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Recovery of Weapon Plutonium as Feed Material for Reactor Fuel

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Recovery of Weapon Plutonium as Feed Material for Reactor Fuel

1. Introduction

This report presents preliminary considerations for recovering and converting weapon plutonium from various U.S. weapon forms into feed material for fabrication of reactor fuel elements. An ongoing DOE study¹ addresses the disposition of excess weapon plutonium through its use as fuel for nuclear power reactors and subsequent disposal as spent fuel. The spent fuel would have characteristics similar to those of commercial power spent fuel and could be similarly disposed of in a geologic repository. A report now being prepared will address the plutonium spent-fuel issues.

Reference 1 describes the five reactor designs that are being considered in the Plutonium Disposition Study. Three are light-water reactors (LWRs), one is the Advanced Liquid-Metal Reactor (ALMR), and one is the Modular High-Temperature Gas-Cooled Reactor (MHTGR). The LWRs are considered to be technologically mature and readily licensable. Existing LWRs use fuel elements that consist of many cold-pressed and sintered uranium oxide pellets contained within a cylindrical tube or "cladding," usually made of Zircaloy.

Until 20 years ago, plans in the U.S. nuclear industry included recycling plutonium in LWRs as mixed oxides of plutonium and uranium. Other countries, notably Japan and France, have continued to pursue the use of plutonium. As a result, a considerable amount of technical data is available on fabrication and performance of mixed-oxide (MOX) fuel. Accordingly, the early emphasis in our analysis is on the process of converting weapon plutonium to plutonium oxide (PuO_2) powder suitable for feed material to fabricate fuel elements for LWRs. Feed material for MHTGR fuel also is assumed to be PuO_2 . If the ALMR is selected for plutonium disposition, it would be preferable that the feed material be in metal form.

The United States produced 89 Mg (1 Mg = 1000 kg = 1 tonne) of weapon-grade (WG) plutonium during the period 1945 through 1988.² Additional plutonium sources include 13 Mg of fuel-grade and reactor-grade plutonium, which have higher ^{240}Pu content. For simplicity, we neglect the differences in these materials. This simplification does not change significantly the results of this study. Production of WG plutonium was suspended in 1988, and all the production reactors have been shut down. A substantial fraction of WG plutonium is in the form of metal. A lesser amount is on hand as PuO_2 . A miscellaneous category accounts for other forms and also includes that expended in some of the 1051 nuclear weapon tests conducted to date by the U.S.³

On this basis, much of the 50 Mg of weapon plutonium postulated by the DOE to be declared excess to U.S. national-security needs will be taken from metal stocks. A similar 50 Mg of Russian weapon plutonium will probably also be declared excess. Because it would be desirable to make U.S. technology available to support the processing of Russian weapon plutonium, we intend to consider how to facilitate such a transfer of technology or equipment.

We postulate, as a base case, that 50 Mg of weapon plutonium is to be converted to feed material for reactor fuel in 20 years. Other inventories and recovery rates may be considered in future extensions of this study.

1.1 Feed-Material Interface Specification

The form of the feed material at the interface in the overall processing required to convert excess weapon plutonium into fuel elements for disposition by fission in an LWR is assumed to be plutonium oxide (PuO_2) powder. The PuO_2 powder would meet specified impurity levels and particle-size distribution, as described below. This interface form directly satisfies three of the five reactor designs being considered by DOE in the Plutonium Disposition Study.

In this report, we first consider the production of PuO_2 powder for LWRs as the nominal feed material at the interface with fuel element fabrication. The desirable feed materials are metal ingots for making ALMR fuel and nitrate for making MHTGR fuel. To avoid shipment of plutonium nitrate, the feed material for MHTGR fuel is tentatively chosen to be PuO_2 .

1.2 Isotopic Distribution and Americium

Weapon-grade (WG) plutonium has the nominal isotopic distribution listed below.⁴ (For the purpose of this report, typical variations from this nominal distribution are not considered to be significant.)

Isotope	Percent
^{238}Pu	0.02
^{239}Pu	93.65
^{240}Pu	5.91
^{241}Pu	0.38
^{242}Pu	0.04

In WG plutonium, ^{241}Am also is present in the amount of about 0.2% of total plutonium. Removal of americium at this concentration from 50 Mg of WG plutonium would produce 100 kg of separated americium. In Sec. 2, we discuss processes that do this. Americium unavoidably grows in from the decay of ^{241}Pu , which has a half-life of 14.4 y. During processing of the excess weapon plutonium upstream of the feed-material interface, americium could be removed to a level less than 10 ppm. Americium will again grow in at a rate dictated by the amount of ^{241}Pu present and the decay constants of ^{241}Pu and ^{241}Am (half-life, 432.7 y). Coordinated scheduling of feed-

material preparation and fuel-element fabrication should avoid an excessive level of ^{241}Am being present during fuel-element fabrication. Expected ingrowth concentrations of ^{241}Am in the feed material (PuO_2 powder) as a function of time after removal from plutonium containing 0.4% ^{241}Pu are given below. The concentration increase with time is essentially linear. A peak concentration of 3558 ppm would be reached in 73.2 y.

Time (mo)	ppm (Pu)
3	48
6	95
9	142
12	188
24	366
36	536

1.3 Chemical Impurities

A principal chemical impurity in weapon plutonium is gallium at a nominal level of 1 wt%. During processing (upstream of the interface), gallium could be removed to a concentration less than 10 ppm. All other chemical impurities will be removed to the levels that will satisfy the impurity levels specified in Table 1-1. In Sec. 2, we describe processes that either remove or retain gallium.

1.4 Physical Characteristics

A homogeneous lot of PuO_2 powder may be obtained from uniform blending of material derived from batch processes with constant process parameters. Large, homogenous lots of powder are desired so that subsequent mixing with other oxides (by the fuel fabricator) can be accomplished predictably without agglomeration. Good control of particle size distribution and dryness is thus essential. The bulk density of the PuO_2 powder must be greater than 1000 kg/m^3 , and its variation from lot to lot must be within 250 kg/m^3 of the mean bulk density. Bulk density will be determined according to the procedure of ASTM B329.⁵

PuO_2 powder must pass through a 325-mesh (45- μm opening) U.S. Standard Sieve, according to the standard test method of ASTM B214.⁶ Additional information to be recorded is particle size, determined according to ASTM B330.⁷

Downstream of the interface, PuO₂ powder will be mixed with larger amounts of UO₂ or Al₂O₃ powder and with lesser amounts of Gd₂O₃ or Er₂O₃ powder. The blended mixed oxides (MOX) will subsequently be cold-pressed and sintered into MOX fuel pellets for the LWRs.

References

1. U.S. Department of Energy Plutonium Disposition Study—Technical Review Committee Report, Vols. 1 and 2, July 2, 1993.
2. DOE Facts (Dec. 7, 1993), p. 21.
3. DOE Facts, (Dec. 7, 1993), p. 1.
4. D. F. Alves, personal communication (1993).
5. ASTM B329-90, *Standard Test Method for Apparent Density of Powders of Refractory Metals and Compounds by the Scott Volumeter* (American Society for Testing Materials, Philadelphia, PA, 1990).
6. ASTM B214-92, *Standard Test Method for Sieve Analysis of Granular Metal Powders* (American Society for Testing Materials, Philadelphia, PA, 1992).
7. ASTM B320-88, *Standard Test Method for Average Particle Size of Powders of Refractory Metals and Their Compounds by the Fisher Sub-Sieve Sizer* (American Society for Testing Materials, Philadelphia, PA, 1988).

Table 1-1. Allowable plutonium dioxide impurity levels for MOX fuel.

	Element	Content (C) (ppm)	Boron (B) equivalent (ppm)	C × B (ppm)
1	Aluminum	400	0.000132	0.0528
2	Boron	1	1	1
3	Carbon	500	0.0000551	0.002755
4	Cadmium	1	0.779	0.779
5	Calcium	250	0.000287	0.07175
6	Chlorine	25	0.0137	0.3425
7	Chromium	400	0.000935	0.374
8	Cobalt	75	0.0125	0.9375
9	Copper	400	0.000945	0.378
10	Dysprosium	2 ^a	0.097	0.194
11	Europium	2 ^a	0.434	0.868
12	Fluorine	130	0.000348	0.04524
13	Gadolinium	2 ^a	4.191	8.382
14	Gallium	400	0.000004	0.0016
15	Iron	400	0.000743	0.2972
16	Lead	400	0.0000123	0.00492
17	Magnesium	200	0.000142	0.0284
18	Manganese	200	0.00401	0.802
19	Molybdenum	400	0.00132	0.528
20	Nickel	400	0.0012	0.48
21	Nitrogen	100	0.00276	0.276
22	Samarium	2 ^a	0.524	1.048
23	Silicon	200	0.0000824	0.01648
24	Silver	25	0.0298	0.745
25	Sodium	400	0.000337	0.1348
26	Tin	400	0.000206	0.0824
27	Tungsten	100	0.00702	0.702
28	Vanadium	400	0.00149	0.596
29	Zinc	100	0.000371	0.0371
30	Zirconium	400	0.0000293	0.01172
	Total	6715 ^b		19.2 ^c

Notes:

^aTotal content of these rare earths must be less than 2 ppm Pu.

^bTotal of these impurities must be less than 2500 ppm Pu.

^cTotal of (C) × (B) must be less than 4 ppm.

