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Nuclear Weapon "Pit" Production: Options to Help Meet a Congressional Requirement

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Summary

A pit is the plutonium core of a thermonuclear weapon. Imploding it with conventional explosives provides the energy to detonate the rest of the weapon. The Rocky Flats Plant made up to 2,000 pits per year (ppy) through 1989; since then, the United States has made 29 pits for the stockpile. Yet the FY2015 National Defense Authorization Act requires the National Nuclear Security Administration (NNSA), which manages the nuclear weapons program, to produce at a rate of 80 ppy for 90 days in 2027. How can that requirement be met?

Pits are to be made at Los Alamos National Laboratory's main plutonium facility, PF-4. To manufacture pits, a facility must have enough laboratory floor space and a high enough limit for Material At Risk (MAR), the amount of radioactive material a worst-case accident could release. Producing 80 ppy requires enough "margin," the space or MAR available to produce pits minus space or MAR required for that production rate. While space and MAR available have been calculated, amounts required to produce 80 ppy have never been calculated rigorously, leaving space and MAR needs undefined. Further, the report cannot address whether certain options could meet the 2027 date because time to implement them cannot be determined. Accordingly, this report presents 16 options that seek to increase the feasibility of producing 80 ppy by 2027, including:

- The radiation dose an individual would receive from a worst-case accident determines MAR permitted in PF-4. A ten-factor equation calculates dose as a function of MAR. NNSA uses worst-case values in this equation, yet median values may provide sufficient conservatism. Median values reduce calculated dose by orders of magnitude, permitting a large increase in PF-4 MAR. Yet merely doubling permitted MAR might suffice for producing 80 ppy. Providing this increase through construction at PF-4 could be costly and take years.
- In determining MAR for PF-4, the closest offsite individual is at a nearby trailer park. Relocating it would place the next closest individual farther away. The added distance would reduce dose, permitting increased MAR in PF-4.
- Using a different meteorological model and different assumptions would greatly reduce the currently calculated dose, perhaps permitting doubling PF-4 MAR.
- Plutonium decays radioactively, creating elements that various processes remove to purify plutonium. One process generates byproducts; plutonium is recovered from them with processes that take space and MAR. Since the United States has tons of plutonium surplus to defense needs, byproducts could be dispositioned as waste.
- Pits use weapons-grade plutonium (WGPu). U.S. WGPu is about 50 years old. About nine-tenths of plutonium-241, a WGPu isotope, decays to americium-241 in that time. Since plutonium-241 is the source of americium-241 in WGPu, removing the current americium-241 would prevent WGPu from ever reaching its americium-241 limit, permitting reduction in equipment for that process and reducing worker radiation exposure.
- A plutonium isotope used in space probes, plutonium-238, is extremely radioactive. It accounts for a small quantity of PF-4 plutonium but a quarter of PF-4's MAR. Building a "module" near PF-4 for plutonium-238 work would free MAR and space in PF-4, so one module might suffice instead of two or three.

- To reduce risk of collapse, loss of life, and radiation release from an earthquake, NNSA increased the seismic resilience of PF-4. More steps are planned; more could be taken.

Achieving the congressionally mandated capacity will probably require choosing among options to create a package. MAR margin could be increased by relocating a trailer park, using a new meteorological model, installing rugged containers in the PF-4 production line, increasing PF-4's seismic resilience, and using less conservative assumptions in the MAR-to-dose equation. Similar choices exist for other options. At issue for Congress: What are the risks, costs, and benefits of the options? What is the optimum combination of options?

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Introduction

This is the third in a series of CRS reports on pit manufacturing.[1] A "pit" is the core of the primary stage of a thermonuclear weapon. Its key ingredient is weapons-grade plutonium (WGPu), which is composed mainly of the fissile isotope plutonium-239 (Pu-239) along with small quantities of other plutonium isotopes. Detonating the pit provides the energy to detonate a weapon's secondary stage.

During the Cold War, the Rocky Flats Plant (CO) made up to 2,000 "war reserve" pits per year (ppy). (A war reserve pit is one that has been accepted for use in the nuclear stockpile, as distinct from developmental or production prove-in pits.) Production at Rocky Flats halted in 1989. Since then, the United States has made 29 war reserve pits total for replacement in W88 submarine-launched ballistic missile warheads between 2007 and 2011.[2] Yet as discussed in "Install Equipment with a Single-Shift Capacity of 50 ppy," the Department of Defense (DOD) stated it needed the National Nuclear Security Administration (NNSA, the separately organized agency within the Department of Energy (DOE) in charge of maintaining the U.S. nuclear stockpile) to have the capacity to produce 50 to 80 ppy. This capacity, it is argued, would support nuclear weapon life extension programs, permit replacement of pits found to be defective, and address geopolitical developments.[3] Pits are to be made at Los Alamos National Laboratory (LANL, NM) in the PF-4 (Plutonium Facility 4) building, potentially in proposed smaller structures called modules that would be connected to PF-4 by tunnels, or in both.

In an effort to increase pit production capacity, Congress focused on inputs, such as requiring a plutonium processing building to be constructed by a certain date at a certain cost. However, in Section 3112 of P.L. 113-291, the Carl Levin and Howard P. "Buck" McKeon National Defense Authorization Act for Fiscal Year 2015, Congress changed tack and focused on output. It directed NNSA to ramp up pit production and demonstrate the capacity to produce at a rate of 80 ppy for at least a 90-day period in 2027. (The legislation permits extending this deadline by two years under certain conditions.) Accordingly, while some argue that the capacity should be larger and others hold that it should be smaller, this report takes as its focus how to move toward 80 ppy, not whether it is the right number.

Production at that rate requires enough "Material At Risk" (MAR) and space. DOE defines MAR as "the amount of radioactive materials … available to be acted on by a given physical stress."[4] It is material that could be released by a disaster, such as an earthquake that collapses a building followed by a fire. It is measured in units of plutonium-239 equivalent to convert all types of radioactive material to a common unit. Space is laboratory floor space, in square feet, available for plutonium operations. To measure "enough," this report uses the concept of margin, which is

[1] The first two reports are CRS Report R43685, *Manufacturing Nuclear Weapon "Pits": A Decisionmaking Approach for Congress*, and CRS Report R43406, *U.S. Nuclear Weapon "Pit" Production Options for Congress*, both by Jonathan E. Medalia.

[2] Marisa Sandoval, "Pit Perfect," *National Security Science,* a publication of Los Alamos National Laboratory, issue 3, 2011, http://www.lanl.gov/science/NSS/issues/NSS-Issue3-2011.pdf.

[3] For a discussion of this debate, see CRS Report R43406, *U.S. Nuclear Weapon "Pit" Production Options for Congress*, section titled "Pit Production Capacity: How Much Is Needed?"

[4] U.S. Department of Energy. DOE Handbook: Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Vol. I, Analysis of Experimental Data, DOE-HDBK-3010-94, December 1994, p. xix.

space available for pit production and supporting tasks minus space required for them to be able to produce at a specified rate, and MAR available for pit production and supporting tasks minus MAR required for them to do so. Space margin and MAR margin are separate; both must be greater than zero to accommodate pit production at the specified rate.

PF-4 has 60,000 square feet (sf) of laboratory space on its main floor. It supports many plutonium missions. Some involve pit production, such as pit fabrication (casting pits from molten plutonium) and purifying plutonium for use in pits; others include preparing plutonium-238 (Pu-238) for use as a power source for space probes, disassembly of pits and conversion of their plutonium to plutonium oxide, and surveillance of pits to check their condition. PF-4 has a ceiling on permitted MAR; as of February 2013, that ceiling was 1,800 kilograms Pu-239 equivalent. To provide perspective, in 2012 pit fabrication and plutonium purification accounted for 12,000 sf and 10,400 sf of PF-4's laboratory space, respectively; as of February 2013, they accounted for 295 kg and 143 kg Pu-239 equivalent of PF-4's MAR ceiling, respectively. A CRS report provides a detailed breakout of PF-4's space and MAR usage.

MAR and space also figure in a function that supports pit production, analytical chemistry (AC). AC analyzes very small samples of plutonium to determine the content of impurities, alloying material, and different isotopes of plutonium. AC techniques include mass spectrometry, x-ray fluorescence, radiochemistry, and material assay. The Radiological Laboratory-Utility-Office Building (RLUOB), which was completed in 2010 and is near PF-4, is to house most AC; PF-4 is to perform some higher-MAR AC and AC support work involving larger samples, such as material preparation. RLUOB's MAR ceiling is 38.6 g Pu-239 equivalent, though NNSA is evaluating a proposal to increase that to 400 g. AC equipment requires substantial laboratory floor space, and RLUOB has 19,500 square feet of space ideally configured for AC.

This report presents options that may increase margin, many of which NNSA and its laboratories are considering. However, while figures for space and MAR available for pit production exist, though they may need updating, *figures for space and MAR required to produce 80 ppy do not exist because they have never been calculated rigorously.* Accordingly, this report cannot find that one or more options would provide *enough* margin for producing 80 ppy or supporting AC. Instead, it presents a progression of options to move toward that goal: options not involving modifications to pit production processes; options involving modification to those processes but not structural modifications to PF-4; and options involving structural modifications to PF-4. While the options seek to increase the feasibility of producing 80 ppy by 2027, the report cannot address whether they could meet that date because time to implement them cannot be determined. Potential hurdles render schedules unpredictable. Construction may encounter delays. Moving equipment in PF-4, making structural changes, or changing plutonium processes must follow detailed procedures supported by extensive analysis. Organizations within DOE, oversight agencies, communities, nongovernmental organizations, and others may contest proposed changes to regulations or to assumptions used in calculations. Implementing such changes may be time-consuming; lawsuits may add delay. Efforts to develop new technologies may fail.

This report considers 16 options. A combination of these and other options may be needed to meet the congressional requirement. While any combination can only be selected if it provides enough MAR margin and enough space margin, other factors will also enter into a choice among options by Congress and NNSA. These include:

- reducing cost;
- accelerating schedule (i.e., making capacity available sooner);

- increasing throughput, the rate at which pits are made or processes completed;
- improving worker safety, which includes reducing the risk of injury from building collapse, fire, industrial accidents, and radiation exposure;
- reducing the risk to the public from radiation exposure if PF-4 were to release a large quantity of plutonium as a result of an earthquake or major accident; and
- reducing radioactive waste.

Each option contributes to increasing the feasibility of producing at a rate of 80 ppy by 2027. **Table 1** summarizes the contributions of each option to that requirement; each section of the report begins with a few words highlighting the most important contributions of that option.

Table 1. Contributions of 16 Options to Increasing Feasibility of Producing at a Rate of 80 Pits Per Year by 2027

Report Section	Increase space margin	Increase MAR margin	Reduce cost	Accelerate schedule	Increase through-put	Improve worker safety	Reduce risk to public	Reduce waste
50 ppy with 1 shift, 80 with 2	x		x	x				
Royal Crest		x	x	x			x	
Pu dispersion		x	x	x				
Remove contaminated eqpt	x				x	x		
Conservative assumptions		x	x	x				
Additive mfg for tooling			x	x				
Fabricate crucibles			x		x	x		x
Containers		x				x	x	
Process samples	x	x	x		x			x
Discard byproducts	x		x		x			x
Calcium chloride	x		x		x			x
Remove americium	x	x	x			x		
Accept more uranium	x		x		x			
Near net shape casting		x	x					x
PF-4 seismic resilience		x				x	x	
Pu-238 module	x	x					x	

Source: CRS.

Options Not Involving Process Modifications

Install Equipment with a Single-Shift Capacity of 50 ppy

This option holds the potential to reduce space requirements and cost, and to accelerate schedule.

