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Wastes From Selected Activities in Two Light-Water Reactor Fuel Cycles

C. R. Palmer
O. F. Hill

July 1980

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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CONTENTS

INTRODUCTION 1
SUMMARY 2
FUEL CYCLE ASSUMPTIONS 2
FUEL CYCLE PROJECTIONS 9
URANIUM FUEL FABRICATION PLANT. 10
MIXED OXIDE FUEL FABRICATION PLANT 11
NUCLEAR POWER PLANT 11
SPENT FUEL PACKAGING FACILITY 15
FUEL REPROCESSING PLANT 17
REFERENCES. 22
ACKNOWLEDGMENTS 23
SELECTED BIBLIOGRAPHY OF LWR WASTE MANAGEMENT LITERATURE. 24
APPENDIX A-1

FIGURES

1 Strategy 1 LWR Once-Through Heavy Element Flow Sheet per GWe yr 6

2 Strategy 2 LWR with U-Pu Recycle Heavy Element Flow Sheet per GWe yr 6

TABLES

1 Summary of Waste Volumes for Reference LWR Fuel Cycles per GWe·yr. 3

2 Fuel Element Fabrication Wastes for Reference LWR Fuel Cycles per GWe·yr. 3

3 Reactor Wastes for Reference LWR Fuel Cycles per GWe·yr 4

4 Unreprocessed Spent Fuel for Reference LWR Fuel Cycles per GWe·yr. 4

5 Reprocessing Wastes for Reference LWR Fuel Cycles per GWe·yr 5

6 Characteristics of the Reference Fuel Cycle Facilities 8

7 Estimated Waste Volumes and Activities from the Reference Uranium Fuel Fabrication Plant 12

8 Estimated Waste Volumes and Activities from the Reference Mixed-Oxide Fuel Fabrication Plant 13

9 Estimated Waste Volumes and Activities from the Reference Nuclear Power Plant 16

10 Estimated Waste Volumes and Activities from the Reference Spent Fuel Packaging Facility 18

11 Estimated Waste Volumes and Activities from the Reference Fuel Reprocessing Plant 20

12 Summary of Operating Wastes from the Reference Fuel Reprocessing Plant by Package Dose Rate 21

A-1 Estimated Operating Waste Volumes and Activities from the Reference Nuclear Power Plant A-1

A-2 Estimated Maintenance Waste Volumes and Activities from the Reference Nuclear Power Plant A-2

A-3 Estimated Waste Volumes and Activities for Entombment of the Reference Nuclear Power Plant A-3

A-4 Estimated Operating Waste Volumes and Activities from the Reference Fuel Reprocessing Plant A-4

A-5 Estimated Maintenance Waste Volumes and Activities from the Reference Fuel Reprocessing Plant A-7

A-6 Estimated Waste Volumes and Activities for Protective Storage/Dismantlement of the Reference Fuel Reprocessing Plant A-8

A-7 Estimated Operating Waste Volumes and Activities from the Reference MOX Fuel Fabrication Plant. A-10

A-8 Estimated Maintenance Waste Volumes and Activities from the Reference MOX Fuel Fabrication Plant. A-11

A-9 Estimated Waste Volumes and Activities from Dismantlement of the Reference MOX Fuel Fabrication Plant. A-12

WASTES FROM SELECTED ACTIVITIES IN TWO LIGHT-WATER REACTOR FUEL CYCLES

INTRODUCTION

The International Nuclear Fuel Cycle Evaluation (INFCE) program was established in 1977 as a cooperative effort among 40 countries and 4 international organizations to review various nuclear power fuel cycle alternatives in search of economical cycles that minimize the risk of nuclear weapons proliferation. The program was organized around several working groups that were established to consider a range of characteristics of fuel cycles, from resource utilization to institutional issues. One working group (WG.7) was charged with the responsibility of comparing a representative selection of nuclear fuel cycles in regard to the management and disposal of radioactive wastes. This report is a result of evaluations in support of WG.7 performed by Pacific Northwest Laboratory under sponsorship of the U.S. Department of Energy.

This report presents projected volumes and radioactivities of wastes from the production of electrical energy using light-water reactors (LWR). The projections are based upon data developed for a recent environmental impact statement[1-6] in which the transuranic wastes (i.e., those wastes containing certain long-lived alpha emitters at concentrations of at least 370 becquerels, or 10 nCi, per gram of waste)* from fuel cycle activities were characterized. In addition, since the WG.7 assumed that all fuel cycle wastes except mill tailings are placed in a mined geologic repository, the nontransuranic wastes from several activities are included in the projections reported.