2. Recovery Process

There are several chemical processing methods for converting weapon plutonium into feed material for nuclear reactors. Some methods produce very pure, aqueously generated oxide (similar morphology to what has been used in mixed-oxide fuels) but require a fairly large plutonium processing facility. Other methods produce less-pure oxide or metal by using a smaller plutonium-processing facility. This section presents an overview of various methods thus providing a starting point to determine which methods are the most cost-effective overall. A primary objective of this evaluation is to minimize the cost of the process for converting weapon plutonium into fuel elements of the type required for the reactor option that eventually is selected. As noted in Sec. 1, an interface specification tentatively has been established for the starting material for manufacturing oxide fuel elements. The processing methods and associated costs leading to this tentative interface are discussed in this section. To provide a basis for evaluating the cost impact and other factors associated with removing americium and gallium, we also consider processes that do not remove these elements. The final selection of the best process must include consideration of a number of other criteria, such as safeguards and waste minimization.

2.1 Introduction

For the last three years, as part of the DOE Weapon Complex Reconfiguration program (Complex 21), teams of experts have examined various methods for recovering and purifying plutonium from nuclear weapons. This effort has resulted in a baseline flow sheet and computer models that provide mass-balance data, operational times, required equipment, and expected radiation dose.¹ The baseline Complex 21 plutonium flow sheet consists of the following six areas: site return/pit disassembly/metal purification, pit fabrication and assembly, nitrate-residue recovery, chloride-residue recovery, solid-waste treatment, and liquid-waste treatment. Each of these areas consists of several unit operations. By eliminating unnecessary areas, such as pit fabrication or some unit operations, various flow sheets were generated for converting weapon plutonium to feed material for reactor fuel elements. The following recovery cases were examined:

- Case 1 - Oxide from aqueous nitrate process using metal feed,
- Case 2 - Oxide from aqueous nitrate process using oxide feed,
- Case 3 - Oxide directly from metal with aqueous recovery of residues,

- Case 4A - Oxide directly from metal without residue recovery or pit disassembly,
- Case 4B - Oxide directly from metal without residue recovery but with pit disassembly,
- Case 5A - Metal containing americium, and
- Case 5B - Metal with the americium removed.

Brief process descriptions of these cases are provided in Sections 2.2 through 2.8, and detailed process flow sheets have been developed for each case.

2.2 Case 1 - Aqueous Nitrate (Metal Feed)

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. (These steps are bypassed if the source material is unconfigured weapon-plutonium metal.) The hemishells from disassembly go to electrolytic dissolution in nitric acid. Following dissolution, the plutonium is separated from impurities, precipitated out of solution, and calcined to oxide. This case results in a high-purity, aqueously generated oxide that meets the requirements of Sec. 1 as feed material for fuel fabrication. All residues are processed to recover contained plutonium, but it is estimated that slightly more than 0.3% of the plutonium pro-

cessed would remain in the waste. It is assumed that all wastes can be made acceptable for the Waste Isolation Pilot Plant (WIPP). WIPP has been designated as the site for permanent geologic disposal of transuranic (TRU) defense waste. The mainline operations in this flow sheet have been production-demonstrated.

2.3 Case 2 - Aqueous Nitrate (Oxide Feed)

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. The hemishells from disassembly go to hydride/dehydride, producing a fine plutonium metal powder. The plutonium metal powder is then oxidized. The plutonium oxide is dissolved in nitric acid by means of standard cascade dissolution technology. Following dissolution, the plutonium is separated from impurities, precipitated out of solution, and calcined to oxide. This case results in high-purity, aqueously generated oxide that meets the requirements of Sec. 1 as feed material for fuel fabrication. All residues are processed to recover contained plutonium, but it is estimated that almost 0.2% of the plutonium processed would remain in the waste. The only mainline operation in this flow sheet that has not been extensively production-demonstrated is hydride/dehydride. The hydride/dehydride operation has been used in production operations but not as a mainline operation.

2.4 Case 3 - Nonaqueous System with Aqueous Residue Processing

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. The hemishells from disassembly go to hydride/dehydride, producing a fine plutonium metal powder, which is then directly oxidized. Because weapon plutonium is very low in impurities, the oxide that results should meet the requirements of Sec. 1 for chemical purity as feed material for fuel fabrication. The americium and gallium are not removed but stay with the product plutonium oxide. The aqueous nitrate

line processes the residues and recovers any contained plutonium and americium as oxide. All residues are processed to recover plutonium, but the waste would contain about 500 ppm of the processed plutonium. Maturity and production readiness of the flow-sheet unit operations are the same as for Case 2.

2.5 Case 4A - Nonaqueous without Disassembly

In this case, the weapon pits are taken through receiving and gas sampling. The plutonium is converted to hydride inside the pit and removed through the existing penetration. The hydride is dehydrided to plutonium metal powder, which is then directly oxidized. This case results in reasonably pure oxide, the major impurities being gallium and americium, which are not removed. Aside from a higher gallium content, the oxide that results should meet the requirements of Sec. 1 for chemical purity as feed material for fuel fabrication. All wastes (solid), still containing an estimated 0.2% of the processed plutonium, are sent to storage or offsite, so there are no nitrate-, chloride-, or liquid-waste treatment areas. One mainline operation, the hydriding of plutonium in a pit and removing it through the existing penetration, has not yet been demonstrated, although it has a high level of technical feasibility. This case requires very little equipment, but it is suitable for only a fraction (~30%) of the weapon pits.

2.6 Case 4B - Nonaqueous with Disassembly

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. The hemishells from disassembly go to hydride/dehydride. The resulting plutonium metal powder is then directly oxidized. The product plutonium and waste issues are the same as for Case 4A. Case 4B requires very little equipment and can remove plutonium from all available pits but will generate plutonium contaminated uranium that will require special subsequent handling.

2.7 Case 5A - Metal Product with Americium

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. The hemishells from disassembly go to hydride/dehydride. The resulting metal contains gallium and americium. This case produces reasonably pure metal feed (the major impurities being gallium and americium) for use in a reactor such as the ALMR. The aqueous-nitrate line processes the residues and recovers the plutonium and americium as oxide, which is then converted to metal. All residues are processed to recover plutonium, but it is estimated that wastes will contain about 500 ppm of the processed plutonium. Maturity and production readiness of the flow-sheet unit operations are the same as for Case 1B.

2.8 Case 5B - Metal Product without Americium

In this case, the weapon pits are taken through receiving, gas sampling, and then disassembly. The hemishells from disassembly go to hydride/dehydride. Americium is removed from the metal by the molten salt extraction (MSE) process. This case produces reasonably pure metal feed (the major impurity being gallium) for use in a reactor such as the ALMR. The MSE salt is scrubbed, and the Pu-Am alloy button is oxidized and processed through the nitrate line. The nitrate line separates the americium for disposal. The PuO_2 generated from the nitrate processing of residues is converted to metal. All residues are processed to recover plutonium, but it is anticipated that the waste will contain slightly more than 0.5% of the processed plutonium. Maturity and production readiness of the flow-sheet unit operations are the same as for Case 1B.

2.9 Evaluation of Cases

Cases 1 and 2 produce high-purity, aqueously generated oxide within a plant that can treat all residues and wastes. These cases fully meet the interface specification discussed in Sec. 1. This oxide should have the morphology that will produce high-density fuel pellets upon

sintering. Cases 3, 4A, and 4B do not remove gallium and americium, the major impurities in weapon plutonium, and produce oxide that is generated directly from metal oxidation. Case 3 treats all residues and wastes, whereas 4A and 4B have no residue treatment and only minimal waste-treatment capability. Cases 5A and 5B are provided for reactor fuels that use metal instead of oxide as feed material. In case 5A, the major impurities in the plutonium metal are gallium and americium; in case 5B, the major impurity is gallium.

The interface specification given in Sec. 1 embodies the assumption that americium is removed from the plutonium. Removal of americium requires significantly more processing and results in an americium waste stream that may not be readily disposable. Leaving the americium with the plutonium may impact fuel-fabrication somewhat but may also result in less overall cost and will eliminate americium as a separate waste stream. Therefore, to provide a means to judge the relative merits of americium removal, flow sheets of processes that do not remove americium are included in this evaluation of processing methods.

Data from the Complex 21 modeling effort were used to provide estimates of process equipment requirements, waste volumes, plant sizes, and costs for each case. Reference 1 assumes that the plant operates 1 shift/day, 5 days/week, and 40 weeks/year. These estimates are tabulated for comparison purposes in Table 2-1 and illustrated in Figs. 2-1 through 2-5. These estimates are based on recovery of 50 Mg of plutonium over a 20-year period. The discounted cost value consists of the capital cost and the operating costs discounted over the plant life, 20 years, with a discount factor of 4.5%. A considerably more aggressive operating schedule appears possible. If so, the duration of the recovery operation could be greatly compressed or the plant size greatly reduced.

Results of this study show that directly recovering metal or oxide and not removing the americium or gallium (Cases 3, 4, and 5A) have major cost and waste advantages.

Case 3 provides a system that treats all residues and wastes and decontaminates uranium from composite pits. Decontaminated uranium then can be processed/fabricated for reactor fuel.

Cases 4A and 4B were included to provide a comparison to a "minimum" facility. Inherently, these cases generate residues that may not meet

direct disposal requirements. In addition, uranium from composite pits is not decontaminated in Case 4B and must be stored indefinitely or processed in a plutonium-contaminated system.

Case 4A was not evaluated for composite pits. Therefore, this case would apply only to about 30% of available weapons. Insufficient data were available to include in this study the processing of composite pits without disassembly (Case 4A).

Current inventories suggest that a large fraction of excess weapon plutonium will come from weapon pits or other metallic forms. A smaller fraction of the excess weapon plutonium may come from inventories of oxide and residues. Therefore, multiple systems or a single flexible processing system may be required. Case 3 is a minimum plant that has processing systems required for residues. A more comprehensive analysis can be performed once detailed information is available regarding what forms of plutonium are considered to be excess.

