, because the composition is classified. Given the potentially chemically reactive nature of stardust, regulators would be justifiably concerned about its presence in WIPP drums. Therefore, WIPP options that can allow DOE to terminate safeguards without the use of stardust may be preferable.

Conclusion

The MOX program has taken the nation off on the wrong track for disposing of excess weapons-grade plutonium. Immobilization or downblending are the only technologies clearly capable of handling the bulk of the current and projected future inventories of excess plutonium, and the DOE should explore the full range of options before making a decision on which alternative to choose. Given the lengthy period of time that will be needed to complete the mission for any option, the DOE should take the time to make the right decision.

FIGURE 2. **DOE Graded Safeguards Table** (DOE 2011)

Appendix B: Graded Safeguards Tables

	Attractiveness Level	Pu/U-233 Category (kg)				Contained U-235/Separated Np-237/Separated Am-241 and Am-243 Category (kg)				All E Materials Category IV
		I	II	III	IV[1]	I	II	III	IV[1]	
WEAPONS Assembled weapons and test devices	A	All	N/A	N/A	N/A	All	N/A	N/A	N/A	N/A
PURE PRODUCTS Pits, major components, button ingots, recastable metal, directly convertible materials	B	≥2	≥0.4<2	≥0.2<0.4	<0.2	≥5	≥1<5	≥0.4<1	<0.4	N/A
HIGH-GRADE MATERIALS Carbides, oxides, nitrates, solutions (≥25 g/L) etc.; fuel elements and assemblies; alloys and mixtures; UF_4 or UF_6 (≥50% enriched)	C	≥6	≥2<6	≥0.4<2	<0.4	≥20	≥6<20	≥2<6	<2	N/A
LOW-GRADE MATERIALS Solutions (1 to 25 g/L), process residues requiring extensive reprocessing; Pu-238 (except waste); UF_4 or UF_6 (≥ 20% < 50% enriched)	D	N/A	≥16	≥3<16	<3	N/A	≥50	≥8<50	<8	N/A
ALL OTHER MATERIALS Highly irradiated[3] forms, solutions (<1 g/L), compounds; uranium containing <20% U-235 or <10% U-233[2](any form, any quantity)	E	N/A	N/A	N/A	Reportable Quantities	N/A	N/A	N/A	Reportable Quantities	Reportable Quantities

[1]The lower limit for Category IV is equal to reportable quantities in DOE O 474.2.
[2]The total quantity of U-233 = (Contained U-233 + Contained U-235). The category is determined by using the Pu/U-233 side of this table.
[3]In this Technical Standard "highly irradiated is defined in the definitions.

However, every dollar spent on installing equipment in the MOX plant that may never be used is a wasted dollar, and moves a potential repurposing of the structure further out of reach. Congress should give the DOE the flexibility to stop throwing good money after bad while it determines the best path to future success.

FIGURE 3. **Additional Criteria for Determining Material Attractiveness Levels** (DOE 2011)