The LWR fuel cycles considered are the LWR, once-through fuel cycle (Strategy 1), in which spent fuel is packaged in metal canisters and then isolated in geologic formations; and the LWR U/Pu recycle fuel cycle (Strategy 2),

*As defined in Reference 7; the radionuclides included are ^{233}U (with its daughter products), plutonium and transplutonium nuclides except ^{238}Pu and ^{241}Pu.

wherein spent fuel is reprocessed for recovery and recycle of uranium and plutonium in LWRs. While not all unit operations of these fuel cycles are considered in this analysis, the fuel element fabrication, reactor, spent fuel packaging and spent fuel reprocessing segments are examined in detail. Wastes from the "head-end" facilities (mining, milling, refining, conversion, and enrichment) are not included because they are considered similar in chemical and radiochemical nature, and can thus be evaluated on the basis of fuel cycle heavy element requirements.

Estimates of waste generation are sensitive to the fundamental assumptions employed, and the assumptions used here are generally consistent with those used by other analysts who supported WG.7. In some cases where no data were available, WG.7 assumptions were modified so that projections could be made. Where our estimates appear to differ significantly from other WG.7 analyses, a comment is provided on the rationale underlying the difference.

SUMMARY

Tables 1 through 5 summarize the wastes projected for the two LWR fuel cycles. (Waste category numbers in these tables correspond to those shown in Figures 1 and 2.) The reactor operations and decommissioning were found to dominate the rate of waste generation in each cycle. These activities account for at least 85% of the fuel cycle waste volume (not including head-end wastes) when normalized to per unit electrical energy generated. At 10 years out of reactor, however, spent fuel elements in Strategy 1 represent 98% of the fuel cycle activity but only 4% of the volume. Similarly, the packaged high-level waste, fuel hulls and hardware in Strategy 2 concentrate greater than 95% of the activity in 2% of the waste volume.

FUEL CYCLE ASSUMPTIONS

The fuel cycle characteristics assumed in this analysis are generally those described in Reference 8. Figures 1 and 2 depict the flow and quantities of heavy element materials in the two fuel cycles, as adopted by WG.7.[8] Fuel cycle facility characteristics that were important in the projections are

TABLE 1. Summary of Packaged Waste Volumes for Reference LWR Fuel Cycles per GWe·yr

	Facility	Packaged Waste Volume, m^3/GWe·yr	Fraction of Total Waste Volume
Strategy 1 -	(Once-through)		
	UO_2 fuel fabrication	40	0.05
	Reactor	720	0.90
	Spent fuel packaging	42	0.05
	Total	800	1.00
Strategy 2 -	(U/Pu Recycle)		
	UO_2 fuel fabrication	26	0.03
	Mixed-oxide fuel fabrication	21	0.02
	Reactor	720	0.85
	Fuel reprocessing	85	0.10
	Total	850	1.00

TABLE 2. Fuel Element Fabrication Wastes for Reference LWR Fuel Cycles per GWe·yr

INFCE/WG.7 Category	Description		Strategy 1 (once-through)	Strategy 2 (U/Pu recycle)
3.1	UO_2 fuel waste[a]			
	Volume	m^3	40	26
	U content	kg	220	150
3.2	Mixed-oxide fuel waste[b]			
	Volume	m^3	-	21
	U content	kg	-	13
	Pu content	kg	-	0.6

(a) Assumes that only enriched UF_6 is converted to UO_2 (via the ADU process). Fluoride waste is disposed of as CaF_2 at 70% of theoretical density. Maintenance and decommissioning wastes are included [decommissioning waste is calculated based upon 1500 MTU/yr capacity, 30-yr lifetime, and 36.8 MTU/GWe·yr (Strategy 1) or 24.8 MTU/GWe·yr (Strategy 2) fuel requirements].

(b) Assumes that natural uranium is provided by the refinery as fuel-grade UO_2. Maintenance and decommissioning wastes are included (decommissioning waste assumes immediate dismantlement, and is calculated based upon 400 MTHM/yr capacity, 30-yr lifetime, and 11.8 MTHM/GWE·yr mixed-oxide fuel requirement).

TABLE 3. Reactor Wastes for Reference LWR Fuel Cycles per GWe·yr

INFCE/WG.7 Category	Description		Strategy 1 (once-through)	Strategy 2 (U/Pu recycle)
4.1	Wastes from operation[a]			
	Volume	m^3	610	610
	Radioactivity	*kCi*	*5*	*5*
4.2	Maintenance waste[a,b]			
	Volume	m^3	9	9
	Radioactivity	*kCi*	*0.4*	*0.4*
4.3	Control rods, etc.[c]			
	Volume	m^3	5	7
	Radioactivity	*kCi*	*190*	*190*
4.4	Decommissioning waste[d]			
	Volume	m^3	100	100
	Radioactivity	*kCi*	*2*	*2*