Comparison of Cases 2 and 5A shows that the plant size and cost for producing oxide are equivalent to the those for producing metal.

It should be noted that, at present, this study is only scoping in nature, and thus each case has not been optimized. Results should be used only for comparison between cases and not as an absolute for any given case. In all cases, the equipment, space, personnel, and thus the cost required to perform analytical chemistry are not included.

Case 1 was used to examine the effect of operating times. Results of various operating times between 5 and 50 y are shown in Table 2.2 and illustrated in Figs. 2-6, 2-7, and 2-8. Other cases would have exhibited similar results. These data show that significant savings can be realized by extending plutonium recovery operations over a longer period of time, such as 20 y. The most cost-effective operating time, and therefore plant size, would be established on the basis of several factors such as the schedule for startup of recovery plants and fuel-fabrication facilities and the requirements for fuel delivery.

2.10 Technology/Equipment Portability

It appears that recovery of plutonium could be accomplished on Russian weapons by Russians using equipment developed for recovering U.S. weapon plutonium. We are examining two approaches that might allow expedient application of U.S. recovery technology in Russia.

Reference

1. *Material Balance Calculation for Conceptual Design of the Plutonium Reprocessing Facility—Version 2.2 Flowsheet*, Los Alamos National Laboratory, Los Alamos, NM, Report A-7: 93-C-77, September 1, 1993.

Table 2-1. Summary of plant characteristics for various processing cases (20-y recovery operation).

Case	Summary description	²⁴¹ Am removal	Weapon applicability (%)	No. of work stations	Plant size (m ²)	Capital cost (\$M)	Operating cost (\$M/y)	Discounted cost (\$B)	TRU waste (m ³ /y)	Low-level waste (m ³ /y)	Pu recovery (%)
1	Oxide/aqueous process/metal feed	Yes	100	118	14,800	590	60	1.30	92	280	99.66
2	Oxide/aqueous process/oxide feed	Yes	100	150	16,800	664	73	1.50	93	290	99.83
3	Oxide/from metal/aqueous residue recovery	No	100	59	10,100	420	35	0.85	52	26	99.95
4A	Oxide/from metal/no pit disassembly residue recovery	No	~30	30	7,700	360	23	0.67	59	2	99.83
4B	Oxide/from metal/pit disassembly/no residue recovery	No	100	27	8,000	360	28	0.73	86	6	99.63
5A	Metal/no americium removal/residue recovery	No	100	60	10,300	430	35	0.87	52	26	99.95
5B	Metal/americium removal/residue recovery	Yes	100	71	11,400	470	43	0.98	92	38	99.43

Table 2-2. Characteristics of a Case 1 plant as a function of time for excess weapon plutonium recovery.

Time (y)	Plant size (m ²)	Capital cost (\$M)	Operating cost (\$M/y)	Total discounted cost (\$B)
5	36,700	1,400	210	2.5
10	26,100	1,000	120	1.9
15	18,600	740	79	1.5
20	14,800	590	60	1.3
50	9,200	340	28	0.8

Figure 2-1. Number of work stations required for the various recovery cases.

Figure 2-2. Plant size, as characterized by floor area, for the various recovery cases.

Figure 2-3. Capital (a) and annual operating (b) costs for the various recovery cases.

Figure 2-4. Discounted costs by recovery case.

Figure 2-5. Annual waste volume generated by the various recovery cases.

Figure 2-6. Plant size vs time for recovery operations for Case 1.

Figure 2-7. Capital and operating costs vs time for recovery operations for Case 1.

Figure 2-8. Total discounted cost vs time for recovery operations for Case 1.

3. Environment, Safety, and Health

A key factor in selecting the plutonium-disposition method and conducting all disposition operations is the manner in which environment, safety, and health (ES&H) issues will be managed. In this section, we examine in a general way the relevant ES&H topics and applicable regulations. In a subsequent study, we plan to examine in greater detail the ES&H aspects of one or more specific plutonium-recovery processes.

3.1 Public Health and Safety

Since plutonium is one of the more toxic radioactive materials, its handling, processing, storage, and transportation require a high degree of containment. This is done mainly by means of highly engineered containment systems. These engineered systems include glove boxes, rooms, and facilities that have multiple stages of high efficiency particulate-air (HEPA) filters incorporated into the ventilation system. HEPA filters are designed to be at least 99.97% efficient for aerodynamic particles $0.3\ \mu\text{m}$ (or greater) in diameter. Other engineered systems include containment structures that are designed to maintain containment integrity during design-basis accidents and natural phenomena such as earthquakes, tornados, and fires. In addition, weapon plutonium is shipped in containers designed to withstand accidents that could be encountered during transportation. Thus, the handling, storage, and transportation of plutonium do not generally pose a hazard to the general public during normal operations or during most accident conditions.

3.1.1 Radiological Hazard from Dispersed Plutonium

The principal hazard to the public associated with the recovery of weapon plutonium as feed material for reactor fuel would be an incident that somehow breached the engineered containment system and dispersed plutonium to the environment. If we assume that plutonium dispersed to the environment in an accident is not accumulated in sufficient quantities to result in a criticality accident (see Sec. 3.2.1), the principal radiological hazard results from the intake of plutonium into the body. This is consistent with the fact that dispersed PuO_2 does not present a

hazard outside the body. Radionuclides in weapon plutonium are primarily alpha emitters, which in general do not have sufficient energy to penetrate the dead layer of the skin. X rays and gamma rays emitted from weapon plutonium are relatively low energy or low abundance.

The four pathways by which plutonium can enter the body are inhalation, ingestion, injection or wound contamination, or absorption through the skin.

Inhalation. The primary hazard pathway associated with the dispersal of plutonium to the environment is inhalation. Inhalation of plutonium particles can occur during passage of the plume following release and from the resuspension of plutonium that is deposited on the ground. In general, particles that have aerodynamic diameters $<10\ \mu\text{m}$ are considered to be respirable. Two of the most likely dispersion scenarios would involve either an explosion or a fire, either of which would most likely produce plutonium in the oxide form (PuO_2). The fraction of the plutonium involved in a high-explosive detonation that can be released in respirable particle sizes is about 20%. On the other hand, if dispersal results from a hydrocarbon fire, the fraction released in respirable particle sizes is only about 0.05%.¹

The deposition pattern of plutonium in the respiratory tract depends on the particle size of the inhaled plutonium. The human respiratory tract is divided into three regions: the nose and throat, the tracheobronchial region, and the pulmonary region, which is the lower part of the lungs where oxygen exchange takes place. Essentially all (99%) of the PuO_2 deposited in the nose and throat and in the tracheobronchial region is cleared to the gastrointestinal (GI) tract in less than a day. This material is of relatively

little concern because the body absorbs very little plutonium from the GI tract.

In general, the smaller the particle size, the more likely the particle is to penetrate to the pulmonary region of the lungs, where the clearance mechanisms are not as effective as in the upper respiratory tract. As an example, for an aerosol with an aerodynamic diameter of 1 μm , about 25% of the inhaled PuO_2 will be deposited in the pulmonary region of the lungs.

Eventually, most of the plutonium in the pulmonary region of the lungs is dissolved by the body fluids and is translocated primarily to the liver and the bone, where it is retained with half-lives of 20 and 50 y, respectively. Because of the relatively long retention of the PuO_2 in the lungs, liver, and bone and because it is an alpha-particle emitter, the integrated radiation dose to these organs is relatively high. The approximate committed effective radiation dose is about 3 Sv/ μCi of inhaled PuO_2 (about 12 μg), assuming an aerodynamic particle size of 1 μm . A 1- μm particle of PuO_2 has an activity of 0.44×10^{-6} μCi . Thus, more than 2 million such particles would need to be inhaled to achieve a committed effective radiation dose of 3 Sv.

The approximate quantity of plutonium required to produce acute respiratory effects has been estimated to be about 2 mCi (25 mg). If this quantity of plutonium were deposited in the pulmonary region of the lungs, the radiation damage to the surface of the lungs from the alpha particles would cause severe irritation and edema such that oxygen exchange would be impeded. This condition has never been observed in humans and is based on extrapolations from animal experiments. The likelihood that this acute exposure situation would be encountered in a situation involving plutonium accidentally dispersed to the environment is extremely small.

Ingestion. The ingestion pathway is the least serious intake pathway because the body absorbs very little plutonium, typically only a few parts per hundred thousand, as it passes through the GI tract. Thus, the ingestion pathway would not normally pose a significant hazard if plutonium were accidentally dispersed to the environment.

Injection or wound contamination. Since PuO_2 is relatively insoluble in body fluids, it tends to remain at the wound site and translocates only slowly to the bone and liver. Other, more soluble compounds such as nitrates and

chlorides would translocate from the wound site more rapidly. If plutonium is taken into the body through a contaminated wound, the wound should be irrigated to remove as much contamination as possible. If the quantity of plutonium in the wound were more than a few nanocuries, excision should be considered. Plutonium is relatively easy to detect in shallow wounds down to a small fraction of a nanocurie.

Absorption through the skin. Since PuO_2 is relatively insoluble in body fluids, essentially no absorption occurs through intact skin.

3.1.2 Risk from Radiation Exposure to Dispersed Plutonium

The risk from exposure to dispersed plutonium is directly related to the quantity of plutonium deposited in the body via the various intake pathways. The amount of plutonium in the body and its subsequent distribution to other organs can be estimated by bioassay techniques (e.g., urine and fecal sampling) and direct measurement techniques (e.g., lung counting and wound counting). It should be understood that the deposition, distribution, and clearance models are only approximate and that there is considerable biological variation from one person to another. However, these models, coupled with standard dose-calculation methodology, can provide a reasonable estimate of the radiation dose that would be received following an intake of plutonium. Thus, given an estimate of the plutonium intake, the intake pathway, and knowledge of the chemical form of the plutonium, the integrated dose to the individual can be estimated.