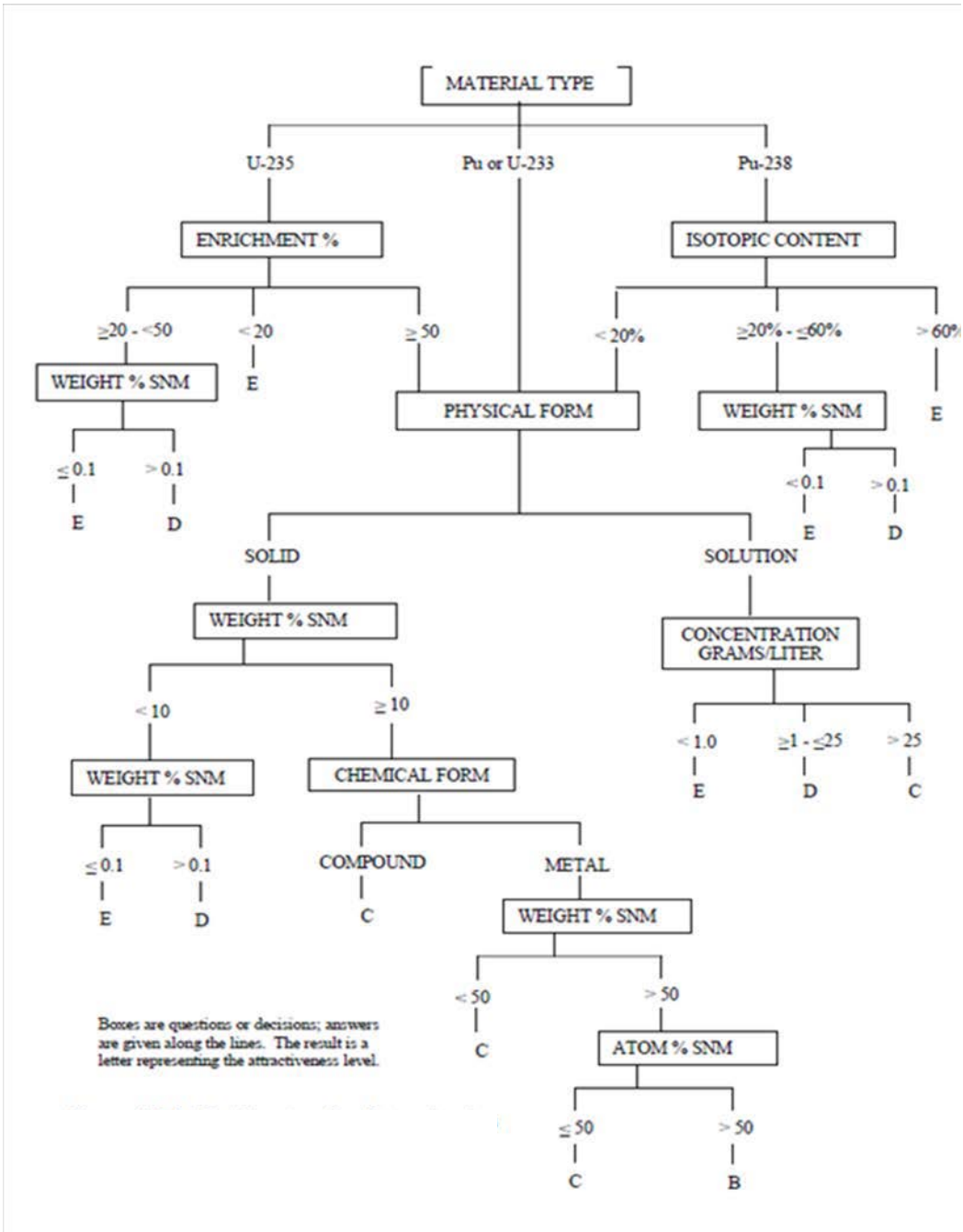


FIGURE 4. **Additional Criteria for Making Attractiveness Level E Determinations** (DOE 2011)

Table 6.2-3. Additional Attractiveness Level E Criteria for SNM

Description/Form	Maximum SNM concentration* (wt%) for MC&A and physical protection termination	Maximum SNM concentration* (wt%) for only physical protection equivalent to Category IV
SNM solutions and oxides: nitrate, caustic or chloride solutions, contaminated/impure oxides, metal fines and turnings, glove box sweepings	0.1	N/A
SNM amenable to dissolution and subsequent separation: pyrochemical salts, chloride melt, hydroxide cake, floor sweepings, alumina, condensates reduction residues, sand, slag, and crucible, magnesium oxide crucibles spent fuel and spent fuel residues	0.1	0.2
SNM in organic matrixes or requiring mechanical separation disassembly and subsequent multiple recovery operations: HEPA filters, organic solutions, oils and sludges, graphite or carbon scrap, surface contaminated plastics, metal components, combustible rubber	0.2	1.0
SNM bound in matrix of solid, sintered, or agglomerated refractory materials: SNM embedded in glass or plastic, high-fired incinerator ash, spent resins, salt sludges, raffinates, and sulfides	0.5	2.0
SNM microencapsulated in refractory compounds or in solid-dilution: vitrified, bituminized, cemented, or polymer-encapsulated materials, SNM alloyed with refractory elements (tungsten, platinum, chromium, stainless steel); ceramic/glass salvage	1.0	5.0

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