DOD has stated a need for NNSA to have a capacity to manufacture 50 to 80 ppy. As John Harvey, then Principal Deputy Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs, said in 2013,

> We established that requirement back in 2008 for a capability to produce in the range of 50 to 80 per year. That evolved from a decision to basically not take the path that we originally were taking with the Modern Pit Facility, but to go and be able to exploit the existing infrastructure at Los Alamos to meet our pit operational requirements. The capability at Los Alamos was assessed to be somewhere in the range of 50 to 80 per year that they could get with the modernization program they anticipated. The Nuclear Weapons Council looked at that number. It's a capacity-based number, and said it's probably good enough. We'll have to accept some risk, but it's probably good enough.[5]

As it happens, Los Alamos "estimates that a second shift would increase pit-manufacturing capacity by 60% so that establishing a 50-ppy capacity could supply 80 ppy using a second shift."[6] This range leaves uncertain whether there will be a need for 80 ppy, or whether 50 ppy would suffice. Adding to this uncertainty are NNSA's decision to defer to FY2030 the projected delivery of the first production unit of the first interoperable warhead (IW-1),[7] which might be the first to use a newly manufactured pit since 2011; the possibility that certain retired pits might prove suitable for reuse, reducing the number of newly manufactured pits needed; and the possibility that pit lifetime could turn out to be longer than currently expected. (Estimates of pit lifetime have increased. In 2003, pit life was thought to be 45 to 60 years.[8] A 2007 study placed the intrinsic life for plutonium in most pit types in the stockpile at over 100 years.[9] A 2012 study by Lawrence Livermore National Laboratory placed the figure at 150 years; Los Alamos raised uncertainty about that claim.[10])

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[5] Reserve Officers Association, Air Force Association and National Defense Industrial Association Capitol Hill Breakfast Forum with Linton Brooks, Senior Adviser at the Center for Strategic and International Studies; and John Harvey, Principal Deputy Assistant Secretary of Defense for Nuclear, Chemical and Biological Defense Programs, on "The Nuclear Infrastructure Challenge And Deterrence Implications," June 13, 2013, http://secure.afa.org/HBS/transcripts/2013/June%2013%20-%20Brooks.pdf. The Modern Pit Facility was to be a pit factory. NNSA approved a mission need for the facility in FY2002, with a capacity between 125 and 450 ppy; Congress eliminated funds for it in the FY2006 budget cycle.

[6] Information provided by Los Alamos National Laboratory, email, April 1, 2015.

[7] U.S. Department of Energy. Office of Chief Financial Officer, *FY 2015 Congressional Budget Request*, Volume 1, National Nuclear Security Administration, DOE/CF-0107, Washington, DC, February 2015, p. 94, http://www.energy.gov/sites/prod/files/2015/02/f19/FY2016BudgetVolume1%20_1.pdf.

[8] U.S. Department of Energy. National Nuclear Security Administration, Draft Supplemental Programmatic Environmental Impact Statement on Stockpile Stewardship and Management for a Modern Pit Facility, Summary volume, DOE/EIS-236-S2, Washington, DC, May 2003, pp. S-12, http://energy.gov/sites/prod/files/EIS-0236-S2-DEIS-Summary-2003_1.pdf.

[9] R. J. Hemley et al., Pit Lifetime, The MITRE Corporation, JASON Program Office, JSR-06-335, McLean, VA, January 11, 2007, p. 19, http://www.fas.org/irp/agency/dod/jason/pit.pdf.

[10] See Arnie Heller, "Plutonium at 150 Years: Going Strong and Aging Gracefully," *Science & Technology Review,* (continued...)

Compared to equipment to manufacture 80 ppy with a single shift, installing equipment to manufacture 50 ppy with a single shift would reduce cost and space because fewer pieces of equipment would be needed. Space reduction is of particular value because if this and other space-saving techniques could enable pit production to be done in PF-4, it may be possible to avoid the need for one or more modules for that purpose, potentially avoiding several billion dollars of added cost.

There are several disadvantages to building capacity for 50 ppy as a means to reach production of 80 ppy. A higher operating tempo would place more strain on the equipment while allowing less time in which to maintain and repair it, though this disadvantage would occur only if the equipment were operated with two shifts a day. A few production processes run continuously for more than one shift, so adding a shift would not increase their capacity. It would be much harder to surge production beyond 80 ppy if that proved necessary.

Increasing PF-4's capacity substantially would require changing the layout of gloveboxes and equipment. Such actions would have to comply with many regulations and other requirements; as a result, they would be time-consuming and costly. This would be true for any reorganization of space, but time and cost would in all likelihood increase as capacity in PF-4 increased, so it would probably be faster and less costly to reorganize space for 50 ppy than for 80 ppy.

Relocate a Trailer Park at Los Alamos

This option holds the potential to increase MAR permitted in PF-4 faster and at lower cost than new construction.

Los Alamos National Laboratory is located on one side of Los Alamos Canyon; the city of Los Alamos is located on the other side. The Royal Crest trailer park, with several dozen trailers, is on the lab side of the canyon. It contains the non-lab inhabited structures closest to PF-4, about 3,500 feet away. The next closest structures occupied by the public are located on Trinity Drive in the city of Los Alamos, about 6,000 feet from PF-4, and the next closest such structures after those in Los Alamos are in the city of White Rock, about five miles southeast of PF-4. **Figure 1** shows the location of Royal Crest, PF-4, and the southern portion of the city of Los Alamos.

Figure 1. Royal Crest, PF-4, Los Alamos

Source: Graphic, Google Maps; annotation, CRS.

Royal Crest is the posited location of the maximally-exposed offsite individual (MEOI), the hypothetical person outside the lab boundary who would receive the highest radiation dose from an accident in PF-4 that released plutonium. The significance is that if Royal

(...continued)

December 2012, pp. 12, 14, https://str.llnl.gov/Dec12/pdfs/12.12.2.pdf, and David Clark, "Summary Remarks on Plutonium Aging," LA-UR-13-27541, Los Alamos National Laboratory, September 2013, p. 1.

Crest were no longer the location of the MEOI—and the road, E. Jemez, that it is on were to be placed under the control of the lab—then the next closest inhabited structure would be 2,500 feet farther away. The quantity of radioactive particles deposited per unit of area generally decreases with distance from the radioactive source because more particles are deposited closer to the source and those deposited at a greater distance are spread out over a wider area. As a result, for a wind blowing from PF-4 toward Royal Crest and Los Alamos, dose to an MEOI in Los Alamos would be expected to be less than to an MEOI at Royal Crest. Since the MAR ceiling in PF-4 depends on dose to the MEOI, reducing the dose to the MEOI would—by itself—permit increasing MAR in PF-4. Based on preliminary calculations related to the dispersion of radioactive materials from PF-4 in an accident, Los Alamos National Laboratory estimates that if the MEOI is at E. Jemez Road, dose to him or her would be reduced by 4%, and if that individual is at the southern border of Los Alamos city, dose would be reduced by 40%.[11] The reduction in dose would, if incorporated into PF-4 safety calculations, permit an increase in MAR in PF-4. If wind always blew directly from PF-4 toward Royal Crest and the city of Los Alamos, then a 40% reduction in dose would permit a 67% increase in PF-4 MAR. However, calculation of dose must factor in the probabilities of each direction the wind blows at PF-4. As a result, the increase in MAR permitted by relocating Royal Crest would be considerably less than 67%. A detailed calculation would be required to arrive at a precise figure. Nonetheless, relocating Royal Crest could permit an increase in MAR at PF-4 faster, and probably at substantially lower cost, than new construction.

Improve Modeling of Atmospheric Dispersion of Plutonium

Compared to the current calculation, using a different computer model and different assumptions on plutonium dispersion reduces calculated dose by up to orders of magnitude. This revised calculation holds the potential to permit more than doubling of PF-4 MAR quickly and at essentially no cost.[12]

NNSA calculates dose to an MEOI from an accident at PF-4 using computer models. The models use assumptions on the amount and form of plutonium released into the atmosphere, mechanisms for releasing it from PF-4, wind direction and speed, temperature, humidity, and the like. Three changes to accident modeling produce very different results than those currently assumed in the PF-4 safety documentation.

- First, LANL, consistent with guidance from NNSA, uses a particular atmospheric transport and dispersion model to calculate how much material reaches the MEOI. However, a different model that the Nuclear Regulatory Commission has used for decades, which includes "plume meander," generates a wider dispersion pattern and thus a lower dose.[13]
- Second is an assumption on how long the doors to PF-4 are open during the accident as personnel evacuate. This seemingly minor assumption is important

[11] Information provided by Los Alamos National Laboratory, April 20, 2015.

[12] Information in this section provided by Los Alamos National Laboratory, April 2015.

[13] U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants*, Regulatory Guide 1.145, November 1982, p. 1, http://pbadupws.nrc.gov/docs/ML0037/ML003740205.pdf. NRC applies this model for wind speeds of up to 6 meters per second (about 13 mph) at a height of 10 meters. Ibid., p. 3.

because less plutonium would escape if the doors were open for less time. The new calculation reduces the time that the doors are assumed to be open based on historical data during drills.[14]

- A third assumption has to do with time of day. The least dispersion of particles occurs at night, when winds are calmer. More dispersion occurs with daytime wind patterns. Greater dispersion results in a lower dose to an MEOI at any spot. Yet more plutonium is in process, and at risk, during the day, when technicians are working with it; at night, it is stored in a minimally vulnerable state. At present, the model assumes daytime MAR and nighttime dispersion. Harmonizing MAR and time of day reduces dose: at night, there is less dispersion but less plutonium that can be dispersed, reducing dose; during the day, more plutonium is at risk but an accident would disperse it more widely, reducing dose.

These three changes, plus others, in PF-4 accident modeling could reduce the calculated dose to the MEOI by several orders of magnitude. That reduction, if incorporated into PF-4's safety documents, would permit more than doubling the MAR permitted in PF-4. It would surely be faster and less costly to change to a more realistic model and assumptions than to build a new plutonium building. A more conservative model, almost by definition, produces a lower dose, though changes to reduce conservatism a model, if valid, do so as well. At issue for Congress are whether a change made to PF-4's MAR allowance in consequence of using the more realistic model would increase risk to the public and, if so, whether the benefits obtained by using that model would be worth the added risk. Public perception is also at issue: would members of the public believe that NNSA permitted the change in model in order to save money at the expense of public safety?

Remove Contaminated Equipment

This option holds the potential to reduce the risk of contamination—thereby improving worker safety and reducing risk to throughput—and to increase space available in PF-4.

The Defense Nuclear Facilities Safety Board (DNFSB) monitors health and safety issues at DOE defense nuclear facilities, and provides the President and Secretary of Energy with advice and recommendations on these issues.[15] A DNFSB report of October 2014 stated, in a section on PF-4,

> an entire wall of legacy gloveboxes, including some that housed a former incineration process for plutonium-238 contaminated rags, contains degraded conditions that workers suspect has contributed to multiple contamination events during the past few years. LANL management does not currently have a plan to remove these gloveboxes in order to both eliminate the hazard and free up the considerable space for new programmatic work.[16]

[14] Complete collapse of PF-4 would render door opening time moot; on the other hand, the rubble generated by the collapse would contain much of the plutonium.

[15] See Defense Nuclear Facilities Safety Board, "Who We Are," http://www.dnfsb.gov/about/who-we-are.

[16] Defense Nuclear Facilities Safety Board, "Los Alamos Report for Week Ending October 10, 2014," October 10, 2014, 1 p., http://www.dnfsb.gov/sites/default/files/Board%20Activities/Reports/Site%20Rep%20Weekly%20Reports/Los%20Alamos%20National%20Laboratory/2014/wr_20141010_65.pdf.

While the amount of Pu-238 is apparently small, it is much more radioactive than Pu-239, so removing the gloveboxes would reduce MAR by a small amount. Of greater importance, removing the gloveboxes would reduce the risk of a contamination accident, which would remove a room from service until the contamination was cleaned up. Minimizing the risk of such accidents increases the availability of the room to support pit production. Removing these gloveboxes would also "free up the considerable space." The gloveboxes will have to be removed eventually for decontamination and decommissioning at the end of PF-4's life; there is a tradeoff between gaining the advantages of removing them sooner and the drawback of incurring the cost now rather than later.