The primary risk from chronic radiation exposure, whether from plutonium or other sources of radiation, is latent cancer induction. The risk to the individual is assumed to be directly proportional to the integrated dose received. The currently assumed risk of fatal cancer induction from ionizing radiation exposure based on exposure to high doses is estimated to be about 5×10^{-2} /Sv. If a person inhaled 0.01 μCi (0.12 μg) of PuO_2 , the committed effective dose over the next 50 y would be about 30 mSv. The individual's increased risk of getting cancer from that exposure would thus be about 0.0015 or 0.15%. Since the risk of dying of cancer from all causes is about 20%, the individual's risk of contracting fatal cancer would be increased to 20.15%.

3.1.3 Potential for Toxic Releases

The potential for releases of toxic material would be a function of the type of operation and the specific toxic material used. However, since five of the cases being considered involve the use of nitric acid, the potential for the release of this material to the environment must be considered.

The aqueous nitrate dissolution process (Cases 1 and 2) uses large quantities of nitric acid, which, if spilled, usually are contained locally. The only public health and safety issue occurs during transportation. Cases 3, 5A, and 5B use nitric acid for waste treatment. The oxides of nitrogen that form as byproducts of the dissolution process are toxic and may pose public-health issues on windless days or when inversion layers are present.

In general, if a nitric acid solution containing a significant quantity of plutonium is dispersed to the environment, the potential plutonium hazard predominates over the chemical hazard.

3.1.4 Design-Basis Accidents

According to DOE Order 6430.1A, *General Design Criteria*,² facilities that handle or store plutonium must be designed to maintain their confinement integrity during accidents. Specifically, the confinement structure and safety-class equipment must be designed to ensure the safe shutdown of operations, maintain the facility in a safe shutdown condition, maintain the integrity of the confinement barrier, and monitor the release of toxic material that could result in potential exposures to the public. The accident categories include fire, criticality, and explosion. The most severe impact, referred to as the design-basis accident, must be considered for each accident category.

The specific design-basis accidents would be a function of the specific activities being conducted in the particular facility. Plutonium handling and storage facilities would have to meet the design criteria specified in Division 13, "Special Facilities," of DOE Order 6430.1A.

3.1.5 Natural-Phenomena Hazards

According to DOE Order 6430.1A, *General Design Criteria*, facilities that handle or store plutonium also must be designed to maintain their confinement integrity during natural force events. The natural-phenomena event categories include tornados, earthquakes, and floods. The

most severe impact, referred to as the design-basis natural-force event, must be considered for each natural-force category.

The specific design-basis natural-phenomena events would be a function of the geographical area and the specific activities being conducted in the particular facility.

3.2 Occupational Safety

3.2.1 Criticality Safety

Processing and handling plutonium isotopes in significant quantities introduce a potential for a nuclear criticality incident. If such an incident were to occur, a potentially lethal level of gamma and neutron radiation would be produced, causing damage to equipment and death to personnel in the immediate vicinity of the occurrence. In addition, radioactive noble gases and volatile materials produced by the accident could be discharged into the environment. It is essential that such an event will not occur during the process of converting weapon plutonium to feed material for reactor fuel.

Criticality safety requirements and guidelines governing plutonium-recovery operations are provided in DOE Order 5480.24.³ The basic designs of the plutonium-recovery facilities—which include the operating equipment, the storage vault layouts, and the glove boxes—must possess sufficient safety controls to ensure that the likelihood of a criticality accident is low. Criticality safety assessments must also be performed to ensure that criticality safety requirements in DOE orders are satisfied.

Criticality safety controls. Sufficient safety controls must be incorporated into the design and operation of the plutonium-recovery processes such that they are criticality safe under all normal conditions and satisfy the double-contingency principle during off-normal conditions. The double-contingency principle requires that at least two unlikely, independent, and concurrent changes must occur in process conditions before a criticality accident is possible. These controls comprise the following engineered design features and administrative procedures:

- Physical separation of individual work stations;
- Physical plutonium mass limits for work stations and glove boxes;

- Moderator controls;
- Administrative control on material movement;
- Rigorous housekeeping practices to minimize material holdup.

These engineered design features and administrative controls are provided to ensure safe recovery operation from the standpoint of criticality safety. These criticality safety controls are reinforced by operator training and certification, periodic safety audits, and management oversight.

Criticality safety assessments. In accordance with the requirements of DOE orders, criticality safety assessments must be conducted to determine that all plutonium-recovery operations satisfy the double-contingency requirement and are subcritical under both normal and abnormal conditions that could reasonably be expected to occur. The criticality safety assessments are performed to evaluate the adequacy of the design and operation of the recovery process. The assessments can be based on criticality handbooks or results of validated computational methods (computer analyses). When a statistics-based Monte Carlo computer code is used to calculate the neutron multiplication factor (k_{eff}) of a fissile system, the acceptance criterion is

$$k_{\text{eff}} + 2\sigma \leq 0.95, \quad (1)$$

where σ is the standard deviation of the analysis.

Criticality safety assessments must demonstrate compliance with the double-contingency principle and show that, in many cases, more than two contingencies exist. The assessments also must be thoroughly reviewed and documented in accordance with DOE Order 5480.24.

3.2.2 Occupational Radiation Exposure

The mixtures of plutonium and americium radionuclides handled in the plutonium-recovery operations present both internal and external radiological hazards. The alpha radiation from plutonium and americium presents an internal hazard if inhaled, ingested, or absorbed into the bloodstream through breaks in the skin. Gamma and neutron radiation emitted from the mix of radionuclides can expose plutonium workers to significant external radiation fields.

Inhalation is by far the most likely intake pathway. The potential doses and risks

associated with inhalation as well as pathways are also discussed in Sec. 3.1.1.

Penetrating radiation is emitted from plutonium isotopes and ^{241}Am in the form of x rays, gamma rays, and neutrons. The x rays have energies in the range of 14 to 20 keV. Americium-241 emits 60-keV gamma rays, and ^{239}Pu emits relatively low-intensity gamma rays in the range from 380 to 420 keV. Neutron radiation is produced primarily by spontaneous fission and alpha-neutron (α, n) reactions. In the recovery of weapon plutonium, most of the neutron radiation is expected to come from the spontaneous fission of ^{240}Pu and the (α, n) reactions in the oxide compounds.

The intensity of the penetrating radiation components associated with the plutonium-recovery operation would depend on the specific composition of the radionuclide mix, the chemical form [which could affect the production of (α, n) neutrons], the physical form (which would affect the inherent shielding), and any external shielding. In general, low-energy x rays and 60-keV gamma rays from ^{241}Am are relatively easy to shield. Neutron radiation is more difficult to shield. High-energy gamma rays, although more difficult to shield, have relatively low intensity and normally do not present a major external radiation hazard.

The specific plutonium recovery process and composition of the radionuclide mix would have to be evaluated to determine the potential external radiation doses to the extremities and the whole-body doses to workers. This evaluation would also serve as the basis for dose-minimization techniques such as addition of shielding, automation of operations, minimizing work time, and increasing the distance between workers and radioactive materials.

Contamination control. One of the primary objectives in designing and operating plutonium-recovery facilities is to completely isolate the process material from workers. As stated in DOE Order 6430.1A, "Design objectives for the confinement system shall be an essentially zero exposure of the plant personnel and the public to airborne contamination." This is accomplished primarily through the use of highly engineered containment systems. These engineered systems include glove boxes, rooms, and facilities that have multiple stages of HEPA filters incorporated into the ventilation system. Normally the confinement system consists of three barriers:

(1) the glove boxes in which the operations are conducted, (2) the room in which the glove boxes are located, and (3) the building. Pressure differentials are maintained across these physical barriers by the HEPA-filtered ventilation system. Airflow in the facility is always directed from regions of lower contamination potential to regions of higher contamination potential. The glove boxes are kept at a negative pressure with respect to the room, which is kept at a negative pressure with respect to the rest of the building. This design reduces the probability that contamination can escape from the facility if the primary barrier is breached.

Typically, rooms in which plutonium is processed are equipped with continuous air monitors to alert workers in the event plutonium is released into the room. In addition, workers check their hands for contamination when removing them from the glove box, and they check their hands and feet for contamination when leaving the room.

Radiation dose reduction. Radiation shielding and other dose-reduction techniques must be used to ensure that radiation doses received by facility workers are below the applicable dose limits and as low as reasonably achievable (ALARA). Wherever shielding cannot provide the necessary reduction in dose, remote handling methods and robotics must be employed.

DOE Order 5480.11⁴ establishes radiation exposure limits to radiation-zone workers. The current annual limit for the whole body and lens of the eye is 50 mSv. The current limit for extremities (e.g., hands, forearms) is 500 mSv. Design criteria or radiation protection in accordance with DOE Order 6430.1A are generally lower than the operating limit. For example, the annual limit for the whole body, based on design, is usually set at 10 mSv.

Although the radiation level emitted from weapon plutonium is lower than that emitted from commercial reactor-grade plutonium, a radiological assessment must be performed to ensure that the radiological design and operation requirements are met.

3.2.3 Toxicological Hazards

Recovery cases that use an aqueous nitrate dissolution process use large quantities of nitric acid, which is corrosive to skin and mucous membranes, is highly toxic when inhaled, and poses a fire risk when it comes in contact with

organic materials. The hydride chlorination step also involves gases and liquids that are corrosive to skin and highly toxic when inhaled. Aqueous waste generated by these processes is also toxic.