(a) Assumes that combustible/compactable wastes are compacted, wet wastes are immobilized in cement, and noncombustible wastes are packaged directly.
(b) Includes coolant system filter cartridges and ventilation system filters.
(c) Strategy 1: PWR control rods remain inserted within fuel assemblies, and consequently do not contribute additional packaged waste volume; BWR control rods are packaged in separate spent fuel canisters.
Strategy 2: All control rods are mechanically dissected and packaged in convenient canisters.
(d) Assumes the reactor is entombed upon shutdown; approximately one-half the process system (piping) external to the containment building, and all miscellaneous (nonstructural) radioactive wastes are shipped offsite for disposal. Decommissioning waste calculated based upon 1200 MWe installed capacity, 70% load factor, 30-yr lifetime.

TABLE 4. Unreprocessed Spent Fuel for Reference LWR Fuel Cycles per GWe·yr

INFCE/WG.7 Category	Description		Strategy 1 (once-through)	Strategy 2 (U/Pu recycle)
5.1	Treated fuel assemblies[a]			
	Volume	m^3	35	--
	Canisters, PWR		53	--
	Canisters, BWR		22	--
	U content	Mg	35.7	--
	Pu content	Mg	0.29	--
	Radioactivity (10 yr)	*MCi*	*12.7*	—
5.2	Spent fuel treatment waste[b]			
	Volume	m^3	7	--
	Radioactivity (10-yr)	*kCi*	*0.15*	—

(a) Assumes fuel assemblies are packaged directly in canisters:
PWR canister - 0.32 m dia x 4.9 m long (1 assembly/canister)
BWR canister - 0.41 m dia x 4.9 m long (3 assemblies/canister).
(b) Assumes only failed fuel assemblies are overpacked (2% frequency). Maintenance and decommissioning wastes are included (decommissioning waste assumes immediate dismantlement and is calculated based upon 2000 MTU/yr capacity, 30-yr lifetime, and 36.8 MTU/GWe·yr fuel requirements).

TABLE 5. Reprocessing Waste for Reference LWR Fuel Cycles per GWe·yr

INFCE/WG7 Category	Description		Strategy 1 (once-through)	Strategy 2 (U/Pu recycle)
6.1	Hulls, spacers, insolubles[a]			
	volume	m^3	--	12
	U content	kg	--	18
	Pu content	kg	--	0.22
	radioactivity	*MCi*	--	*0.94*
6.2	Vitrified high-level waste[b]			
	volume	m^3	--	4.3
	U content	kg	--	180
	Pu content	kg	--	2.2
	radioactivity (10 yr)	*MCi*	--	*9.9*
6.3	Noble gases[c]			
	volume	m^3	--	0.1
	gas flasks		--	3
	radioactivity	*MCi*	--	*0.3*
6.4	Depleted uranium waste[d]			
	volume (as UO_2)	m^3	--	2.3
	U content	Mg	--	11
6.5	Medium-level and plant maintenance waste[e]			
	volume	m^3	--	51
	U content	kg	--	160
	Pu content	kg	--	1.4
	radioactivity	*kCi*	--	*62*
6.6	Low-level waste[f]			
	volume	m^3	--	9
	radioactivity	*kCi*	--	*0.01*
6.7	Plant decommissioning waste[g]			
	volume	m^3	--	6
	radioactivity	*kCi*	--	*0.005*

(a) Assumes uncompacted waste is immobilized in cement. Fuel lost to waste is assumed to be 0.05 wt%.
(b) Volume of glass only (packaged volume is 1.25x). Assumes 15 wt% waste loading, 0.5 wt% uranium and plutonium contained in this waste.
(c) Assumes fractional distillation of krypton; stored in 42-ℓ cylinders under 34 atm (500 psi) pressure.
(d) Taken from Reference 3.
(e) Medium-level waste defined as having a surface dose rate ≥0.2 R/hr.
(f) Low-level waste defined as having a surface dose rate <0.2 R/hr.
(g) Assumes plant is placed in protective storage for 30 yr and then dismantled.