Increase Material-At-Risk Ceilings by Using Conservative Rather Than Very Conservative Assumptions

This option holds the potential to increase permitted MAR in PF-4 by several orders of magnitude by using different assumptions in a calculation. While such an increase is vastly more than needed, the analysis shows how it might be possible to increase permitted MAR enough to meet mission requirements without construction. It would be faster to change assumptions than to build a new plutonium building, thereby accelerating schedule and avoiding a substantial cost.

This section highlights a tradeoff among costs, benefits, and risks. Using the most conservative assumptions provides the greatest margin of safety, but does so at the highest cost. At issue for Congress is a political judgment: for risk reduction, at what point are the marginal costs no longer worth the marginal benefits? Could funds spent for a small reduction in dose from a sequence of events occurring once in perhaps hundreds of thousands of years be more beneficially spent elsewhere?

A MAR limit is imposed uniquely for each building (except those with a very small amount of material) by a Documented Safety Analysis that is intended to limit MAR so as to ensure that the radiation dose to nearby workers and the public from such a disaster does not exceed certain limits specified by DOE. Dose is calculated for a MAR value using a ten-factor equation that includes the amount of damage the building sustains, the fraction of plutonium that is released into the atmosphere by the event, an individual's breathing rate, and others. MAR is the input variable, and dose is the resultant. Each variable is assigned a value pursuant to a DOE standard or other source. One variable, specific activity (radioactivity per unit mass), varies with the type of material (e.g., uranium, WGPu, or Pu-238). Other variables, such as breathing rate, would under most circumstances be taken as a constant. To keep dose below the specified levels, NNSA typically assigns several variables a very conservative worst-case, or "bounding," value.

In 2014, Kamiar Jamali, Associate Administrator for Safety and Health, Office of Nuclear Safety, NNSA, described the consequences of using multiple variables, each with worst-case values:

> When complex analyses are employed to derive distributions for output variables for calibration of the degree of uncertainties in analysis results, the 95th percentile is generally associated with the upper-bound. … [However,] when several input parameters are taken at their bounding values, the obtained result dwarfs the derived 95th percentile of the output by orders of magnitude.
>
> Extreme conservatism is often intentionally exercised in safety analyses because it can pay dividends in simplified analysis and review efforts. However, the search for increased conservatism cannot be pursued without consequences. Extreme conservatism can lead to

> safety conclusions and decisions with significantly higher safety costs, which can make nuclear facilities, even those with very low hazard and risk profiles, prohibitively expensive.[17]

Jamali also stated, "The mean value is proposed as the metric that is consistent with the concept of reasonable conservatism in nuclear safety analysis, as its value increases towards higher percentiles of the underlying distribution with increasing levels of uncertainty."[18] That is, the more variables in a nuclear safety equation, the closer the product of the equation moves toward (if not beyond) the 95th percentile.

Excessive conservatism has been a concern for years. In 1999, another DOE staff member wrote,

> While nuclear safety analyses must always be conservative, invoking excessive conservatisms does not provide additional margins of safety. Rather, beyond a fairly narrow point, conservatisms skew a facility's true safety envelope by exaggerating risks and creating unreasonable bounds on what is required for safety. The conservatism has itself become unreasonable. …
>
> Unreasonable conservatisms require expensive preventive or mitigative features that provide little or no real improvement in facility safety. Indeed, they are often counterproductive to real safety, diverting attention from other equipment whose actual importance to safety is greater.[19]

Another study found that the assumptions used to calculate health effects of a given dose can make a difference in the projected health effects by as much as several orders of magnitude.[20]

A catastrophe that results in all terms being at their bounding values has a much lower probability of occurring than does the initiating event. An earthquake that collapses PF-4 has a probability of occurring once in 10,000 years. But the worst-case sequence would require a complete building collapse followed by fire. The plutonium in the building would have to be in a form and condition in which it could be dispersed (e.g., spilled onto the floor as a result of a glovebox being knocked over while the plutonium was in molten form). A substantial part of that plutonium would have to be in the form of plutonium oxide particles of a size small enough to reach the lungs when inhaled, and all these particles would have to reach the atmosphere. A high wind would have to be blowing in the "right" direction to expose the MEOI to more than a negligible dose. That unfortunate individual would have to be doing moderate exercise for two hours at the spot at the site boundary that received the most deposition of plutonium. In sum, if the earthquake that initiates this sequence occurs once in 10,000 years, the concatenation of all these events would occur far less frequently. The odds of all these events occurring all at once within the service life of PF-4 are extremely low.

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[17] Kamiar Jamali, "Achieving Reasonable Conservatism in Nuclear Safety Analyses," *National Nuclear Security Administration Technical Bulletin 2014-1,* July 2014, p. 2.

[18] Ibid., p. 2.

[19] Guy Bishop III, Department of Energy, Richland Field Office, Richland, WA, "Removing Unreasonable Conservatisms in DOE Safety Analyses," paper to be presented at Safety Analysis Working Group, Portland, OR, June 13-18, 1999, DOE-0274-FP, pp. 1, 2, http://www.osti.gov/scitech/servlets/purl/782380.

[20] See Richard Chang et al., *State-of-the-Art Reactor Consequence Analyses (SOARCA) Report,* U.S. Nuclear Regulatory Commission, NUREG-1935, November 2012, pp. 78-80, http://pbadupws.nrc.gov/docs/ML1233/ML12332A057.pdf.

While desirable in an ideal world, guarding against the worst case has its costs. It requires much more stringent safety features, much more rigorous standards for equipment, and construction that is much more resistant to threats such as earthquakes. Such features drive up the cost of a building, perhaps to the point where it is no longer affordable. Alternatively, bounding assumptions might require construction of one to three modules costing perhaps $1 billion each.

An alternative is to use the expected, or median, value for each of five variables (airborne release fraction, respirable fraction, damage ratio, leak path factor, and chi/Q, as described in **Table 2**) that could readily be varied. While Jamali suggests using mean values, some DOE documents provide mean values and others provide median. For purposes of safety basis calculations applicable to LANL, however, mean and median are so close together as to be virtually indistinguishable.[21] It is reasonable to use mean or median values rather than bounding values because, as noted, use of multiple bounding values in an equation produces a result—i.e., a dose to the MEOI—orders of magnitude greater than the standard bounding value, i.e., the 95th percentile. Yet an increase in the MAR ceiling in PF-4 by a factor of less than ten, and perhaps less than two—especially when combined with other MAR reduction measures described in this report—would probably provide enough MAR to permit production of 80 pits per year in PF-4. (Meeting MAR requirements would not address space requirements.)

Increasing the MAR ceiling could also benefit analytical chemistry. The Radiological Laboratory-Utility-Office Building is ideally configured for AC, but DOE's regulations, which it has set for itself, limit "radiological facilities" like RLUOB to 38.6 g Pu-239 equivalent. About 26 g of WGPu has the radioactivity of 38.6 g of Pu-239—and the volume of two nickels. Increasing that ceiling by a factor of 40 or less might permit RLUOB to perform most of the AC needed to support production of 80 ppy.

Table 2 shows the relationship between MAR and dose and how different assumptions affect dose. Each row is an equation, with the first nine terms multiplied together to yield dose. In Equation 1, which follows DOE guidelines, a PF-4 MAR of 2,600 kilograms produces a dose to an MEOI of 166 rem in a worst-case accident. (Rem is a measure of radiation dose.) The dose would mainly result from plutonium oxide particles inhaled within two hours of the accident, but since some plutonium would remain in the body for many years, the dose would be the cumulative dose received over 50 years. In Equation 2, which uses median values, that same MAR produces a dose of 0.005 rem. Thus Equation 1 results in a MAR 35,000 times as great as in Equation 2. The same result holds for RLUOB in Equations 3 and 4.

Two scenarios illustrate the difference. Imagine that PF-4 collapsed in an earthquake and was subject to a fire. In one scenario, PF-4 has 35,000 kg of plutonium MAR and the dose to an MEOI is calculated using median values in the equation. In the other scenario, PF-4 has 1 kg of plutonium MAR and the dose to an MEOI is calculated using bounding values. The dose to the MEOI would be the same for both scenarios.

[21] Information provided by Los Alamos National Laboratory, November 18, 2014.

Table 2. Relationship between MAR and Dose Using Very Conservative and Conservative Assumptions

Building and assumptions (bounding or median)	Variables									
	MAR	ARF	RF	DR	LPF	chi/Q	BR	SA	DCF	Dose
1: PF-4, bounding	2.60E+06[a]	2.00E-03[b]	0.3[b]	1[c]	1[d]	8.77E-05[e]	3.30E-04[f]	6.22E-02[g]	5.92E+07[h]	1.66E+02
2: PF-4, median or mean	2.60E+06[a]	3.00E-04[b]	0.5[b]	0.1[i]	0.1[i]	1.00E-06[j]	3.30E-04[f]	6.22E-02[g]	5.92E+07[h]	4.74E-03
3: RLUOB, bounding	4.00E+02[a]	2.00E-03[b]	0.3[b]	1[c]	1[d]	8.77E-05[e]	3.30E-04[f]	6.22E-02[g]	5.92E+07[h]	2.56E-02
4: RLUOB, median or mean	4.00E+02[a]	3.00E-04[b]	0.5[b]	0.1[i]	0.1[i]	1.00E-06[j]	3.30E-04[f]	6.22E-02[g]	5.92E+07[h]	7.29E-07

Source: CRS.

Notes:

The first nine variables are multiplied together to arrive at dose. Values are for plutonium.
Dose is for a maximally-exposed offsite individual (member of the public).
Values are for plutonium in PF-4 and RLUOB.
Bounding assumptions are very conservative; median assumptions are conservative.
Median values are used for ARF, RF, DR, and LPF; mean value, the value available in source (e), is used for chi/Q. According to Los Alamos, for purposes of safety analysis the mean and median values for this term would be almost the same.

Abbreviations:

"E," as in E+06, represents multiplication by 10 to an exponent. Thus, 2.60E+06 = 2.60 x 10^6.
MAR: Material At Risk (grams Pu-239 equivalent), MAR is specified; it is the initial input variable
ARF: Airborne Release Fraction (dimensionless fraction), fraction of MAR released by an event
RF: Respirable Fraction (dimensionless fraction), fraction of ARF particles of a size that can be inhaled
DR: Damage Ratio (dimensionless fraction), fraction of damage a building sustains
LPF: Leak Path Factor (dimensionless fraction), fraction of respirable particles that leak out of building or rubble
chi/Q: Dispersion Coefficient (seconds/cubic meter), how widely the respirable particles disperse
BR: Breathing Rate (cubic meters/second), a measured value based on research
SA: Specific Activity (curies/gram), radioactivity per unit mass, here the value for Pu-239
DCF: Dose Conversion Factor (rem/curie), converts the product of the preceding variables to rem
Dose (rem), the dependent variable, to be calculated
The **Appendix** provides further details on these terms.