3.3 Environmental Issues

3.3.1 Environmental Protection Agency Requirements

A number of federal, state, and local environmental laws and regulations potentially can impact plutonium-recovery efforts. Some of the major federal laws are outlined here. The National Emissions Standards for Hazardous Air Pollutants (NESHAP)⁵ regulate the emissions of certain radionuclides, and the Clean Air Act (CAA)⁶ regulates hazardous air pollutant emissions from industrial processes and, soon, radionuclide emissions as well. The Resource Conservation and Recovery Act (RCRA)⁷ regulates the handling, storage, treatment, and disposal of hazardous waste, and the Clean Water Act (CWA)⁸ regulates the discharge of wastewater from industrial processes. In addition to these federal laws and regulations, each state may impose additional requirements. The states' requirements can be, and often are, more stringent (they cannot be less stringent) than the federal EPA regulations. Consequently, the federal EPA requirements are our baseline for discussing environmental issues, with the understanding that both state and local government entities (e.g., regional air boards, county health departments) can present variations on what is discussed here.

National Emissions Standards for Hazardous Air Pollutants (NESHAP). The NESHAP regulations require that all potential emissions of radionuclides be modeled using an approved model to estimate dose concentrations at the facility's fence line for each emitting process. If emissions from a DOE facility exceed 1.0 μ Sv at the fence line, then in-stack monitoring must be installed. NESHAP does not require an abatement process, but other legal requirements may [including the Clean Air Act (discussed next) and DOE regulations that limit the total radiation exposure of the local population]. Modeling must be repeated every three years or whenever there is a potential significant change in the radionuclide emissions from the facility's processes. The EPA is seeking to delegate

NESHAP regulatory authority to state agencies, and this process is well underway in California and Washington.

Clean Air Act (CAA). The CAA regulates emissions of "criteria pollutants" [SO₂, nitrogen oxides, ozone, PM-10 (i.e., particulate matter of respirable size), CO, and lead] and hazardous air pollutants from all sources. For example, nitrogen oxides given off from the calcining of plutonium nitrate are regulated, and this process could require an air permit. The rigor of the CAA permitting requirements will be impacted by local air-pollution conditions. Among the major quantitative aspects that may affect the impact of these regulations are

- The total potential (maximum estimated) emissions from plutonium-recovery operations,
- The total emissions from all processes in the entire facility where the process is located,
- The existing ambient air quality based on specific pollutant concentrations in the region where the facility is located.

Depending on these and other factors introduced by state and local regulations, there may be one or more specific process permits required or, possibly, a facility-wide permit modification process will be needed. Emissions offsets (to make up for new emissions from the proposed plutonium processes) may also be required, and some type of emissions control technology will have to be provided. Because of the potential for widely varying air quality and associated regulatory requirements, each potential process site must be separately evaluated for air-permitting impacts.

In addition to NESHAP, the 1990 amendments to the CAA also regulate radionuclides as hazardous air pollutants. Efforts to rationalize these two separate regulatory processes are underway by the EPA and state agencies. This probably will result in additional monitoring, permitting, record-keeping, and emission-control requirements for any process that could emit radionuclides (although the quantity of such emissions that would trigger some of these requirements also is being debated).

The Resource Conservation and Recovery Act (RCRA). RCRA and equivalent state regulations regulate the handling, storage, treatment, and disposal of hazardous wastes generated during plutonium-recovery operations.

RCRA defines "hazardous" waste both in terms of hazardous *characteristics* (ignitability, corrosivity, reactivity, and toxicity) and by listing specific hazardous wastes by chemical or generating process. When a hazardous waste is mixed together with a radioactive waste, the combination is called a mixed waste (MW), and RCRA regulates the hazardous portion of the waste while DOE retains oversight of the source, special nuclear, or byproduct material portion as defined by the Atomic Energy Act of 1954 as amended.⁹ MW presents one of the most complex waste problems under RCRA because of this dual regulation and the difficulty of treating the waste.

The greatest potential impact of RCRA would result if any portion of the proposed plutonium-recovery operations were interpreted as treatment of MW because a complete RCRA permitting, reporting, and oversight process would be triggered that would add significant time and cost factors to efforts required to get operations underway. Consequently, all feed stocks for plutonium recovery that potentially could be considered MW must be carefully screened and, if possible, avoided. The RCRA definition of "waste" is very broad and could include some of the "scrap" plutonium sources that are mixed with hazardous contaminants as well as discarded hazardous residues from the plutonium-recovery processes. The RCRA definition of "treatment" also is very broad, so care must be taken when processing residues from the recovery processes to avoid inadvertently setting up a RCRA MW treatment unit that requires permitting. Storage of RCRA waste onsite longer than 90 days also will require a RCRA permit, but one that is relatively easier to obtain than a treatment permit. RCRA permitting also can trigger a requirement for a chemical health risk assessment of potential exposures to offsite populations and the environment.

RCRA has a major impact on the disposal of hazardous and mixed wastes because it requires that such wastes be treated to meet land disposal restrictions (LDRs) prior to disposal on land. The operators of the WIPP are attempting to get permission to accept certain MW without first requiring that the RCRA LDR treatment requirements be met. However, it is not yet known to what degree this effort will succeed, and, in any event, MW with the characteristics of ignitability, corrosivity, and reactivity probably will have to be treated to LDR standards for these characteristics before being accepted at WIPP.

Such treatment currently is difficult to obtain. DOE is expected to develop more MW treatment capacity in response to the requirements of the Federal Facility Compliance Act of 1992,¹⁰ but it may be costly and may not be available for all wastes generated from plutonium-recovery processing. Thus, minimizing hazardous and mixed wastes (based on the relative amount and kind of MW generated) will be important criteria in evaluating the competing plutonium-recovery processes. It is conceivable that certain kinds of MW may be neither acceptable by WIPP nor treatable and thus will preclude the use of a process that generates them.

The Clean Water Act (CWA). The CWA and resulting regulations control the disposition of wastewater. State regulations and local publicly owned treatment works (POTW) requirements can vary significantly between process sites and could impact the choice of plutonium-recovery processes. The degree of pretreatment required before passing wastewater to the local sewage plant can be a significant cost factor. The absence of a POTW at a proposed location could result in the relatively more expensive alternative of treating (onsite or offsite) much of the otherwise "sewerable" wastewater to meet National Pollutant Discharge Elimination System⁸ standards or handling it as RCRA hazardous waste.

EPA-derived regulations summary. The kinds and amounts of wastes generated by a candidate plutonium-recovery process and how these wastes are handled and treated are important criteria from an environmental perspective. Any process that can trigger a RCRA hazardous-waste permitting requirement will introduce a relatively lengthy process that includes public participation and can impact the project timeline significantly. The cost of treatment or disposal of these RCRA wastes also can be significant. Carrying out plutonium recovery at facilities that already have broad-range environmental permits can sometimes be an advantage because only relatively minor permit modifications may be needed. However, more stringent air-permitting requirements may be encountered at a large facility because of large existing emissions from the facility or its location in an area that has polluted air. The state and local regulatory climate can vary dramatically despite the underlying federal regulatory guidelines, and an attempt to

quantify these local factors should be made when evaluating potential recovery methods and sites.

3.3.2. National Environmental Policy Act Requirements

Federal actions of the sort discussed in this report must be evaluated under the requirements of the National Environmental Policy Act (NEPA).¹¹ The purpose of NEPA is to inform the federal decision-maker regarding potential environmental impacts associated with the proposed project and its alternatives. Some states have similar, independently implemented laws, such as the California Environmental Quality Act,¹² that add significant requirements to those imposed by NEPA.

Existing NEPA Coverage. If plutonium recovery is accomplished at federal facilities, some level of NEPA coverage may already exist. The relative breadth and depth of coverage for processes that are similar to proposed plutonium processes are important criteria for choosing a process/site combination. In this context, it could be advantageous to choose a facility with an existing NEPA-reviewed process capacity that can be used for plutonium recovery. An existing sitewide NEPA environmental impact statement (EIS) could also be a plus if it can be used to cover most of the proposed plutonium processing. The proposed programmatic EIS (PEIS) for weapon production may provide partial NEPA coverage for plutonium-recovery projects. It now appears, however, that a stand-alone PEIS for disposing of fissile material may need to be prepared.

Other NEPA Factors. Potential impacts on cultural resources (such as archeological sites or historical buildings) and natural resources (including endangered species, wetlands, and flood plains) are important factors in NEPA evaluations. Potential human health and safety effects also must be evaluated in the context of NEPA. These evaluations include accident scenarios to be incorporated into the environmental assessments or impact statements. The greater the radiation and toxic effects of the proposed project, the more complex the impact analyses become and the more costly the potential mitigation measures. Moreover, the requirement to perform a NEPA evaluation can extend to offsite activities. For example, NEPA applies to projects on DOE property as well as offsite

projects involving DOE funding, personnel, equipment, or permitting. Finally, the history of public awareness and involvement in the proposed site's NEPA projects is useful in predicting the time required for state-level participation and the probability of third-party litigation focused on the NEPA process.

3.4 Waste-Stream Disposal

Each of the plutonium-recovery cases discussed in Section 2 would generate waste streams that contain radioactive material. The handling and final disposition of these wastes comprise one of the issues to be addressed in selecting and designing the system. Disposal of high-level waste (HLW), transuranic (TRU) waste, and spent fuel is subject to NRC regulation under 10 CFR 60,¹³ and disposal of low-level waste (LLW) is subject to 10 CFR 61.¹⁴ Mixed waste containing both radioactive and RCRA hazardous waste is discussed in section 3.3.1.