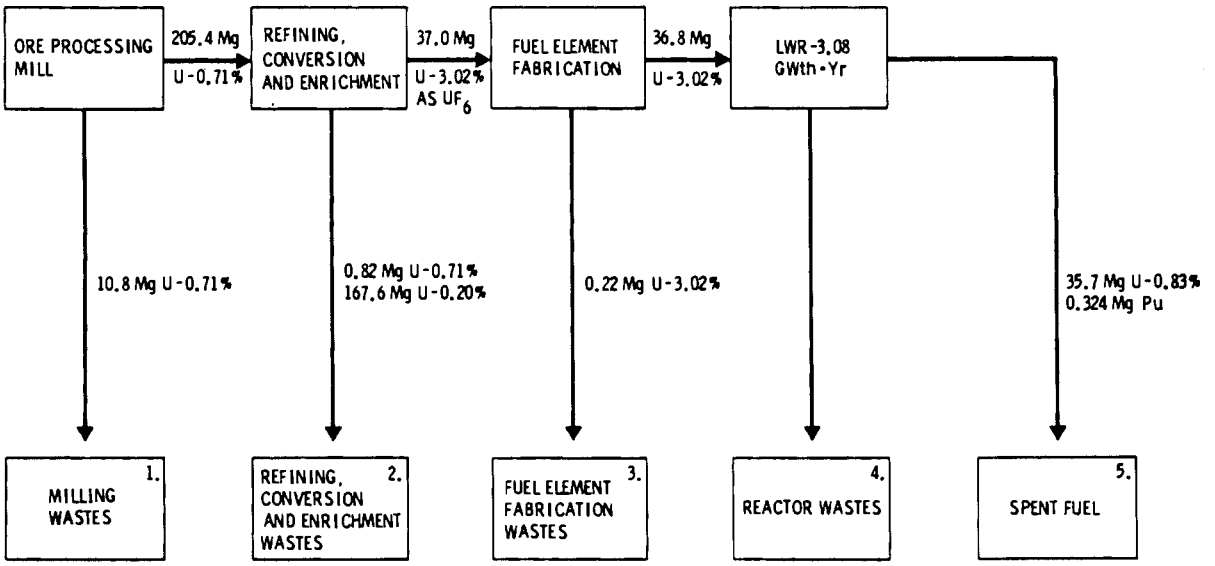

FIGURE 1. Strategy 1: LWR Once-Through Heavy Element Flow Sheet per GWe•yr

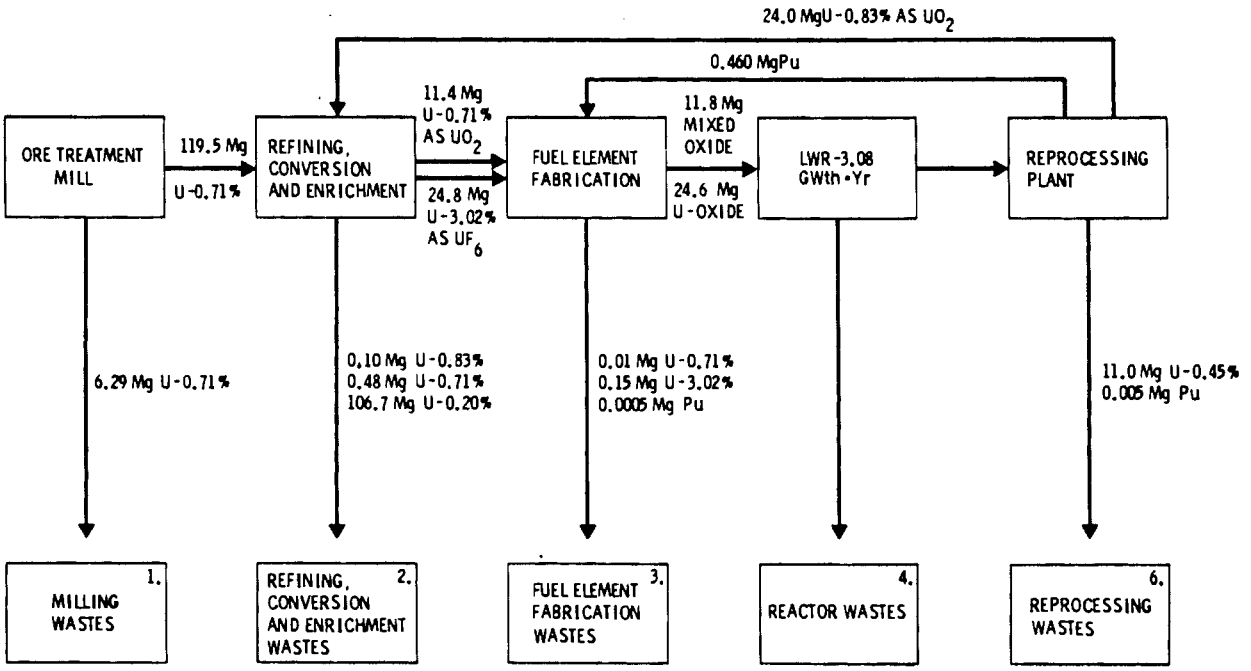

FIGURE 2. Strategy 2: LWR with U-Pu Recycle Heavy Element Flow Sheet per GWe•yr

presented in Table 6. It is noted that the fuel reprocessing plant (FRP) considered here processes irradiated fuel at twice the rate of the reference facility assumed by WG.7.[8] Nevertheless, we believe that the quantity of most wastes generated at the FRP are proportional to plant throughput over the range of processing rates of interest, so that for the purpose of the INFCE comparative assessment, analysis of the 2000 MTHM/year facility in this paper is acceptable.