Source notes for each cell:

a. MAR is specified by user

b. DOE-HDBK-3010-94 December 1994, Reaffirmed 2013: Airborne Release Fractions/Rates and Respirable Fractions for Nuclear Facilities: Volume I, Analysis of Experimental Data, p. 4-9, http://energy.gov/sites/prod/files/2013/09/f2/DOE-HDBK-3010_V1_Reaffirm_2013_0.pdf

c. 1 is the bounding value, as it represents complete collapse of the structure

d. DOE-STD- 3009-94, Change Notice No. 3, March 2006, DOE Standard: Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analyses, p. A-6, http://energy.gov/sites/prod/files/2013/06/f1/doe-std-3009-94_cn3_3-30-06.pdf

e. H. Jordan, G. Smith, and R. Sartor, Consequence Calculations for Safety Analysis at TA-55 and the CMR Facility using ICRP-72 Dose Conversion Factors, LA-UR-09-07272, Los Alamos National Laboratory, November 2009, p. 11

f. NNSA, Guidance on Using Release Fraction and Modern Dosimetric Information Consistently with DOE STD 1027-92, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23,*

Nuclear Safety Analysis Reports, Change Notice No. 1: Supplemental Guidance, NA-1 SD G 1027, approved 11-28-11, p. 4-3, http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/NNSA_Supp_Guide_1027.pdf

g. DOE- STD-1128-2013 April 2013: Good Practices for Occupational Radiological Protection in Plutonium Facilities, p. 2-6, http://energy.gov/sites/prod/files/2013/10/f3/DOE-STD-1128-2013.pdf

h. International Commission on Radiation Protection Publication 72, Age-dependent Doses to the Members of the Public from Intake of Radionuclides - Part 5 Compilation of Ingestion and Inhalation Coefficients, p. 41, September 1995

i. Information provided by Los Alamos National Laboratory, email, November 26, 2014

The March 2011 Fukushima Daiichi accident offers a concrete example of the divergence between calculated and actual effects of an accident involving radioactive release. In an article submitted in April 2012, the authors "[found] that inhalation exposure, external exposure, and ingestion exposure of the public to radioactivity may result in 15 to 1300 cancer mortalities and 24 to 2500 cancer morbidities worldwide, mostly in Japan. Exposure of workers to radioactivity at the plant is projected to result in another 2 to 12 cancer cases."[22] In contrast, a report of May 2013 by the U.N. Scientific Committee on the Effects of Atomic Radiation noted a "release, over a prolonged period, of very large amounts of radioactive material into the environment" from the accident. While those closest to the accident would have been at greatest risk, the report found

> No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident.
>
> The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants.[23]

Use Additive Manufacturing to Make Tooling for Pit Work

This option holds the potential to reduce turnaround time, thereby accelerating schedule, and to reduce cost.

Many see additive manufacturing (AM) as transformative for manufacturing. At issue for Congress: given the potential of AM, what applications, if any, might it have for pit production?

Additive manufacturing, often called 3-D printing, forms physical objects by depositing multiple layers of material using a "digital build file," a computer program that instructs the AM machine where to deposit the material. Objects can range from simple to so complex that they cannot be manufactured in any other way. Many analysts view AM as the future of manufacturing. According to Lawrence Livermore National Laboratory,

> Today, a metal part can be designed using computer-aided design tools and then uploaded to a machine where the part can be built layer by layer, that is, additively manufactured with

[22] John E. Ten Hoevea and Mark Z. Jacobson, "Worldwide health effects of the Fukushima Daiichi nuclear accident," *Energy & Environmental Science,* Received 23rd April 2012, Accepted 26th June 2012, DOI: 10.1039/c2ee22019a, p. 1, http://web.stanford.edu/group/efmh/jacobson/TenHoeveEES12.pdf.

[23] United Nations, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, Sixtieth session (27-31 May 2013), General Assembly Official Records, Sixty-eighth session, Supplement No. 46, A/68/46, pp. 7, 11-12, http://www.unscear.org/docs/GAreports/A-68-46_e_V1385727.pdf.

> quality approaching that of wrought alloys. Within the next decade or two, additive manufacturing (AM) is going to completely change how we view the design and production of metal parts. AM will both replace and complement traditional manufacturing methods and reduce the time, cost, and energy consumption of producing new and existing metal parts. In order to fully implement AM, specific scientific and technical challenges must be addressed.[24]

Industry uses AM to produce complex high-precision parts that require high reliability. For example, General Electric is planning to build fuel nozzles for new jet engines using AM:

> GE chose the additive process for manufacturing the nozzles because it uses less material than conventional techniques. That reduces GE's production costs and, because it makes the parts lighter, yields significant fuel savings for airlines. Conventional techniques would require welding about 20 small pieces together, a labor-intensive process in which a high percentage of the material ends up being scrapped. Instead, the part will be built from a bed of cobalt-chromium powder. A computer-controlled laser shoots pinpoint beams onto the bed to melt the metal alloy in the desired areas, creating 20-micrometer-thick layers one by one. The process is a faster way to make complex shapes because the machines can run around the clock. And additive manufacturing in general conserves material because the printer can handle shapes that eliminate unnecessary bulk and create them without the typical waste.[25]

General Electric "is using laser-powered 3-D printers, 3-D 'inking' and 'painting' machines, and other advanced manufacturing tools to make parts and products that were thought impossible to produce … We see advanced manufacturing as the next chapter in the industrial revolution."[26]

A second example concerns AM for making large parts that undergo high stress:

> In gas turbines, the blades move at the speed of sound and heat up to 1,400°C. The elaborately shaped components are hard to design and costly to make. But Siemens, a big industrial group, is using SLM Solutions' [AM] machines to cut the cost and the time needed to replace the blades on customers' turbines when they break. It hopes eventually to cut the time from order to delivery from 44 weeks to perhaps four. …
>
> Additive manufacturing cuts the cost of tooling and materials: a piece can have all of its holes incorporated into it, with great precision, as it is built up from powder, instead of needing to have them expensively drilled afterwards. Siemens hopes to cut the cost of some parts by perhaps 30%.[27]

These examples show that AM can save time, space, and money; reduce waste; reduce the reject rate, increasing throughput; make parts on demand; and switch rapidly from making one part to making another. It can make complex parts. It can avoid some manufacturing steps, such as drilling holes, saving time and reducing the risk of error. Not all advantages apply to each product. AM is not the best manufacturing method for all materials and components, and it may

[24] Lawrence Livermore National Laboratory, "Accelerated Certification of Additively Manufactured Metals Initiative: Metal Additive Manufacturing," 1/14/2015, https://acamm.llnl.gov.

[25] Martin LaMonica, "10 Breakthrough Technologies 2013: Additive Manufacturing," *MIT Technology Review,* April 23, 2013, http://www.technologyreview.com/featuredstory/513716/additive-manufacturing/.

[26] General Electric, "Transforming manufacturing, one layer at a time," http://www.ge.com/stories/advanced-manufacturing.

[27] "Additive Manufacturing: Heavy Metal," *The Economist,* May 3, 2014, http://www.economist.com/news/business/21601528-three-dimensional-printing-may-help-entrench-worlds-engineering-giants-heavy-metal.

not be suitable for some. But because it is adding value in many ways, it is likely to attract more R&D dollars, leading to advances that will make it applicable to a wider range of products.

Recognizing the potential of AM to transform manufacturing, Congress, in P.L. 113-235, the Consolidated and Further Continuing Appropriations Act for FY2015, provided $12.6 million for AM for the nuclear weapons program, and the appropriations committees directed NNSA to provide "a ten-year strategic plan for using additive manufacturing to reduce costs at NNSA production facilities while meeting stringent qualification requirements."[28] The report is due to the House and Senate Committees on Appropriations 120 days after enactment of this act, which was signed into law on December 16, 2014. In late April 2015, NNSA indicated that it expects to transmit the report, which will be classified, to Congress in several weeks.[29]

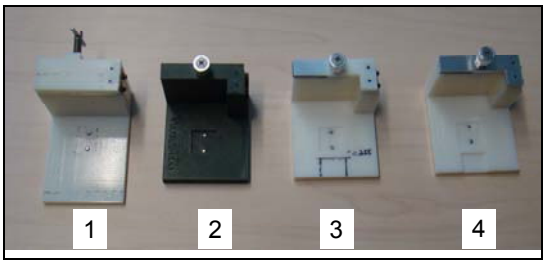
NNSA is exploring applications of AM in the nuclear weapons complex. Donald Cook, Deputy Administrator for Defense Programs at NNSA, said in January 2015, "within the last year, more than half of the new fixturing within the new Kansas City National Security Campus was made with AM processes."[30] (Fixtures hold material in place for machining and inspection.) A Livermore publication states,

> A match drill fixture, the first piece of production-qualified tooling made by AM, has already entered use at Y-12. The new approach for producing this tool consolidates 5 parts into 1, thereby eliminating 12 welds and reducing waste.
>
> NNSA sites estimate that 50 percent of its tools could be made using AM in five years. In which case, tooling production costs would be reduced 75 percent, development time 80 percent, and production time 60 percent, while potentially improving tool performance. Further, the items could be printed on demand, reducing inventory and freeing space.[31]

Figure 2 illustrates the capability of AM to develop prototypes rapidly.[32] It shows a tool, in this case a fixture for holding a part, as it moves through four iterations. Iteration 1 has a screw in the back. Iteration 2 has a shorter horizontal plate, a cutout in the vertical plate, and the screw on top, where it is easier to access. Iteration 3 uses the same material, a plastic, as iteration 2 but with a different color. The metal piece on top was made in a machine shop. The customer drew by hand where an additional indent should be. Iteration 4, with the indent, is the final tool. It

Figure 2. Iterative Development of a Tool

Using Additive Manufacturing



Source: Sandia National Laboratories; annotation by CRS.

[28] "Explanatory Statement Submitted by Mr. Rogers of Kentucky, Chairman of the House Committee on Appropriations Regarding the House Amendment to the Senate Amendment on H.R. 83," *Congressional Record*, daily edition, vol. 160, no. 151, part II (December 11, 2014), p. H9703.

[29] Email, April 23, 2015.

[30] Email, January 12, 2015.

[31] Rose Hansen, "Next-Generation Manufacturing for the Stockpile," *Science & Technology Review*, January/February 2015, p. 6, https://str.llnl.gov/content/pages/january-2015/pdf/01.15.1.pdf. A match drill fixture aligns a drill for machining.

[32] Information provided by Nathan Fuller, Mechanical Engineer, Sandia National Laboratories, emails and telephone conversations, March 3 and 9, 2015.

took two days for Sandia National Laboratories to make each iteration, for $77 apiece, as compared to 42 days for an outside machine shop to manufacture each iteration at a cost of $500 apiece.

AM parts, such as fixtures and tools, might be used in support of pit production. In some cases, they can be stronger and lighter than tools made with conventional methods. For example, AM tools can be "lightweighted," e.g., made with honeycomb in areas that do not require much strength and solid in areas that do, providing ergonomic benefit for glovebox work. AM for tooling might offer modest savings, as tooling is a minor cost of pit manufacturing, but it more likely would save time, as AM can prototype tools quickly and can make them to order. Saving time would help increase throughput. Currently, tools for pit work are made with conventional methods, which is generally satisfactory. However, Livermore notes, "very little work is being done to explore tooling used in conjunction with pit production."[33]

Use a Different Process to Fabricate Crucibles[34]

This option holds the potential to reduce risk to workers, cost, and waste, and to increase throughput.

The electrorefining process for purifying plutonium, discussed in "Discard Byproducts of Electrorefining," below, is conducted in magnesium oxide crucibles, and produces a ring of purified plutonium. To fit in a furnace, this ring must be broken into several pieces in order to be melted down for casting. This procedure has several problems:

- Crucibles are made by casting a slurry of magnesium oxide particles followed by sintering.[35] The crucibles have historically not been made as a single piece because it has been simple to make two separate cups and join the inner cup with an adhesive to the bottom of the outer cup. Sometimes, given the high heat and the reactive nature of plutonium, the adhesive fails and the cups come apart.
- A failed electrorefining run produces more waste, such as the adhesive, than a successful run, and reduces throughput and increases cost.
- The plutonium ring is broken in a glovebox located in the electrorefining area. The glovebox uses a hydraulic breaking press; the breaking operation produces chunks, shards, and grains of plutonium metal. Shards may puncture gloves used in gloveboxes, posing a risk to technicians. Shards and grains must be reprocessed through the chloride recovery line, generating waste and increasing cost. The operation adds a process step and entails worker exposure to radiation.