All of the waste streams of interest have in common the presence of significant amounts of plutonium and other TRU radioisotopes. It is possible that certain of the waste streams would qualify as LLW and would be governed by the acceptance criteria for the LLW disposal compact in which the facility is located. A content of more than 100 $\mu\text{Ci/kg}$ results in the plutonium-containing waste being classified as TRU and not eligible for disposal as LLW.

Most such wastes would qualify for emplacement at a facility such as WIPP. Waste disposal at WIPP is subject to provisions of the EPA, 40 CFR 191,¹⁵ and RCRA, 40 CFR 264/268. In addition, the WIPP Land Withdrawal Act (Public Law 102-579)¹⁶ established a maximum activity limit of 23 kCi/m^3 and a maximum contact dose rate of 10 Sv/h for waste emplaced at WIPP. In addition, a total activity limit of 5.1 MCi is specified for remotely handled TRU waste at WIPP. If the waste streams from the recovery process contain 1% of the assumed 50 Mg excess weapon plutonium inventory, their contribution to the overall activity limit at WIPP would be less than 1%.

As HLW is now defined, it is unlikely (but possible) that plutonium would be categorized as HLW. Barring such an unanticipated interpretation, most of the waste from processing plutonium into reactor fuel would meet the acceptance criteria for TRU disposal. One possible exception to this would be a waste with a high americium

content, if the americium is removed prior to fuel fabrication. Depending on the americium concentration, this waste could produce enough heat to require disposal as HLW at a facility such as that proposed for Yucca Mountain.

NOTE: A recovery process that provides feed material for reactor fuel results in one or more final waste streams that would require disposal as TRU. Disposal of spent reactor fuel and fuel-reprocessing wastes is beyond the scope of this report but will be the subject of a future report.¹⁷

References

1. D. R. Stephens, LLNL, private communication (1994).
2. DOE Order 6430.1A, U.S. Department of Energy, Washington, DC.
3. DOE Order 5480.24, U.S. Department of Energy, Washington, DC.
4. DOE Order 5480.11, U.S. Department of Energy, Washington, DC.
5. National Emissions Standards for Hazardous Air Pollutants, 40 CFR 61.
6. Clean Air Act, 42 U.S.C. 7401 *et seq.*, and 40 CFR Subchapter C, Parts 50–59; Clean Air Act (as amended), 42 U.S.C. 7412.
7. Resource Conservation and Recovery Act, 40 CFR, Subchapter I, Parts 260–299; 42 U.S.C. 6901 *et seq.*
8. Clean Water Act, 33 U.S.C. 1251–1387; 40 CFR Subchapter D, Parts 100–149, and Subchapter N, Parts 400–403.
9. 68 Statute 923.
10. Federal Facility Compliance Act of 1992 (P.L. 102-386).
11. National Environmental Policy Act, U.S.C. 4321 *et seq.*
12. California Environmental Quality Act, California Public Resources Code 21000 *et seq.* and 14 CCR 15000 *et seq.*
13. 10 CFR 60, U.S. Nuclear Regulatory Commission, Washington, DC.
14. 10 CFR 61, U.S. Nuclear Regulatory Commission, Washington, DC.
15. 40 CFR 191, U.S. Environmental Protection Agency, Washington, DC.
16. Waste Isolation Pilot Plant Land Withdrawal Act (P.L. 102-579).
17. W. G. Halsey, *Geologic Disposal of Plutonium Disposition/Utilization Wastes (Initial Concerns and Issues)*, to be published.

4. Safeguards and Security

A well-planned and executed safeguards and security (S&S) system must combine physical protection, material control, material accountability, and personnel assurance. Experience has shown that incorporating S&S measures into early plant designs and integrating them into plant operations provide S&S that is more effective, more economical, and less intrusive. In addition to these more traditional S&S measures, intrinsic safeguards may be included in the material—for example, modified isotopics to reduce material attractiveness. Because of increased concerns about nuclear proliferation, public awareness, and the uniqueness of these plutonium processing facilities, S&S systems will be required to meet the highest standards of performance and compliance. The discussion of S&S in this report is general. In a future study, we plan to assess specific S&S characteristics and requirements for one or more of the recovery processes being considered.

4.1 Introduction

Safeguards must ensure that nuclear materials and information are protected as required by DOE Orders. In particular, special nuclear material (SNM) must be safeguarded according to the graded approach required by DOE Order 5633.3A, *Control and Accountability of Nuclear Materials*.¹ The graded approach is the concept of providing the greatest amount of control and effort to the types and quantities of SNM that can be most effectively used in a nuclear explosive device. The material in the weapon-plutonium recovery facility will be of Category I quantity and attractiveness level A, B, or C, and therefore must be provided the highest levels of protection.

The S&S system must be designed to meet the DOE Design Basis Threat modified for any site-specific threats and protect against all possible malevolent acts, including theft of SNM, radiological and toxicological sabotage, and loss of classified and sensitive information. These threats from both insiders and outsiders include terrorists, criminals, disgruntled employees, and foreign agents. The targets for SNM theft include plutonium pits, metal, and oxides in process and in storage.

While providing the highest levels of protection and compliance, the S&S system must also

- Minimize impact on operations;
- Complement other areas of facility operations, including nuclear safety, process control, quality control, and radiation protection;

- Be integral to the facility design; and
- Minimize S&S costs and maximize reliability by using proven, state-of-the-art technology instead of labor-intensive methods.

Physical protection, material control, and material accountability are important considerations in planning the plutonium recovery facility. Personnel security issues related to plutonium recovery are not identifiably different from those of current DOE facilities. Q clearances and personnel security assurance programs (PSAPs) will be required according to current DOE Orders and guidance. The important aspects of physical protection, material control, and material accountability are discussed in the following sections.

4.2 Physical Protection

Physical protection of facilities includes protection in depth (several layers of protective measures providing detection, delay, and response), balanced protection (nearly equal detection and delay on all possible adversary paths to similar targets), graded protection (detection, delay, and response commensurate with the assets being protected), and reliability (minimal susceptibility to single point failures and low maintenance requirements). The physical protection system will use proven S&S systems and components that have been validated at other facilities or test programs but

allow for future technology advances. Technology will be used to reduce the cost of protective force personnel. The protection system and facility operations will provide compartmentalization of the facility to minimize personnel access to potential targets of malevolent acts. Compartmentalization will also be applied to minimize areas where classified information can be derived. The Argus security system,²⁻⁴ already endorsed by the DOE, can play a key role in meeting these objectives.

4.3 Material Control

Material-control systems will be designed and implemented to be closely associated with recovery process control, access control, and criticality safety. Material-control measures will govern all movement, processing, and access to plutonium. Entrances to the materials-access areas and the individual compartments of the facility will allow only authorized personnel to access the plutonium material and classified information. This access control will be accomplished through modern, integrated, access-control systems such as Argus and could be supplemented with biometric devices. Use of tags and personnel locator systems to monitor movement and location of personnel and materials may also be appropriate. Access-control systems will verify compliance with two-person-rule safeguards and will permit only authorized personnel into compartments of the facility.

Further access controls may be appropriate within individual work compartments. For example, a compartment may have interlocks installed on the access ports to the glove boxes to control the movement of plutonium through the line. These controls would be integrated with criticality safety, and transfers of plutonium into a glove box may require computerized approval to unlock a port. Material control would provide a detailed trail and history of the plutonium movement through the process. Assays and weights at appropriate points in the processes would allow a computer system to monitor the material movements and localize and identify any material losses or abnormal operating conditions.

4.4 Material Accountability

The S&S system will ensure that all materials containing plutonium, including those designated as hold-up or waste, are accounted for and measured according to the concept of graded safeguards. The material-accounting system will play an important role in detecting abrupt or protracted diversion or theft of plutonium and will be structured to provide timely information on the amount and location of all plutonium-bearing materials by using the concept of near-real-time accounting. The following are some general goals for the material accounting system:

- Partition the facility into unit process areas where material balances can be determined;
- Automatically determine material balances incorporating several unit process areas to check for consistency and provide redundancy;
- Minimize reliance on manual information collection and processing; and
- Minimize requirements for process shutdown and cleanup for inventories.

Accountability measurement locations will be coordinated with the process control and monitoring system while maintaining the needed measurement standards and accuracy required for safeguards purposes. In general, separate material balance areas (MBAs) will be planned for each unit operation in the recovery process that is selected and for subsequent operations (e.g., transportation of the plutonium feed material to the reactor-fuel-element fabricator). Accountability measurements must be corrected for bias and precision. A quality-control computer subsystem will be designed to collect, correlate, and process measurement-control data. As appropriate, the facility must have the capability to prepare and certify calibration and other quality-control standards.

All nuclear materials must be inventoried as required by the DOE Orders. Material quantities that cannot be reliably or practically measured must be estimated by using historical process information and modeling. Provisions must be made to measure hold-up and other retained material within the facility. Fixed measurement locations must be built into the process to assist in determining the hold-up. Nuclear materials in interim or prolonged low-maintenance storage must be inventoried as required by DOE Order 5633.3 and its latest implementation manual.

4.5 The Russian Connection

The primary force behind the drive to process, use, and dispose of plutonium from retired nuclear weapons is the desire to reduce the nuclear danger. Although plutonium may represent a potential danger to the environment, the overwhelming danger is that of use in a nuclear weapon. There is considerably more concern about the security of plutonium in Russia than in the United States. Consequently, the disposition of Russian plutonium is of paramount importance. The question then becomes, how can U.S. decisions regarding U.S. plutonium enhance the safety and security of plutonium in Russia?