In estimates of radioactivity for the various waste streams, a post-reactor discharge time of 0.5 year was assumed unless otherwise noted. Significant deviations from this reference cooling time include spent fuel (including waste generated during packaging) and high-level waste (10 years); plutonium fuel fabrication wastes (2.5 years); and decommissioning wastes (activity at time of shipment from site).

Except for the reactor, the general decommissioning philosophy for all facilities is dismantlement. It is assumed that all potentially contaminated material is removed from the site; to ensure complete removal, this may include some uncontaminated material. For the FRP, dismantlement is preceded by a 30-yr protective storage period to allow a reduction in activity levels. (A recent analysis indicates this to be economically more desirable than immediate dismantlement.)[5] For the nuclear power plant, the entombment alternative was selected, wherein the containment building serves as the permanent entombment structure. Only contaminated equipment that will not fit within the internal volume of the structure, and the miscellaneous decontamination and nonstructural wastes are treated and shipped to the repository for disposal.

Final waste volumes depend significantly on the volume reduction and immobilization technologies assumed. In this paper the following treatment assumptions will apply unless otherwise noted:

- Compactable trash/combustible waste: At facilities other than the nuclear power plant, compactable waste is compacted (4:1 volume reduction) and combustible waste is incinerated followed by immobilization of the ash and scrubber solution in cement. Preconcentration of the scrubber solution before solidification in cement is assumed only at the FRP, yielding a

TABLE 6. Characteristics of the Reference Fuel Cycle Facilities

	Strategy 1	Strategy 2
Uranium Fuel Plant		
Nominal processing rate, MTU/year	1500	1500
Plant lifetime, years	30	30
Normalizing factor for decommissioning waste,(a) GWe·yr/plant	1220	1830
Fraction of throughput lost to waste	0.006	0.006
Mixed-Oxide Fuel Plant		
Nominal processing rate, MTHM/year	--	400
Plant lifetime, years	--	30
Normalizing factor for decommissioning waste,(a) GWe·yr/plant	--	1020
Fraction of throughput lost to waste	--	0.001
Nuclear Power Plant		
Ratio of PWRs to BWRs	2:1	2:1
Plant installed capacity, MWe	1200	1200
Load factor, %	70	70
Plant lifetime, years	30	30
Normalizing factor for decommissioning waste,(b) GWe·yr/plant	25.2	25.2
Average fuel exposure, GWd/MTHM	30	30
Thermal-to-electric conversion efficiency	0.32	0.32
Spent Fuel Packaging Facility		
Nominal processing rate, MTHM/year	2000	--
Plant lifetime, years	30	--
Normalizing factor for decommissioning waste,(a) GWe·yr/plant	1630	--
Fuel Reprocessing Plant		
Nominal processing rate, MTHM/year	--	2000
Plant lifetime, years	--	30
Normalizing factor for decommissioning waste,(a) GWe·yr plant	--	1650

(a) Calculated as: $$\frac{\left(\text{Processing rate}\right)\left(\text{Plant lifetime}\right)}{\left(\frac{\text{Heavy element weight}}{\text{GWe}\cdot\text{yr}}\right)}$$

(b) Calculated as: $$\left(\text{Plant Installed Capacity}\right)\left(\text{Plant Lifetime}\right)\left(\text{Load Factor}\right)$$

5:1 volume reduction. In other facilities preconcentration is not assumed (because of the expense of an evaporation system that is resistant to corrosion from chloride, and because of the generally small waste volumes generated). Without preconcentration, there will be no net volume reduction. At the nuclear power plant, incineration was not assumed because few operating LWRs have incinerator systems installed. On the other hand, compaction was assumed since it is frequently used to reduce solid waste volumes, effecting a 4:1 volume reduction for this waste category. In all facilities these wastes are packaged in 200-ℓ drums.

- Concentrated liquids, wet waste and particulate solids: Immobilization in cement was universally assumed, which results in a 60% volume increase over the pretreatment concentrated volume.
- Noncombustible trash, noncompactable scrap, failed equipment: Direct packaging with minimal treatment, leaving the packaged volume the same as the as-generated volume.