[33] Email, April 3, 2015.

[34] This section is based on discussions with Los Alamos National Laboratory staff, November 2014-February 2015, Lawrence Livermore National Laboratory staff, January and April 2015, and "Plutonium Processing at Los Alamos," *Actinide Research Quarterly* (entire issue), third quarter 2008, p. 13, http://arq.lanl.gov/source/orgs/nmt/nmtdo/AQarchive/3rdQuarter08/pdf/ARQ.3.08.pdf.

[35] "Sintering is a heat treatment applied to a powder compact in order to impart strength and integrity. The temperature used for sintering is below the melting point of the major constituent of the Powder Metallurgy material. After compaction, neighbouring powder particles are held together by cold welds." "Sintering in the Powder Metallurgy Process," no author or date, *Powder Metallurgy Review,* http://www.ipmd.net/Introduction_to_powder_metallurgy/Sintering, accessed February 9, 2015. A slurry is a mixture of solid particles suspended in liquid, in this case magnesium oxide particles in water.

- The breaking press glovebox takes up space that could be used to add a metal recovery glovebox, such as an additional electrorefining station. So doing would increase the throughput of that process and support a higher pit production rate.

The United Kingdom's Atomic Weapons Establishment is conducting final development trials of a crucible that addresses these problems. It is made in one piece with ridges running from the outer wall of the inner cup to the inner wall of the outer cup in order to deposit molten purified plutonium in segments. This eliminates the need for a separate glovebox for breaking the plutonium ring and the resulting problems. The crucible is made with the same "slip casting" process used to make current crucibles. "Slip" refers to the thick water-magnesium oxide slurry. The molds are made of plaster of paris; an inner and outer mold are used to make complex shapes such as the ridged crucible. The slurry is poured between the two molds. Plaster of paris draws water out of the slurry, leaving magnesium oxide in the desired shape, which is then heated to high temperature in a furnace to sinter the magnesium oxide particles into a dense solid. These crucibles would appear to be applicable to U.S. electrorefining operations. On the other hand, development of the new crucibles is not complete, and there is no operational experience with them, so there is no guarantee that they will function properly in practice. A decision on whether to use them, or to continue using existing crucibles, must therefore await additional data.

Options Involving Process Modifications

Develop and Qualify Accident-Resistant Containers

This option holds the potential to improve worker safety, reduce MAR, and reduce risk to the public.

Radioactive material is "at risk" if it can be acted upon by an event. In the case of PF-4, "acted upon by an event" means plutonium released into the atmosphere by a worst-case accident, such as an earthquake followed by a fire. One way to reduce MAR in PF-4 is to place plutonium in containers designed to withstand an accident. If 10% of the plutonium in a container is expected to escape, as compared to all of that plutonium in a glovebox, MAR for that plutonium is reduced by 90%. The damage ratio indicates the fraction of plutonium expected to escape: for a damage ratio of 1.0, all the plutonium is expected to escape; for a damage ratio of 0.1, one-tenth is expected to escape.

To reduce MAR, the reduction in damage ratio must be credited in PF-4's Documented Safety Analysis, which, among other things, sets the ceiling on the amount of MAR allowed in PF-4. To qualify containers as having a certain damage ratio, they are subjected to intense testing, such as dropping them from a height of several meters, placing them in a pool of burning kerosene, and heating them to red-hot in an oven. Technicians measure the amount of particulate that comes out of the container after each test. The damage ratio does not apply to a complete collapse of PF-4, as containers are not expected to survive that event.

Some years ago, Los Alamos used a Hagan container, which had a damage ratio of 0.05. Since then, a newer container, a SAVY-4000, has been introduced commercially, with a damage ratio of 0.01. These containers are intended for long-term storage, not for ease of use in gloveboxes. Yet a substantial amount of plutonium on PF-4's lab space is in process. Placing more of that plutonium in containers when not in immediate use would reduce MAR on the main floor.

Examples of how broader use of qualified containers could further reduce MAR include:

- Containers could be designed for use on the pit production line, such as in gloveboxes. These containers would have to be small enough to fit in a glovebox, heavy enough to withstand severe accident conditions, and easy to open and close. They would have to be tested in various ways to confirm that they meet a certain damage ratio. Since plutonium and other radioactive materials are tracked continually in PF-4, containers on the production line would have more impact on MAR fluctuations, and the ability to stay within MAR limits, than would containers holding plutonium for long-term storage, which are seldom opened.
- Pu-238 is 277 times more radioactive than Pu-239, so while PF-4 housed less than 2 kg of Pu-238 in February 2013, it contributed about a quarter of PF-4's MAR. The main application of Pu-238 is in space probes: radioisotope thermoelectric generators convert the intense heat from its radioactive decay to electricity. Pu-238 for use in these generators is converted to a powder. This is done by ball milling, in which a piece of Pu-238 is put in a container with stainless steel shot pellets. The container is tumbled, and the pellets grind the Pu-238. Given the intense radioactivity of Pu-238, this operation is performed in a particularly robust container, which has a damage ratio of 0.01. However, the container has not been credited in the Documented Safety Analysis as having that damage ratio, so tests would have to be done and paperwork completed so it could be credited. So doing would reduce MAR in PF-4.
- Plutonium casting is a major source of MAR in PF-4, second only to Pu-238 operations. Arranging casting equipment so that plutonium is not at risk during casting would help reduce MAR in PF-4. Minimizing MAR from casting would be particularly important in a ramp-up to 80 ppy because more casting would be needed to make more pits. A concern is that, as a result of a catastrophic accident, molten plutonium could spill out into the room and could then burn, forming plutonium oxide particles that could be lofted into the air, resulting in dose to workers or the public. Conducting plutonium casting in a credited container would reduce this risk. At present, molten plutonium is poured into graphite molds to form hemishells. This operation takes place inside robust stainless steel containers attached to the bottom of gloveboxes. However, these containers have not been qualified, so the plutonium in them counts toward MAR. Upgrading the containers so they could be qualified would require a tight and sturdy lid, and the upgraded container would have to be put through various tests. A key advantage of this approach is that it is passive. It would not rely on electrical, plumbing, or other systems to function, a major advantage in the event of a catastrophic accident.

Process Plutonium Samples More Efficiently

This option holds the potential to reduce cost, MAR, space, and waste, and increase throughput.

Pit production requires a detailed characterization of plutonium at various stages, from the electrorefined product to hemishells to waste streams, to determine if the sample falls within required specifications. This characterization is done with analytical chemistry. Samples of metal for AC are taken from larger pieces of plutonium, such as purified metal produced by electrorefining and excess material from hemishell casting. These metal samples, typically 5 g

each, are dissolved in acid and the resulting liquid is split into smaller samples for analysis. Many of these samples contain milligram or smaller quantities of plutonium. Samples are also taken from liquid waste, such as from nitric or hydrochloric acid processes. Rocky Flats Plant, which produced up to 2,000 ppy during the Cold War, took an average of 10.5 metal samples per pit in 1989, the year when plutonium operations at that plant halted. When LANL produced pits after Rocky Flats closed, it took an average of 12 metal samples per pit.

Most of LANL's plutonium AC is conducted in the Chemistry and Metallurgy Research (CMR) building. CMR opened in 1952 and is in poor condition. NNSA plans to halt programmatic activities there by FY2019.[36] As part of that plan, NNSA plans to move most AC from CMR to the Radiological Laboratory-Utility-Office Building. However, as noted, it is not known if RLUOB has enough space and a high enough MAR limit (even if increased to 400g Pu-239 equivalent) to conduct, along with PF-4, the AC needed to support production of 80 ppy. One way to reduce space and MAR required for AC is to reduce the number of samples per pit, or the amount of plutonium per sample. So doing would offer several advantages:

- The amount of equipment needed for AC increases, though not linearly, with number of samples. Analyzing fewer samples per pit would enable fewer pieces of equipment, and fewer gloveboxes, to support a given rate of production, reducing space requirements and cost and increasing throughput.
- Processing fewer samples per pit would increase the likelihood that RLUOB could perform most AC needed, which would reduce the AC capacity and the types of AC capabilities needed in PF-4, reducing encroachment on space there.
- Reducing the number of samples per pit would reduce the amount of waste generated per pit. This would reduce the load on AC—permitting more AC capacity to be used to support pit production—and on waste processing.
- New equipment may provide sufficient confidence with smaller samples, reducing MAR for those analyses. For example, LANL is developing techniques, using new instruments, to reduce the quantity of plutonium per AC sample from 250 mg to 50 mg for certain analyses. This reduction in MAR becomes particularly important as production rate increases.

Accepting less accurate analytic techniques may increase throughput.

- Hemishells require detailed isotopic analysis, which can take 7 to 10 working days for the "gold standard" technique (thermal ionization mass spectrometry). In contrast, samples not requiring war reserve certification, such as metal supply and recovery, could use a less precise technique (gamma ray analysis), which takes 2 to 3 days. The latter approach would also generate less waste.

The chief concern about taking fewer or smaller samples per pit or performing fewer or less accurate analyses is a reduction in precision. This concern can be addressed in several ways.

- Not all pit production process steps for which samples are taken require the highest level of precision. The final product, plutonium in hemishells, requires the greatest accuracy. Less accurate methods, or fewer samples per pit, could

[36] U.S. Department of Energy, *FY 2016 Congressional Budget Request*, Volume 1, National Nuclear Security Administration, p. 65.

provide adequate precision for the initial supply of plutonium, because the goal would be to ensure that production processes were operating properly. Characterization of plutonium metal recovered from salts remaining after electrorefining may not require a full suite of AC with the highest accuracy because the metal would undergo further processing and characterization. Samples taken for waste processing, criticality analysis, and material control and accountability do not require the same level of accuracy as samples for weapon certification. Thus, alternative AC methods might be used or number of samples reduced for some steps.

- As pit production rate increases, fewer samples per pit taken during metal production would probably suffice to demonstrate that production processes were operating properly; the number of samples leading to final certification of a pit would presumably remain unchanged.
- Skill and experience level of personnel affect the success of analysis and production. The experience level of technicians would be expected to increase as production rate increased, which would reduce the need for rework and increase throughput of sample analysis.

Discard Byproducts of Electrorefining

This option holds the potential to reduce cost and waste, increase throughput, and make more space available.

Plutonium decays radioactively, yielding, directly or indirectly, uranium, americium, and neptunium, as detailed in **Table 4**. These, and any impurities from other sources, must be removed before plutonium can be used in pits. There are several steps in purifying plutonium for weapons use; the final step is electrorefining.

Figure 3. A Crucible for Electrorefining Plutonium

Source: Los Alamos National Laboratory

Notes: The diameter of the outer crucible is about 4.5 inches.

In electrorefining, an ingot of impure plutonium is placed in a small magnesium oxide crucible at the bottom center of a larger crucible of the same material. (See **Figure 3**.) The rest of both crucibles are filled with a salt mixture (sodium chloride and potassium chloride) that acts as an electrolyte. Both are melted at 740°C, well above the melting point of plutonium (639°C). An electric current is used; the anode is a tungsten rod inserted into the molten plutonium and the cathode is a circular ribbon of tungsten in the molten salt above and outside the inner ring. The current draws plutonium atoms through the salt to the cathode, where drops of metallic plutonium fall into the space between the two crucibles, forming a ring. (See **Figure 4**.) The United States has used this process for decades, so it is well characterized—a major advantage.

Figure 4. Electrorefined Plutonium

Source: Los Alamos National Laboratory

As plutonium is drawn from the ingot of impure plutonium, the concentration of impurities in the inner crucible increases, eventually becoming so high that the temperature is not high enough to keep the mixture remaining in the inner crucible from solidifying.[37] At that point, the reaction stops. The process produces the ring of purified plutonium and two byproducts, the remaining ingot of plutonium with impurities concentrated, called the "heel," in the inner crucible, and the salt, which retains some plutonium (here referred to as the Pu-salt mixture). The plutonium in the heel is converted to plutonium oxide; it and the Pu-salt mixture are dissolved (separately) in hydrochloric acid to recover their plutonium.