There is, of course, always the possibility of a U.S.-Russian formal agreement or treaty to use or dispose of certain amounts of plutonium in equivalent ways. However, recent history suggests that mutual unilateral actions, such as the Bush-Gorbachev actions to eliminate tactical nuclear weapons, are more immediate and less costly than are formal treaties such as START. Urgency is dictated by the current cooperative environment in Russia. However, it may already be more difficult to influence actions in Russia this year than it was last year.

Besides attempting to influence events in Russia by unilateral action, the United States could offer direct aid and support in addition to the Nunn-Lugar funding for a storage facility for nuclear materials in Russia. In particular, if we

have or develop a more cost-effective and environmentally benign method of processing plutonium from weapons, we should consider transferring such technology and the appropriate safeguard mechanisms to Russia. Joint U.S.-Russian R&D on plutonium processing, use, and disposal (including the development of safeguards for each step) also could lead to a substantial reduction of the nuclear danger. Finally, a U.S.-Russian fully safeguarded and secure means of recovering plutonium from weapons could be a model for reducing world stockpiles of nuclear weapons and materials.

References

1. DOE Order 5633.3A, *Control and Accountability of Nuclear Materials*.
2. G. E. Davis, *Secure Interactive Livermore Alarm System (SILAS)*, Lawrence Livermore National Laboratory, UCRL-98830 (1988).
3. R. P. Rumble, D. Y. Jong, and S. M. Kluz, *The CAIN II Access-Control System*, Lawrence Livermore National Laboratory, UCRL-98829 (1988).
4. J. Smart, *Integrated Workstations for Reliable, Site-Independent Security Monitoring and Control*, Lawrence Livermore National Laboratory, UCRL-98832 (1988).

5. Transportation

Transportation of plutonium and associated wastes will be subject to government regulations and DOE orders. At its discretion, the DOE may adopt national-security exemptions for transporting sensitive forms of special nuclear materials. Such instances have become increasingly rare. Different regulations may apply for different portions of the plutonium-recovery operation, which generally starts with the weapon pits and ends with feed material for fuel-element fabrication.

Transportation issues include criticality control, shielding, and containment of the contents. Allowable limits on each of these issues are specified by the applicable (or selected) regulation. The composition and form of the radioactive materials to be transported will determine, in part, the applicable portions of the regulations as well as the packaging design.

5.1 Packaging Issues

Packaging design and transportation of a package containing radioactive material must ensure that the contents of the package remain subcritical, that the dose rate at the surface of the package is at an acceptable level, and that the release rate of the contents remains below specified allowable levels during storage and normal shipment and in the event of an accident.

5.1.1 Criticality

Criticality control may be the limiting factor in packaging design and transportation plans for plutonium in its various forms at various points in the recovery operation. Criticality criteria are given in Secs. 5.3.3 and 5.3.4. Criticality is not an issue for shipment of LLW from recovery operations.

5.1.2 Shielding

Shielding that must be provided by packaging will be dictated by the allowable surface dose rate and the radionuclide contents of the package. Additional shielding is required for shipments containing americium or plutonium oxide.

5.1.3 Containment

Containment criteria are determined by the radionuclide content of the package and the form of the material. Material in a nondispersible form, such as metal, is easier to contain than a potentially dispersible form, such as PuO_2 powder.

PuO_2 powder, unless exempted, must be doubly contained (i.e., in a sealed inner container that is wholly within a sealed outer container).

5.2 Regulations

Packaging and transportation of radioactive materials are subject to regulation by various government agencies, such as the Nuclear Regulatory Commission (NRC), the Department of Transportation (DOT), or the DOE. For defense program activities, the DOE may either comply with NRC regulations or select to transport materials under a national-security exemption.

5.2.1 National-Security Exemption

For the purpose of national security, DOT regulation 49 CFR 173.7 (b)¹ allows the DOE to ship radioactive material under escort by personnel designated by the DOE, thus waiving the DOT regulations in 49 CFR 170-189.²

5.2.2 DOE Order 5610.1, *Packaging and Transportation of Nuclear Explosives, Nuclear Components and Special Assemblies*³

Most current DOE shipments of nuclear explosives, nuclear components, and special assemblies not carried out under national-security exemptions are performed under DOE Order 5610.1. This order requires that nuclear explosives, nuclear components, and special assemblies must be packaged and transported to provide a level of safety at least equal to that

provided by packaging and shipping in accordance with regulations applicable to other radioactive materials.

5.2.3 10 CFR 71, *Packaging and Transportation of Radioactive Material*⁴

This NRC regulation establishes the requirements for packaging, preparation for shipment, and transportation of licensed material and for the procedures and standards for obtaining NRC approval of packaging and shipping procedures for fissile material and Type B quantities of other licensed materials. (A quantity of weapon plutonium in excess of ~25 mg constitutes a Type B quantity per 10 CFR 71.) This NRC regulation incorporates, by reference, DOT regulation 49 CFR 170-189. Whenever possible, the DOE transports radioactive materials under NRC regulations.

5.2.4 Nonconforming Shipments

All DOE shipments of material, components, and assemblies must meet the normal conditions of transport requirements of 10 CFR 71. If the shipment does not meet the hypothetical accident condition stated therein, however, the DOE may require that a risk assessment be performed. The DOE may then authorize the shipment, subject to restrictions determined by the results of the risk assessment. These may include restrictions on the mode of transport, type of vehicles, freight container, or supplementary operational requirements and may require a DOT exemption from some part of the DOT regulation.

5.3 General Logistics

Routes between the various plant locations in the recovery operation will determine the general logistics. The transport index (TI) of a package with fissile contents is based on nuclear criticality control (as determined by regulations). The limit of the number of packages (and hence the contents) per shipment is based on the TI. The minimum number of shipments for a campaign is simply the amount of material to be shipped divided by the maximum amount of material allowed per shipment. Safeguards and security must be in place to ensure that diversion of plutonium does not occur.

5.3.1 Location of Transportation End Points

Figure 5-1 shows the transportation end points being considered for the purpose of providing a definitive framework in which to evaluate transportation issues. This figure depicts several possible scenarios to illustrate the transportation issues involved. Collocation of the necessary facilities would avoid or minimize the need for transportation. Pits are assumed to be isolated from their weapons at Pantex. Plutonium recovery, as outlined in Sec. 2, could be done at Pantex, or the pits could be shipped to a fuel-processing facility at Hanford, the Nevada Test Site (NTS), or the Savannah River Plant.

In the first case, the plutonium feed material could be shipped to the standard (hypothetical) Electric Research Power Research Institute (EPRI) power station in the Great Lakes region [which is used as the baseline location for "greenfield" cost estimates of the disposition reactor(s) being made in the Plutonium Disposition Study]. The feed material would be delivered to a fuel-fabrication facility located adjacent to the reactor. Alternatively, the pits could be processed at Hanford, NTS, or Savannah River, and the feed material subsequently shipped to the fuel-fabrication facility.

In another scenario, the fuel-fabrication facility and reactor(s) are located at Hanford, NTS, or Savannah River. The only transportation required would be to move pits from Pantex to one of these three sites.

At the recovery-process site, radioactive waste will be produced that must be transported properly to the appropriate waste repository.

Collocation of facilities at a DOE site would simplify transportation issues. Onsite transportation would be subject only to site limits, instead of the constraints placed on transportation over a public highway system. Site safeguards and security would ensure that the material transported onsite is secure.

5.3.2 Transportation Route

Transportation of plutonium from one facility to another is more complex than onsite transportation. If the DOE decides to transport plutonium using the national-security exemption of 49 CFR 173.7 (b), selection of a route that will minimize the probability and consequences of an accident is necessary. Codes such as RISKIND⁵ or RADTRAN⁶ can be used to calculate the radiological consequences of incident-free transporta-

Figure 5-1. Transportation end points being considered for the purpose of providing a definitive framework in which to evaluate transportation issues. Route distances are approximate and are subject to change, depending on results of risk analyses. (H = Hanford, N = Nevada Test Site, P = Pantex, M = "Midtown" standard (hypothetical) EPRI site, S = Savannah River.)

tion and the accident risk of transporting radioactive materials. The accident risk is based on (1) how the radioactive material is dispersed in various types of accidents and (2) the health and economic effects of dispersing the material.

5.3.3 Amount of Material per Shipment

The amount of fissile material contained within a package may be determined by criticality, decay-heat, or radiation-dose considerations. The package must remain subcritical during normal and abnormal "accident" conditions of transport, as defined by regulations such as 10 CFR 71.55 or IAEA Safety Series No. 6.⁷ The amount of fissile material per package and the maximum number of packages per shipment—based on criticality and external radiation-level considerations—will determine the amount of material per shipment. For exclusive-use shipments of fissile material, the number of packages may be double the number used to establish the transport index (TI), as defined below. The radiation dose rate must not exceed 2 mSv/h on the outer surfaces or 0.1 mSv/h at any point 2 m outside the outer surfaces of the conveyance used for exclusive shipment.

5.3.4 Transport Index

For exclusive-use shipment of fissile material (as would be the case here), the sum of the TIs of the packages in the shipment, based on criticality control, must be ≤ 100 .

The TI for criticality control is obtained by dividing 50 by the allowable number N of the packages that can be stacked together such that

- If the undamaged packages are stacked together in any arrangement and closely reflected on all sides of the stack by water, 5 times the allowable number of the packages would be subcritical, or
- If the packages damaged by the application of a series of hypothetical regulatory tests are stacked together in any arrangement, closely reflected on all sides of the stack by water and with optimum interspersed hydrogenous moderation, 2 times the allowable number of the damaged packages would be subcritical.

5.3.5 Number of Shipments

The minimum number of shipments required to ship 50 Mg of plutonium to the feed fabricators (over public roads) depends on the number of

packages allowed per shipment. The required rate of shipments will be determined by the rate capacities at the plutonium-recovery and fuel-fabrication points, the fuel requirements for the reactor, and the storage capacity at each facility.