FUEL CYCLE PROJECTIONS

Wastes from activities in LWR fuel cycles, with or without fuel recycle, can be characterized either as operating wastes (generated during operation of the nuclear power plant and other fuel cycle facilities), as maintenance wastes (generated during the periodic maintenance of fuel cycle facilities),* or as decommissioning wastes. Wastes can be further categorized by their physical form or special characteristics: 1) gaseous; 2) compactable trash and combustible wastes, hereafter referred to as "general trash"; 3) concentrated liquids, wet wastes and particulate solids ("wet waste"); 4) failed equipment and noncompactable, noncombustible wastes ("scrap"); 5) HLLW (recycle only); 6) fuel residues (hulls and hardware, recycle only); and 7) spent fuel

*Maintenance wastes were defined by WG.7 to include those created by the scheduled replacement of components in order to prevent failure that is expected but unpredictable. Except as otherwise noted, all ventilation system filters and failed equipment were considered maintenance waste.

(once-through only). Wastes are projected according to these categories in subsequent tables; gaseous wastes other than krypton are not included, although secondary wastes arising from gaseous waste treatment are included. Both primary and secondary wastes for other categories are estimated.

Information from a wide variety of sources was evaluated to arrive at these waste projections. Sources include surveys of operating experience at existing fuel cycle facilities; published waste characterizations and projections; other available literature, listed in the partial bibliography; conceptual facility designs; and prevalent operating philosophy.

While waste projections are generally presented to two significant figures, the range of actual volumes and activities to be encountered is large and will vary with facility design philosophy, fuel characteristics, exposure history, fuel and waste age, and specific operating conditions. Two significant figures are provided, not to imply an accuracy of the projections, but to illustrate generic differences among waste streams and treatment alternatives.

The following paragraphs discuss the waste projections by facility and compare the projections with estimates presented in Reference 8 when significant differences are apparent.

URANIUM FUEL FABRICATION PLANT

Operating wastes in this facility arise from three basic operations: chemical conversion of enriched UF_6 to UO_2; mechanical processing including pellet production and fuel element fabrication; and recovery of uranium from scrap and off-specification material. It is assumed that chemical conversion is done by the conventional ammonium diuranate (ADU) process, in which the fluoride wastes are disposed of as CaF_2 packaged in 200-ℓ drums.[9] As no data were available for maintenance waste from this facility, it was arbitrarily assumed to be 10% of operating waste. Decommissioning of the plant at the end of its economic lifetime would involve decontamination of most process systems to releasable limits and removal of some surface concrete contaminated to levels exceeding those specified by regulatory authorities. The remaining uncontaminated structure is expected to be left in place.

Table 7 presents the waste projections for this facility. It was assumed that the natural uranium requirements for mixed oxide fuel fabrication are met by means other than conversion of natural UF_6 to UO_2 at the uranium fuel plant (e.g., fuel grade natural UO_2 may be produced at the refinery and shipped directly to the mixed oxide plant). Thus the requirement for enriched UO_2 in Strategy 2 is 67% of that for Strategy 1, and the resulting wastes are in the same proportion.

MIXED OXIDE FUEL FABRICATION PLANT

The principal source of radioactivity in the mixed oxide fuel fabrication plant (MOX-FFP) waste is the plutonium that has been separated from spent fuel at the FRP. The feed material to this facility is dry oxides of natural uranium and plutonium, which are mechanically mixed and pelletized and are then sealed in zirconium alloy tubing to produce mixed oxide assemblies. One year is assumed to elapse between reprocessing and refabrication of fuel at the MOX-FFP.

Wastes generated in MOX-FFP operations include bagging plastics, glove box gloves, decontamination solutions, scrap fuel cladding, and plutonium transfer containers. Maintenance wastes include HEPA ventilation filters and failed glove box equipment. Decommissioning of the MOX-FFP involves dismantlement of the facility upon shutdown. The radionuclide inventory in the plant at shutdown is based upon an accumulation of 1 kg Pu (with 22 kg U) per year over the 30-yr lifetime of the plant. This accumulation represents $\sim$0.005 wt% of the plant throughput. Table 8 presents the projected waste arisings for the MOX-FFP. Tables A-7 through A-9 of the Appendix provide additional detail regarding these wastes.

NUCLEAR POWER PLANT

The wastes from the reference nuclear power plant represent a composite of wastes that would result from operation of LWRs at a ratio of 2 PWRs:1 BWR. The wastes generated in routine operations are assumed to be identical in both fuel cycle strategies. They include 1) combustible trash from servicing

TABLE 7. Estimated Waste Volumes and Activities from the Reference Uranium Fuel Fabrication Plant[a]

Waste Stream	Strategy 1: LWR Once Through			Strategy 2: LWR U/Pu Recycle		
	Volume, m^3/GWe·yr		Activity,[c] Ci/GWe·yr	Volume, m^3/GWe·yr		Activity,[c] Ci/GWe·yr
	As Generated	As Shipped[b]		As Generated	As Shipped[b]	
General trash	64	12	NS[d]	43	8	NS
Wet waste[e]	21	21	9.9E-2 (2.2E5 g uranium)	14	14	7.1E-2 (1.5E5 g uranium)
Scrap	7	7	NS	4	4	NS
Total uranium fuel plant wastes	95	40	9.9E-2 Ci (2.2E5 g uranium)	63	26	7.1E-2 Ci (1.5E5 g uranium)