PF-4 has two "aqueous" process lines, i.e., those that involve a liquid, in this case one line that uses hydrochloric acid and another that uses nitric acid. They dissolve plutonium-bearing salts or oxide in acid, and use various processes to recover plutonium from the liquid. Aqueous recovery involves extensive MAR, space, and labor. Might it be possible to reduce this burden? **Table 3** shows the results of 653 electrorefining runs at Los Alamos from 1964 to 1977. While the data are old, the process for electrorefining plutonium has not changed much since that time, so the figures are useful as a rough order of magnitude of the products of electrorefining.

[37] The temperature cannot be raised further because so doing would generate a substantial amount of sodium and potassium metal, which ignite when exposed to oxygen—an undesirable characteristic around plutonium.

Table 3. Kilograms of Plutonium in Products Resulting from Electrorefining

Year	No. of Runs	Anode	Salt and Crucible	Cathode	Product Ring
1964	38	17.181	13.370	0.951	85.567
1965	41	10.007	12.121	1.381	103.871
1966	25	7.567	8.379	0.953	81.050
1967	47	14.862	16.131	1.649	105.183
1968	44	10.542	14.092	1.552	103.605
1969	45	10.256	13.777	1.552	110.175
1970	56	14.369	17.535	1.862	136.598
1971	63	20.581	19.243	2.703	146.836
1972	89	26.494	28.522	3.534	215.101
1973	33	8.577	12.755	1.567	81.198
1974	54	14.439	22.439	2.036	129.608
1975	33	7.764	10.402	1.195	78.057
1976	46	11.790	12.970	2.028	121.457
1977	39	8.728	11.291	1.630	90.016
Sums	653	183.157	213.027	24.593	1568.322

Source: L.J. Mullins and A.N. Morgan, "A Review of Operating Experience at the Los Alamos Plutonium Electrorefining Facility, 1963-1977," Los Alamos National Laboratory, LA-8943, UC-25, December 1981, http://ftp.fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00307321.pdf.

Notes: Total amount of plutonium in these products is 1,989.099 kg.

The table shows 9.2% of the plutonium left at the anode (the heel); 10.7% left in the salt and stuck to the crucible, almost all of which is in the salt; a small amount stuck to the cathode; and 78.8% purified in the product ring.

Might it be possible to discard the Pu-salt mixture, the heel, or both? So doing would lose some plutonium, but would avoid the need to use aqueous processes to recover the plutonium. The loss of plutonium would arguably not be a problem. The U.S. plutonium inventory was 95.4 metric tons as of September 2009, of which 43.4 metric tons were surplus to defense needs;[38] pits use kilogram quantities of plutonium. Secretary of Energy John Herrington said in 1988, "Plutonium, we're awash with plutonium. We have more plutonium than we need."[39] The need for plutonium has fallen since 1988 because the size of the U.S. nuclear stockpile has decreased considerably in the intervening years. Thousands of pits in storage at the Pantex Plant (TX) could be melted to purify their plutonium for use in new pits. Pits from weapons requiring new pits could similarly be recycled. At a rate of 80 ppy, existing plutonium would supply needs for many decades, if not centuries, and would do so for longer if existing pits could be used without modification in an LEP, as has been done, or if retired pits could be reused, a concept under study.

[38] U.S. Department of Energy, *The United States Plutonium Balance, 1944-2009*, Washington, DC, June 2012, p. 2, http://nnsa.energy.gov/sites/default/files/nnsa/06-12-inlinefiles/PU%20Report%20Revised%2006-26-2012%20%28UNC%29.pdf. One metric ton is 1,000 kilograms, or 2,205 pounds.

[39] U.S. Congress, Senate Committee on Appropriations, Subcommittee on Interior and Related Agencies, *Department of the Interior and Related Agencies Appropriations for 1988*, Part 7, 100th Cong., 2nd sess., February 23, 1988 (Washington: GPO, 1988), p. 23.

The Pu-salt mixture from an electrorefining run could probably be sent directly to the Waste Isolation Pilot Plant (WIPP), the nation's underground storage repository for defense transuranic waste, once it reopens, or to another storage repository.[40] The heel could not be sent directly to WIPP, as that facility does not accept plutonium in metal form, but it could readily be converted to plutonium oxide for shipment. Plutonium-containing waste bound for WIPP must be placed in drums (similar in size to 55-gallon drums). This process is elaborate, requiring nondestructive analysis to verify the contents of each drum; material control and accountability; ensuring that each drum is compliant with limits on plutonium content, heat generation, surface dose, and so on. This process is well understood, as it has been performed thousands of times over the years. Shipping the material directly to WIPP would avoid the need to send it through aqueous processes. That would permit either a reduction in the space and MAR needed for these processes, though offset somewhat by added space and MAR needed for packaging the drums, or would permit existing equipment to process more plutonium in order to support a higher rate of pit production. It would involve more shipments to WIPP and more work at that facility, but less work at LANL. Congress may wish to consider the tradeoffs involved, and the consequences of the loss of plutonium. More generally, Congress may wish to have NNSA analyze, on a case-by-case basis, whether the benefit of recovering nuclear material from the many waste streams resulting from nuclear weapons complex activities is worth the cost.

Use Calcium Chloride for Electrorefining

This option holds the potential to reduce cost and waste, increase throughput, and make more space available.

Electrorefining using sodium chloride and potassium chloride has several problems:

- Plutonium held in salts reduces yield (fraction of total plutonium recovered as pure plutonium), increasing time, space, equipment, MAR, cost, process steps, and worker exposure required to produce a given amount of pure plutonium.
- Hydrochloric acid processing for recovering plutonium produces a substantial waste stream that requires further treatment.
- The plutonium content of this waste must be monitored with analytical chemistry techniques, adding to the workload, to provide for material control and accountability and to ensure against criticality problems (concentration of enough plutonium to create a fission reaction). The latter is a serious concern, as 21 of 22 known criticality accidents from 1953 to 1999 involved aqueous processes.[41]
- Preparing this plutonium-contaminated waste for disposition takes up space in PF-4 and elsewhere at LANL. The back end of this process, from waste generation to processing to disposition, is costly and imposes a high workload.

An alternative would be to use calcium chloride as the electrolyte. Lawrence Livermore National Laboratory (LLNL) has used this method since 1992 and the United Kingdom's Atomic Weapons

[40] For the WIPP home page, see http://www.wipp.energy.gov/index.htm. "Transuranic" refers to elements, notably plutonium, having a higher atomic number than uranium.

[41] Thomas McLaughlin et al., *A Review of Criticality Accidents,* 2000 revision, LA-13638, Los Alamos National Laboratory, May 2000, Appendix B, Equipment Diagrams and Tabular Physical and Yield Data for the 22 Process Accidents, pp. 120-143.

Establishment (AWE) has used this method for over a decade. This approach offers several advantages.

- Compared with sodium chloride and potassium chloride, calcium chloride retains less plutonium after an electrorefining run because plutonium has different electrochemical behavior with calcium chloride, increasing the yield. As a result, fewer gloveboxes would be needed to supply a given amount of plutonium, making more space in PF-4 available, or a given number of gloveboxes could be used to support a higher rate of pit production.
- It is possible to remove plutonium, in combination with chlorine or other elements, from the calcium chloride-plutonium mixture using a "salt scrub": adding calcium metal to the mixture and heating it produces calcium chloride and plutonium metal. The latter, which is nearly twice as dense as lead, sinks to the bottom of the crucible and forms a "button" that is easily separated from the salt. Electrorefining with calcium chloride would remove more plutonium than would sodium chloride and potassium chloride, and the salt scrub would remove most of the rest of the plutonium. As a result, the salt left after the salt scrub would be expected to contain very little plutonium.[42]
- Disposing of that salt as waste would release aqueous process capacity, which could be used to recover plutonium from the "button." In this way, the equipment could produce more plutonium, supporting a higher rate of pit production.

While LLNL and AWE use this method, LANL had poor results when it tried it in the 1990s. This might have been because there was too much moisture in the calcium chloride; the salt is extremely hygroscopic (attracts and holds water molecules from the atmosphere). Alternatively, LANL might not have been able at that time to control the process so as to maximize yield. LANL plans to revisit this option. While LANL will use sodium chloride and potassium chloride when electrorefining in PF-4 resumes, it plans to convert to calcium chloride if the process can be successfully demonstrated. The process would require not only a dry atmosphere in the gloveboxes, but also a facility for producing dry calcium chloride and equipment for moving calcium chloride from production through use in dry conditions. LANL expects to draw on LLNL and AWE resources and experience in this effort.

Remove Americium from Plutonium

This option holds the potential to reduce worker exposure to radiation, to reduce MAR and cost, and to make more space available in PF-4.

Weapons-grade plutonium consists of about 94% Pu-239, the main isotope that supports a nuclear chain reaction, and several other plutonium isotopes. Each isotope undergoes radioactive decay at a rate (the half-life) particular to that isotope. With radioactive decay, each plutonium isotope becomes an isotope of a different element. Pu-241 decays much more rapidly than the other isotopes in WGPu; its half-life is 14.4 years. It decays into americium-241 (Am-241, half-life 432 years), which in turn decays into neptunium-237 (half-life 2.1 million years). All the other plutonium isotopes decay into uranium isotopes. As a result, the composition of WGPu—both the

[42] Plutonium in the button would be impure, so it would have to be evaluated to determine if it could be processed through electrorefining.

plutonium isotopes and their decay products—changes slightly over time. **Table 4** shows the composition of WGPu, the decay products, and the approximate amount of various plutonium isotopes remaining after 50 years.

Table 4. 50-Year Decay of Isotopes in Weapons-Grade Plutonium

Plutonium isotopes in new WGPu	Half-life, years	Isotope in new WGPu, % by weight	Isotope in WGPu after 50 years, % by weight
Pu-238	87.7	0.01	0.01
Pu-239	24,110	93.77	93.64
Pu-240	6,563	6.00	5.97
Pu-241	14.35	0.20	0.02
Pu-242	373,300	0.02	0.02
Decay products			
Pu-241→Am-241	432.2	0	0.17
Am-241→Np-237	2,144,000	0	0.01
Pu-238→U-234	245,500	0	0.00
Pu-239→U-235	703,800,000	0	0.13
Pu-240→U-236	23,420,000	0	0.03
Pu-242→U-238	4,468,000,000	0	0.00
Total		100.00	100.00

Source: Los Alamos National Laboratory and CRS.

Notes: "→" means "decays to,"
Grams Am-241 per kg WGPu after 50 years: 1.72
Grams uranium isotopes per kg WGPu after 50 years: 1.67.

The main reason to remove americium-241 is that it is an intense emitter of gamma rays. Workers handling aged WGPu in gloveboxes have only their gloves to protect them, so the main gamma ray dose they receive is to their hands. This dose can be the limiting factor in how many days per year federal regulations and LANL policies permit them to handle plutonium while staying within dose guidelines.

Purifying plutonium for weapons use involves several chemical processes. (These processes do not alter the isotopic composition of plutonium.) Electrorefining, for example, produces pure plutonium, but does not work efficiently for plutonium with a large fraction of impurities because the impurities stop the electrorefining process while much of the plutonium remains unpurified. Another process, metal chlorination, removes most americium but leaves uranium, neptunium, alloying material, and any other impurities. Metal chlorination involves bubbling chlorine gas through molten impure plutonium. This produces a salt, americium chloride, that captures almost all the americium from the plutonium. Chlorine also forms another salt, plutonium chloride. These salts form a crust, which is easily removed, on top of the plutonium metal. This metal, which includes uranium and neptunium, can then be processed through electrorefining. The salt

crust contains about 90% plutonium chloride; this plutonium is recovered by dissolving the crust in hydrochloric acid and using several other process steps.