5.3.6 Security

All plutonium must be shipped as an exclusive shipment using safe secure trailers (SST) to minimize the potential for diversion of the materials.

5.3.7 Example

As an example, consider the shipment of plutonium oxide in a DOT-specification 6M package.² (The enveloping volume of this package is $\sim 0.25 \text{ m}^3$.) The limit of plutonium in oxide form that could be placed in this package is about 4.5 kg, based on a 10-W decay-heat limit of the packaging design. The plutonium oxide must be doubly contained, with the outer container being a DOT-specification 2R containment vessel.² Thus, about 11,000 packages would be needed to transport 50 Mg of weapon plutonium as PuO_2 .

The TI for fissile Class II plutonium contents in the 6M package is a function of the form of the plutonium (metal, alloy, or compound) and the ratio of hydrogen to fissile atoms with all sources of hydrogen in the containment considered.

For a package containing 4.5 kg of plutonium as oxide with a ratio of 3 hydrogen atoms to fissile atoms, the TI is 0.5 per 49 CFR 173.417. For an exclusive-use shipment such as in the SST, the allowable number of packages containing 4.5 kg of plutonium as oxide per shipment is 200. Sufficient room (5 m^3) exists for 200 packages in the SST. If the containment components can withstand 2 kW of total decay heat from 200 packages and the external radiation level remains below the regulatory limit, the mass of plutonium (in oxide form) per shipment would be 900 kg. Thus, transport of 50 Mg of plutonium as oxide would require about 55 shipments. A 20-y campaign

would require about three shipments per year. For a package of plutonium metal instead of oxide, the TI would be 1, so twice as many metal shipments would be required. Thermal considerations may well lower the number of packages for each shipment.

5.4 Waste Transportation

All offsite shipments of radioactive waste from the weapon-plutonium recovery operations, including both low-level waste and TRU, must be packaged and shipped in accordance with 10 CFR 71.

References

1. 49 CFR 173.7 (b), U.S. Department of Transportation, Washington, DC.
2. 49 CFR 170-189, U.S. Department of Transportation, Washington, DC.
3. DOE Order 5610.1, *Packaging and Transportation of Nuclear Explosives, Nuclear Components and Special Assemblies*, U.S. Department of Energy, Washington, DC.
4. 10 CFR 71, *Packaging and Transportation of Radioactive Material*, U.S. Nuclear Regulatory Commission, Washington, DC.
5. Y. C. Yuan, S. Y. Chen, D. J. Lepoire, and R. Rothman, *RISKIND—A Computer Program for Calculating Radiological Consequences and Health Risks from Transportation of Spent Nuclear Fuel*, Argonne National Laboratory, Argonne, IL, ANL/EAIS, Rev. 0 (1993).
6. K. S. Nuehauser and F. L. Kanipe, *RADTRAN 4 User Guide*, Vol. 3, Sandia National Laboratories, Albuquerque, NM (1992).
7. IAEA Safety Series No. 6, International Atomic Energy Agency, Vienna, Austria.

6. Research and Development

6.1 Introduction

Research and development activities will be required in the following areas:

- Unit operations for plutonium removal from pits that have not been production demonstrated,
- Fuel pellet fabrication of oxide produced from metal, and
- Fuel-pellet fabrication and reactor operability of oxide containing gallium or americium.

Each of these areas should be examined, and the level of R&D required to address each

concern should be established to minimize overall project cost and environment impacts.

Each of the cases considered has unit operations that require development prior to implementation in a production operation. Table 6-1 lists the unit operations that need additional development, the current stage of development, and to what cases this operation pertains.

Several unit operations have been identified as being potential "show stoppers." These are generally residue-treatment operations that may require new technology to meet regulatory requirements.

Table 6-1. Unit operations requiring further development

Unit operation	Current status	Case						
		1	2	3	4A	4B	5A	5B
Mainline								
Electrolytic dissolution		X						
Hydride/dehydride	Production prototyping		X	X		X	X	X
Hydride	Production prototyping							
In-pit hydriding	Conceptual				X			
Metal-powder oxidation	Laboratory scale		X	X		X	X	
Hydride chlorination	Laboratory scale							
Secondary								
Pyrolysis/calcination	Laboratory scale	X	X	X			X	X
Organic destruction	Laboratory scale	X	X	X			X	X

6.2 Required R&D, Demonstration Tests by Reactor Vendors

This report emphasizes the metal-to-oxide processes as the means of converting weapon-grade plutonium to feed material for LWR fuel. Plutonium oxide powder is thus considered here as the feed material for further fabrication of mixed-oxide (MOX) fuel.

Weapon plutonium is different from reactor-grade plutonium, not only in its isotopic compositions but also in the level of contained chemical impurities. The presence of impurities, if they exceed the reactor vendor's specified limits, could affect the performance of the MOX fuel during irradiation in the reactor core. The plutonium oxide powder resulting from the recovery process should also possess adequate physical characteristics to promote the homogeneity and sinterability of the MOX blend. Hence, it is essential to conduct demonstration tests of the plutonium oxide powder to ensure its suitability as feed material before it is mechanically mixed with the uranium oxide. Demonstration tests of the MOX fuel are also required.

6.2.1 Americium

The presence of ^{241}Am in plutonium will increase the radiation dose to the extremities of workers who manually handle the plutonium in glove boxes. The alternatives for the fuel fabricators is to specify a low upper limit for ^{241}Am content in plutonium, provide mechanical assists to the plutonium worker, or handle the plutonium in an automated facility. Tight specification for ^{241}Am in plutonium will probably result in an americium-removal step in the recovery operations. Fuel fabricators should conduct demonstration tests with ^{241}Am to ensure that worker health and safety are protected.

As stated in Sec. 1.2, the content of ^{241}Am in weapon plutonium is about 0.2%, or 2000 ppm. This amount of americium is a factor of 4 less than the current limit (8000 ppm) imposed on reactor-grade plutonium for fabrication of MOX fuel in foreign countries.¹ Even higher contents of americium are being considered by some foreign fabricators. Thus, at this stage, it appears that americium removal may not be necessary.

6.2.2 Gallium

Table 1-1 lists typical allowable impurity levels in plutonium oxide. Weapon plutonium should be free of most of the impurities on the list. The only principal impurity in weapon plutonium is gallium. About 1% (by weight) of gallium is added to the plutonium to enhance the stability of the weapon pit. If gallium is not removed during oxide conversion, gallium oxide could affect the homogeneity or the hot-pressing characteristics of the plutonium oxide powder. Because plutonium oxide will be mixed with much greater amounts of uranium oxide, the sinterability of MOX will depend on a "diluted" concentration of gallium oxide that is considerably less than 1000 ppm. Therefore, fuel fabricators should conduct demonstration tests for gallium to establish the level of gallium to be specified in Table 1-1.

Reference

1. Max Freshley, Pacific Northwest Laboratories, private communication, January 10, 1994.

7. Discussion and Next Steps

Processing cases that produce PuO_2 from plutonium metal powder generally require much less equipment and will be less expensive to operate than aqueous processing cases. The subsequent behavior of the PuO_2 particles during sintering of fuel pellets and the quality of the sintered pellet are the principal issues associated with the method used to produce the PuO_2 . Reactor fuel pellets generally are produced from aqueously generated oxides, which have a specific particle-size distribution and morphology. Dry blending of PuO_2 and UO_2 powders has also been shown to be successful. A fundamental consideration is whether PuO_2 produced from weapon-plutonium metal powder will have an acceptable size distribution and morphology and thus will blend with UO_2 powder and sinter to form acceptable fuel pellets.

Processing cases that do not remove americium and gallium from the plutonium will require much less equipment, will generate less waste, and will be less expensive to operate. If plutonium is a minor component in a mixed oxide or metal fuel, then removal of gallium and americium may not be economically justified. The disposal of separated americium is not trivial. Placing the americium into the reactor fuel may be the best means for handling americium.

The largest risk to the public in recovering weapon plutonium for fabrication of reactor fuel will occur while transporting the plutonium feed material on public roads. The number of shipments for 50 Mg of plutonium in oxide form appears to be about 55. However, this number probably will increase as a result of decay-heat considerations. A major consideration in siting plutonium-recovery facilities is the applicable environmental regulations, which will impact both cost and schedule for the start of operations. Local regulations are generally more stringent than federal regulations. Although a national-security exemption could be obtained for transportation, current DOE philosophy would be better served by shipments conforming to 10 CFR 71.

We have presented an overview of pertinent aspects of weapon-plutonium recovery operations to provide feed material for reactor fuel. The recovery operations appear to be feasible, and therefore, a more detailed study appears to be warranted. To further define the recovery operation, we suggest the following next steps:

- Select a base-case recovery process that produces PuO_2 and does not require americium or gallium removal. Compare this process with one that removes americium and one that removes both americium and gallium.
- Size the recovery facility for an aggressive (but realistic) work schedule.
- Initiate experimental/analytical studies of the effect of gallium on MOX reactor fuel.
- Establish a base-case siting scenario for the recovery facility, the MOX fuel-fabrication facility, and the reactor.
- Assess transportation-package requirements and SST shipment configurations. Conduct sufficient preliminary safety analyses to ensure safety of shipments.
- For the base-case scenario, address all regulatory issues associated with environment, safety, and health. Include consideration of local government regulations.
- For the base-case scenario, address all safeguards and security issues, including S&S cost.
- Address transfer of technology/equipment to Russia and the impacts of U.S. decisions on recovery process.

The result of this effort would be a realistic schedule of regulatory activities that would allow startup of the recovery facility and the associated shipments.

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