(a) 1500 MTU/yr plant capacity, 30-yr lifetime; uranium requirements are 36.8 MTU/GWe·yr in Strategy 1, 24.6 MTU/GWe·yr in Strategy 2; projections include operating, maintenance and decommissioning wastes.
(b) As-shipped volume assumes combustibles are incinerated, compactables are compacted, wet waste (except CaF_2) is immobilized in cement, and scrap is packaged directly.
(c) Assumes 3.02% ^{235}U enrichment, 0.6 wt% of throughput lost to waste.
(d) Not significant.
(e) Principally CaF_2 containing 0.5 wt% uranium, assumed to be packaged directly at 70% of theoretical density.

TABLE 8. Estimated Waste Volumes and Activities from the Reference Mixed-Oxide Fuel Fabrication Plant[a]

Waste Stream	Volume, m^3/GWe·yr		Activity, Ci/GWe·yr[c]		
	As Generated	As Shipped[b]	U	Pu	Other Actinides
Operating Waste					
General trash	5.9	5.9	5.6E-2 (3.4E3g)	2.1E3 (1.5E2g)	3.5E1
Wet waste	4.3	7.0	2.0E-2 (1.2E3g)	7.6E2 (5.5E1g)	2.3E0
Scrap	2.4	2.4	1.8E-3 (1.1E2g)	6.9E1 (5.0E0g)	1.1E0
Total operating waste	13	15	7.8E-2 (4.7E3g)	2.9E3 (2.1E2g)	3.8E1
Maintenance Waste[d]					
General trash	1.2	1.2	1.3E-1 (7.8E3g)	4.9E3 (3.3E2g)	8.0E1
Scrap	2.4	2.4	1.8E-3 (1.1E2g)	6.9E1 (5.0E0g)	1.1E0
Total maintenance waste	3.6	3.6	1.3E-1g (7.9E3g)	5.0E3 (3.4E2g)	8.1E1
Decommissioning Waste[e]					
General trash	0.1	0.1	2.9E-3 (2.5E2g)	9.5E1 (1.0E1g)	2.0E0
Wet waste	0.3	0.2	1.1E-3 (9.6E1g)	3.7E1 (4.0E0g)	7.8E-1
Scrap	2.4	2.4	2.9E-3 (2.6E2g)	9.9E1 (1.1E1g)	2.1E0
Total decommissioning waste	2.8	2.7	6.9E-3 (6.1E2g)	2.3E2 (2.5E1g)	4.9E0
Total mixed oxide fuel plant waste	19	21	2.1E-1 (1.3E4g)	8.1E3 (5.8E2g)	1.2E2

(a) The MOX fuel fabrication plant is assumed to be operated and maintained by contact means, with a nominal throughput of 400 MTHM/yr, 11.8 MTHM/GWe·yr, and 30-yr lifetime.
(b) As-shipped volumes assume compactable waste is compacted, combustible waste is incinerated, wet wastes are immobilized in cement, and scrap waste is packaged directly.
(c) Activities are at 2.5 yr after reactor discharge.
(d) Includes failed equipment and ventilation filters.
(e) Decommissioning alternative is immediate dismantlement upon shutdown. Assumes an accumulation of 1 kg Pu/yr and 22 kg U/yr over the 30-yr lifetime of the facility.

coolant system plumbing; 2) water cleanup wastes such as ion exchange resins and evaporator bottoms; 3) filter precoat sludges from blowback of coolant filters; and 4) noncompactable trash such as coolant reheaters, steam generators, and turbine parts. Sources of radioactivity in the wastes include neutron activation of structural metals and their corrosion products; irradiation of tramp uranium on the external surfaces of fuel elements; neutron activation of coolant components including coolant additives; and fission products from irradiated fuel, in the event of fuel rod cladding failure.

The maintenance wastes from the reactor include spent coolant system cartridge filters, ventilation system filters, and activated core parts such as control elements and flow channels. Because of the extremely high concentration of activation products in the core parts, these materials were estimated separately. Note that although it is assumed that PWR control rods in Strategy 1 are packaged with spent PWR fuel (thereby contributing no additional waste volume), the net fuel cycle volume for this waste category is still nearly as large as for Strategy 2 (in which all control rods are packaged separately). This is because in a fuel cycle having nuclear power plants in the ratio of two PWRs to one BWR, the BWR contributes about three-fourths of the core-parts waste volume. Hence a relatively significant economy in PWR core-part volume still results in a minor reduction for the Strategy 1 fuel cycle.