Of the Pu-241 in newly produced WGPu, 89% will have decayed into Am-241 after 50 years. U.S. WGPu is quite old. Some was produced during the Manhattan Project of World War II; most was produced between 1956 and 1970.[43] When newly produced, it had essentially no radioactive impurities; plutonium that has been purified since then has, in effect, had its age reset to zero, albeit with a slightly different mix of plutonium isotopes. As of September 2009, the United States had produced or acquired 111.7 metric tons (MT) of plutonium, an inventory of 95.4 MT, 14.0 MT removed from inventory, and an "inventory difference" (production and acquisition minus inventory and removals) of 2.4 MT.[44] Further, "there remain uncertainties about how much plutonium was actually produced, processed, and discarded to waste, especially for the period from the mid-1940s to 1970."[45] Accordingly, there is no official unclassified figure (and perhaps no classified figure) for the average age of plutonium remaining in the DOE inventory. It appears, however, based on preliminary calculations by Los Alamos, that the average age of that plutonium is about 50 years.

Because of radioactive decay, little Pu-241 is left to form additional Am-241 after 50 years. Since Pu-241 decay is the only source of Am-241, after passing aged plutonium through a final run of metal chlorination to remove Am-241, so little Pu-241 would remain that even if all of it decayed to Am-241, the latter would never reach the level found in 30-year-old WGPu, and the weapons laboratories have certified weapons with pits that old (and older) as acceptable for use in the stockpile. This final run would have two results. First, it would greatly reduce worker exposure to gamma radiation. Second, since additional runs of metal chlorination would not be needed for WGPu thus processed, the metal chlorination line could be reduced in capacity, reducing space and operating cost. (The line could not be eliminated entirely because it would be needed if, for example, a batch of old pits was sent to Los Alamos for purification.)

Accept More Uranium in Weapons-Grade Plutonium

This option holds the potential to reduce cost and space and increase throughput.

Pu-241 has the shortest half-life of the plutonium isotopes in WGPu. The others have half-lives ranging from 87.7 years for Pu-238 to 373,000 years for Pu-242. Pu-239, which accounts for 94%

[43] These figures are based on U.S. Department of Energy. *Plutonium: The First 50 Years. United States Plutonium Production, Acquisition, and Utilization from 1944 to 1994,* available at http://fissilematerials.org/library/doe96.pdf. Pages 29 and 33 show plutonium production, by year, WWII-1988. The United States had two sites that produced weapons-grade plutonium in ton quantities, Hanford (WA) and Savannah River Site (SC), with production ending in 1988. Page 29 of the DOE report has a table that splits plutonium production at Hanford into WGPu and fuel-grade plutonium. Page 33 has a table that shows plutonium production at Savannah River Site; The report, pp. 30-31, states, "The Savannah River reactors produced primarily weapon grade plutonium with a Pu-240 content of about 6 percent. Starting in 1981, to increase the availability of plutonium for the weapons program, the Savannah River P, K, C-Reactors were operated to produce weapon grade plutonium with a 3 percent Pu-240 content. This method of operating accelerated reactor operations, decreased target irradiation time, and increased fuel throughput." Assuming all Savannah River Site plutonium is WGPu, the United States had produced 6.9% of its WGPu through 1955, and 79.9% through 1970. If 80% of Savannah River production were WGPu, then 81.8% of total WGPu would have been produced through 1970.

[44] U.S. Department of Energy, *The United States Plutonium Balance, 1944-2009,* p. 4.

[45] Ibid., p. 3.

of the plutonium in WGPu, has a half-life of 24,110 years. As a result, uranium ingrowth will continue for many thousands of years. ("Ingrowth" refers to decay products that remain in the plutonium.) A concern is that a change in the composition of WGPu could affect its performance during implosion. After 50 years, uranium ingrowth accounts for 0.17% of WGPu, and ingrowth will continue at this rate, declining only slightly, for millennia. Further, 79% of the uranium ingrowth will be U-235; that fissile isotope has also been used in nuclear weapons, though it is not as effective (in terms of explosive yield per kg) as WGPu.

At issue is whether newly fabricated pits can use plutonium that has not been purified for several decades, despite the ingrowth of uranium. Some weapons in the U.S. stockpile are old. For example, the first B61 bomb was produced in 1966. The last year in which the United States made war reserve pits, excepting 29 for the W88 warhead, was 1989. NNSA plans a B61 life extension program (LEP), with the first production unit expected in FY2020. Thus, while some versions of the B61 were produced after 1989, the newest pit in B61s would, in 2020, be at least 30 years old. Yet the LEP is to use existing pits, and weapon designers expect to be able to certify the performance of life-extended B61 bombs. Similarly, the W76 warhead was first manufactured in 1978 and is now undergoing an LEP that does not use new pits. A 2007 report by the JASON group evaluated studies on pit lifetime performed by Los Alamos and Lawrence Livermore National Laboratories. The JASON report found,

> Most primary types have credible minimum lifetimes in excess of 100 years as regards aging of plutonium; those with assessed minimum lifetimes of 100 years or less have clear mitigation paths that are proposed and/or being implemented. … As a result of the Los Alamos/Livermore efforts, JASON concludes that there is no evidence from the [underground nuclear testing] analyses for plutonium aging mechanisms affecting primary performance on timescales of a century or less in ways that would be detrimental to the enduring stockpile.[46]

Thus there may not be a need to conduct electrorefining to purify plutonium for pits for decades. Further, there may be a benefit from delaying plutonium purification. Livermore notes a difference between uranium in aged pits and in pits made from purified plutonium:

> The uranium present in existing pits is formed within the plutonium lattice and does not significantly affect the nuclear or mechanical properties of the plutonium. Therefore, uranium ingrowth in existing plutonium containing pits is not considered an issue. However, if the plutonium is recovered from an existing weapon and recast, the uranium is likely to go to the plutonium grain boundaries which may affect the mechanical properties.[47]

There is thus a tradeoff between the advantages of purifying aged plutonium to remove Am-241, as discussed in "Remove Americium from Plutonium," and delaying purification.

Capacity and space could be further reduced if weapon designers were willing to accept a larger maximum allowable uranium content in the WGPu specification. Acceptance would depend on detailed studies of metallurgical and other properties of WGPu with levels of uranium isotopes that are in existing pits. If the study results proved acceptable, electrorefining capacity and space could be reduced.

[46] R.J. Hemley et al., "Pit Lifetime," JASON, The MITRE Corporation, JSR-06-335, January 11, 2007, p. 1, http://fas.org/irp/agency/dod/jason/pit.pdf.

[47] Email, April 3, 2015.

Use Near Net Shape Casting to Fabricate Hemishells

This option holds the potential to reduce MAR, waste, and cost.

A hemishell may be visualized as a "bowl" made of plutonium. The current method to cast hemishells involves pouring molten plutonium between an inner and outer mold. When the plutonium solidifies, the molds are separated and the cast part is removed. The part is then heat-treated to impart the required material properties. It is then machined to final dimension.

The cast part, before machining, is necessarily thicker than the hemishell. Machining it produces plutonium chips. If these chips are to be recycled for use in subsequent pits, they would have to undergo purification processes, such as metal chlorination and electrorefining. Alternatively, they could be converted to plutonium oxide and sent to WIPP.

Near net shape casting (NNSC) simply has a thinner space between the inner and outer molds, and the molds produce a cast part much closer to final dimension. Otherwise, the processing (casting, heat treating, machining, etc.) is the same.

The thinner space between molds reduces the amount of plutonium needed for casting, reducing the amount of plutonium that must be machined away to produce the hemishell. On the other hand, a thinner cast part could result in a higher reject rate, as there would be less margin for error in machining. To offset this disadvantage, NNSC could use various electronic techniques to align the part more precisely and remove excess material more precisely. One such technique is in-process inspection. With traditional casting, hemishells are measured after they are machined to determine if they meet dimensional specifications. With in-process inspection, hemishells could be measured and, if necessary, realigned while in production, such as after each pass of a cutting machine, allowing the technician to compensate for errors while there was some excess material.

Current equipment is adequate to purify enough plutonium to support low production rates. The critical advantage of NNSC would come into play with higher pit production rates, when the supply of purified plutonium would become a major bottleneck. NNSC would use less plutonium per hemishell, and would produce less scrap that must be recycled. As a result, it would place less demand on the existing plutonium purification equipment, enabling it to support a higher production rate. Reducing the amount of purified plutonium per pit would also reduce the waste stream, such as the plutonium-contaminated acids and salts from purification processes. This reduction is another advantage given the cost, effort, and procedural requirements of processing radioactive waste. Using less plutonium per pit would reduce the burden on material control and accountability: less material results in less material to be accounted for, saving time and effort. Using less plutonium per pit would also reduce, on a per-pit basis, worker exposure, MAR, and cost. It would not save space, but since each pit would require less plutonium, it would allow existing equipment, in the existing space, to provide plutonium for a higher rate of pit production.

LANL has conducted some R&D into NNSC using gravity feed and plans to use this method in the future if it proves successful. It is included in LANL's planning basis for future pit manufacture. Manufacture could include new pits for certain LEPs and new pits to replace pits destroyed during surveillance. Livermore worked on developing NNSC as early as 1994.[48] It has

[48] "LLNL Casting Technology," by Arthur B. Shapiro and William J. Comfort, III, Technical Editors, UCRL-ID-116320, January 1994, p. 5, http://www.osti.gov/scitech/servlets/purl/10133336/.

demonstrated NNSC using plutonium die casting, in which molten plutonium is forced into the space between an inner and outer mold. Livermore states, "Die casting technology is another approach to significantly reduce the amount of plutonium required per casting and therefore, the amount of feed metal."[49]

Options Involving Structural Modifications to PF-4

Augment Seismic Resilience of PF-4

This option would increase permitted MAR, worker safety, and public safety.

PF-4 became operational in 1978; since then, seismic studies have shown a greater threat to the building than was envisioned when it was designed. For example, an older model assumed that an earthquake would shake the building, while a newer model treated an earthquake as a wave of earth moving toward PF-4 that could push the building over. As a result of these studies, concern grew that PF-4 could collapse in a major earthquake:

> In public comments at a Capitol Hill Club event this summer [2013], DNFSB member Jack Mansfield explained the Board's concerns. The [PF-4] facility, built in the late 1970s, is "brittle," Mansfield said. "It was discovered after this facility was built that large buildings, to be survivable in serious earthquakes, have to have a bit of ductility. It was also discovered after the Loma Prieta earthquake that round columns, if accelerated up into the plywood they support, crumble. Those two vulnerabilities were identified early, but they're not built into PF-4."
>
> He added: "The result is that there is a probability, albeit small, that the building could collapse, with great loss of life within and with dispersal of plutonium." Previous upgrades were based on calculations that did not fully characterize the problems facing the facility, Mansfield said. Those calculations were "very good" and "did a lot," Mansfield said, but "the problem is that any of the columns, crushed like the ones on the highway did—the whole roof would go down like a zipper."[50]

To reduce the dose resulting from an earthquake that collapsed the building, followed by a fire that lofted plutonium oxide particles into the air, LANL reduced PF-4's MAR allowance for the main (laboratory) floor in 2013 from 2,600 kg of plutonium to 1,800 kg. To increase MAR, reduce potential dose, and reduce the risk of collapse, LANL is taking steps to protect PF-4 against collapse and fire.

To strengthen PF-4 against seismic shaking, LANL added a drag strut to the roof, among other things, as described in more detail in CRS Report R43685, *Manufacturing Nuclear Weapon "Pits": A Decisionmaking Approach for Congress*. (A drag strut gathers lateral forces from a large flat surface and transmits them to a shear wall, which is designed to resist those forces.) Other steps were taken to strengthen PF-4 against pushover. Many columns that run from the basement to the roof support PF-4. Some of these columns run through the vault, which holds a

[49] Email, April 3, 2015.

[50] Todd Jacobson, "DOE Says Alternate Analysis of PF-4 Seismic Risks Will Be Done in Dec.," Nuclear *Weapons & Materials Monitor,* September 6, 2013, http://www.lasg.org/press/2013/NWMM_6Sep2013.html.

large quantity of plutonium, in the basement. These columns are held rigidly in place by the vault ceiling and are not free to move, making them more vulnerable to shear forces that could cause them to collapse. Their collapse could result in massive pieces of concrete and steel crashing through the vault ceiling, killing workers and releasing plutonium. To strengthen the columns, LANL wrapped them in carbon fiber sealed with epoxy, a measure completed in February 2014. LANL is now working to strengthen the ties between girders, which are located above the laboratory floor of PF-4, and other structural elements. As with columns, collapse of girders onto the laboratory floor could kill workers and release plutonium.

Structural upgrades to PF-4 can make a very large difference in the amount of plutonium released in a major earthquake. An NNSA accident analysis of PF-4 in June 2011

> evaluated the effect of a combined earthquake, fire, and partial building collapse. The calculated radiation dose to the hypothetical maximally exposed off-site individual (MEOI) was conservatively estimated to be 2,100 rem Total Effective Dose Equivalent1 (TEDE) for a postulated once-in-5,000-year accident (Case 1). By October 2011, PF-4 was structurally upgraded, reducing the calculated MEOI dose to 143 rem once-in-2,000 years (mitigated, Case 2). By April 2012, additional repairs will be completed that protect PF-4 safety basis assumptions and reduce the calculated MEOI dose to less than 25 rem TEDE.[51]

LANL has taken steps to reduce the risk of fire. For example, it removed about 20 tons of combustible material from PF-4, mostly from the laboratory floor.[52] It is planning to enhance the capability of the fire water loop to protect PF-4. This loop includes two 40,000-gallon water tanks, two pump houses, and an underground pipe loop that carries water to buildings in TA-55 for fire suppression. (Technical Area 55, or TA-55, is the main area at LANL for plutonium work; it consists of PF-4 and supporting buildings.) Some buildings in TA-55 are not seismically qualified, and would be more likely than PF-4 to collapse in an earthquake. If they collapsed or began to burn, water from the tanks would flow to them, reducing or eliminating the amount available for PF-4. LANL proposes to decouple these buildings from the loop and provide them with their own separate fire water supply. The Consolidated and Further Continuing Appropriations Act, 2015, P.L. 113-235, provides $1,000,000 for TA-55 seismic safety mitigation for FY2015.[53]

Build One Module for Plutonium-238 Work

This option would make more space and MAR available in PF-4, and holds the potential to reduce risk to the public.

Pu-238 is 277 times more radioactive than Pu-239, the fissile material in weapons-grade plutonium. It is so radioactive that energy from its radioactive decays generates enough heat to

[51] Letter from Donald L. Cook, Deputy Administrator for Defense Programs, to The Honorable Peter S. Winokur, Chairman, Defense Nuclear Facilities Safety Board, January 30, 2012, Enclosure 1, p. 1, http://www.dnfsb.gov/sites/default/files/Board%20Activities/Letters/2012/ltr_2012130_18446_0.pdf.

[52] Letter from Donald Cook, Deputy Administrator for Defense Programs, National Nuclear Security Administration, to Peter Winokur, Chairman, Defense Nuclear Facilities Safety Board, January 30, 2012, Enclosure 2, p. 1, http://www.dnfsb.gov/sites/default/files/Board%20Activities/Letters/2012/ltr_2012130_18446_0.pdf.

[53] Explanatory Statement Submitted by Mr. Rogers of Kentucky, Chairman of the House Committee on Appropriations, Regarding the House Amendment to the Senate Amendment on H.R. 83, *Congressional Record*, daily edition, vol. 160, part no. 151—book II (December 11, 2014), p. H9703.

make a small quantity, even 200 grams, glow red. It is used in deep space probes, where its heat is used to generate electricity. It has some military applications but is not used in pits.

As of February 27, 2013, before most of its operations were suspended, PF-4 held about 1.6 kg of Pu-238, but because of its high radioactivity it accounted for 24.5% of the building's MAR, or 441 kg of Pu-239 equivalent. For comparison, pit fabrication accounted for 26.4% of the building's MAR. In addition, Pu-238 programs accounted for 9,600 square feet, or 16%, of PF-4 laboratory floor space.

One approach to providing more MAR and space in PF-4 for pit fabrication is to build modules, buried reinforced-concrete structures with about 5,000 square feet of lab space connected to PF-4 by tunnels. As stated in the FY2016 DOE budget request, "NNSA is planning to construct not less than two modular structures that will achieve full operating capability not later than 2027."[54]

However, Pu-238 is not uniformly distributed within the space for Pu-238 programs. If some Pu-238 work were moved to a 5,000-square foot module, that module could accommodate most of the Pu-238-related MAR from PF-4, making that same amount of MAR and space available for pit production or other plutonium work. Thus one module for Pu-238 might suffice to enable pit production within PF-4.

Building one module may offer other advantages. It would provide experience and lessons that could help reduce cost if additional modules were built at LANL or elsewhere in the nuclear weapons complex. In particular, a review of the Uranium Processing Facility at the Y-12 National Security Complex recommended against what it called a "big box" approach in which all capabilities would be placed in one large building, and instead favored perhaps four smaller "new builds."[55] Further reducing cost if multiple modules were to be built, modules as envisioned would have a basic design, and each module would be customized with only the equipment and capabilities needed for its specific mission and hazards. In contrast, a large multi-mission building would need all features needed for any one mission, adding cost, and it would probably cost less to fix a problem in subsequent modules after building one than to retrofit a big box building. NNSA also states that modules also offer "the potential to scale facility acquisition to appropriations and adapt more quickly to changes in program requirements."[56] Since the module would be buried, it would be expected to contain plutonium better than PF-4 in the event of an earthquake, reducing risk to the public. On the other hand, some lessons from building a module might increase cost. For example, if it turned out that there was a design flaw, that modules needed to be larger, or that more concrete was needed, the second module could be more expensive than initial construction (excluding retrofits) of the first. Also at issue is whether other measures to increase MAR and space margin, such as those discussed in this report, might provide enough margin without building any modules.

[54] U.S. Department of Energy, *FY 2016 Congressional Budget Request*, Volume 1, National Nuclear Security Administration, p. 239.

[55] Thom Mason, Chair, Committee to Recommend Alternatives to the Uranium Processing Facility Plan in Meeting the Nation's Enriched Uranium Strategy, *Final Report of the Committee to Recommend Alternatives to the Uranium Processing Facility Plan in Meeting the Nation's Enriched Uranium Strategy,* April 15, 2014, p. 7, http://www.nnsa.energy.gov/sites/default/files/nnsa/05-14-inlinefiles/Uranium_Review_Final_Report_unclassified_withappendices.pdf.

[56] Email, April 17, 2015.

Conclusion: Choosing a Package of Options

This report shows options, many of which NNSA and its labs are pursuing, that can help move toward enough capacity to manufacture pits at a rate of 80 per year. One option by itself will not provide the capacity to manufacture pits at that rate. As a result, NNSA faces the prospect of assembling a package of options, whether from the ones presented here or others, and Congress faces the prospect of evaluating, perhaps amending, and approving it. Any package chosen would need to optimize among such goals as margin, cost, worker safety, and throughput. Questions and tradeoffs to consider in formulating a package include the following:

- MAR reduction techniques include seismic strengthening of PF-4, using special containers to hold plutonium not in use, and removing contaminated gloveboxes. Would all such techniques need to be implemented, or would some, by themselves, provide enough MAR margin?
- Relocating the Royal Crest trailer park could also reduce the need for these techniques. Conversely, some of these techniques might provide more MAR margin than relocating Royal Crest, though perhaps at higher cost.
- Using a different wind model and more realistic assumptions could result in a calculated dose reduction by more than half in the event of a major accident at PF-4, permitting more than doubling the MAR allowance for PF-4 quickly and at essentially no cost, producing more MAR allowance than relocating Royal Crest. But would a doubling of the MAR allowance suffice? If not, what combination of measures that increased MAR allowance would do so?
- Techniques to increase space margin include removing contaminated gloveboxes, setting up a production line able to make 50 ppy with one shift per day and operating it with two shifts per day, and building a module for Pu-238 work. Which combination of techniques would be most cost-effective?
- Building a module, whether at Los Alamos or elsewhere, for Pu-238 work would move a substantial amount of MAR out of PF-4 and would free up some space there as well. Would that module be cost-effective, or would other alternatives provide enough space and MAR margin so as to render the module unnecessary? Or would other advantages argue for building a Pu-238 module even if sufficient margin could be obtained by other means?
- Using calcium chloride instead of sodium chloride and potassium chloride in electrorefining would reduce the amount of plutonium to be recovered through aqueous processes; near net shape casting would do so as well. Both together may permit a reduction in the space needed for aqueous processes, and a reduction in MAR as well, since aqueous processes are high in MAR.
- Alternatively, would it be cost-effective to recover the plutonium remaining in the salt and in the ingot of impure plutonium after electrorefining runs? If not, these materials could be packaged and shipped to WIPP.
- Some techniques offer increases in both space margin and MAR margin, such as removing contaminated gloveboxes.
- Some techniques may increase margin at little or no cost, and may provide savings. Using conservative rather than very conservative assumptions in

calculating dose could reduce the need for costly physical changes, such as construction or procurement. The cost to remove contaminated gloveboxes is essentially zero, as the boxes would need to be removed at the end of PF-4's life, and removing them would avoid the risk of contamination accidents that are costly and time-consuming to clean up.

In sum, while arriving at a satisfactory package will require complex analyses, many options offer the potential to boost U.S. pit production capacity toward, if not to, the congressionally mandated capacity of 80 pits per year.

Appendix. Explanation of Terms in Table 2

Terms are listed in the order in which they appear in **Table 2**.

Material At Risk (MAR): The amount of material, in this case plutonium, acted upon by an event. It is measured in units of grams of Pu-239 equivalent, a standard used to compare the radioactivity of diverse materials.

Airborne Release Fraction (ARF): The fraction of Material At Risk released into the air as a result of the event. ARF is specific to the type of material (e.g., plutonium oxide, plutonium metal, plutonium in solution).

Respirable Fraction (RF): The fraction of the material released into the air that is of a particle size (3 microns in diameter or less for plutonium oxide) that, when inhaled, remains in the lungs. An RF of 1 represents the worst case.

Damage Ratio (DR): The amount of damage to a structure or container, with 0 being no damage and 1 being complete collapse. A DR of 1 represents the worst case, complete collapse of PF-4 or full destruction of a container.

Leak Path Factor (LPF): The fraction of material that escapes the building; even if a building or container was fully destroyed, not all material would necessarily be released into the air. While ARF is related to material type, LPF is related to engineered containment mechanisms, such as robust containers. An LPF of 1 represents the worst case (i.e., no containment is assumed).

Chi/Q: The rate at which plutonium particles are deposited (fall to the ground). It includes such factors as wind speed, wind direction, and distance from the facility to the individual receiving the dose.

Breathing Rate (BR): The volume of air, in cubic meters per second, that an individual breathes in. This is important in calculating dose because the more air an individual breathes in, other things being constant, the higher the dose.

Specific Activity (SA): A measure of the radioactivity of a material, expressed in curies (a measure of the number of radioactive disintegrations per second) per gram of material. **Table 2** shows SA for Pu-239.

Dose Conversion Factor (DCF): Multiplying SA by this factor converts SA to dose.

Dose is expressed in rem, a measure of ionizing radiation absorbed by human tissue.

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