The nuclear power plant may be decommissioned in one of two ways: immediate entombment (assumed in this report) or dismantlement. Entombment of the nuclear power plant involves placement of as much contaminated equipment and structural components as possible (60% in the case of a PWR) within the portion of the containment building below ground level, which is then covered by a thick, reinforced concrete slab. All penetrations to the structure are permanently sealed, and the external surfaces may have an impermeable sealant applied. All contaminated materials not placed within the entombment structure are appropriately treated, packaged and shipped for disposal.

Dismantlement, which has been described in another study,[10] involves complete removal of contaminated materials from the site to the extent required

to terminate the facility license. This may include removal of some uncontaminated structural materials to ensure compliance with regulatory requirements. The actual dismantling activities may be preceded by an interim protective storage period (e.g., 50 years) to allow for decay of ^{60}Co.

Table 9 shows the distribution of nuclear power plant wastes that were estimated. Refer to Appendix Tables A-1 through A-3 for details. Comparison of these estimates with the INFCE/WG.7 Table of Waste Arisings[8] requires two comments. First, operating wastes in Table 9 are large in volume compared to other fuel cycles evaluated by WG.7.* The estimate is based upon actual operating data obtained from existing LWRs in the United States, where shallow-land burial is routinely practiced. If the more expensive geologic disposal constraint assumed in this study were actually imposed upon nuclear power plant operators, a greater incentive for waste volume reduction would exist, thereby lowering the projected waste volume. The second comment is that the projected decommissioning volume presented here assumes that only the portion of the reactor containment building below grade is available for use as the entombment structure, requiring that some 75 m^3/GWe·yr of contaminated piping and equipment be sent offsite for disposal. If all such wastes remain onsite in an enlarged entombment structure, then a smaller repository waste volume will result.

SPENT FUEL PACKAGING FACILITY

The spent fuel packaging facility (SFPF) receives fuel that has been in interim storage at the reactor or at an independent storage basin. The reference fuel age for repository emplacement is taken to be 10 years, thus it is assumed that the SFPF receives fuel at 9 years out of reactor. Wastes from about 8.5 years of interim spent fuel storage are not included in this analysis.

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*Actually, operating and maintenance wastes should be summed before comparison of waste arisings among different fuel cycles. This is because the distinction between operating wastes and maintenance wastes for many facilities and activities is difficult to discern. Taken together, they represent a fairly consistent category of wastes amenable to intercycle comparison.

TABLE 9. Estimated Waste Volumes and Activities from the Reference Nuclear Power Plant[a]

Waste Stream	Volume, m^3/GWe·yr		Activity, Ci/GWe·yr[c]	
	As Generated	As Shipped[b]	Activation Products	Fission Products
Operating Waste				
General trash	190	48	5.8E1	2.8E0
Wet waste	330	520	1.0E3	4.0E3
Scrap	38	38	1.7E-1	8.0E-1
Total operating waste	558	606	1.1E3	4.0E3
Maintenance Waste[d]				
General trash	5	1	4.2E0	3.2E0
Wet waste	5	8	3.5E2	2.0E0
Total maintenance waste	10	9	3.5E2	5.2E0
Core Parts				
Control rods[e]	6	5 or 7	1.9E5	1.2E0
Total core parts	6	5 or 7	1.9E5	1.2E0
Decommissioning Waste[f]				
General trash and wet waste	-	18	1.9E3	NS
Scrap	-	83	4.0E1	NS
Total decommissioning wastes	-	101	1.9E3	NS
Total nuclear power plant wastes	574	723	1.9E5	4.0E3

(a) Light water reactors, at equilibrium operation, 2/3 PWR - 1/3 BWR, 1200 MWe generating capacity each, 70% load factor, 30 GWth·d/MTHM average fuel exposure, 32% thermal-to-electric conversion efficiency, 36.4 MTHM/GWe·yr, approximately one-third of fuel is assumed to be mixed-oxide.
(b) As-shipped volume assumes general trash is compacted, wet wastes are immobilized in cement, and scrap is packaged directly.
(c) Activities are at 0.5 year.
(d) Includes coolant system filter cartridges and ventilation filters.
(e) Strategy 1: PWR control rods remain inserted within fuel assemblies and are packaged in spent fuel canisters; BWR control rods are packaged in separate spent fuel canisters. Resulting volume is 5 m^3/GWe·yr.
Strategy 2: All control rods are mechanically dissected and packaged in convenient canisters. Resulting volume is 7 m^3/GWe·yr.
(f) Decommissioning alternative for the nuclear power plant is entombment.

The SFPF receives fuel assemblies into its heavily shielded air environment through a water-filled canal from the cask unloading station. The assemblies are dried and inspected for damage before packaging. Unfailed fuel assemblies are sealed in single helium-filled stainless steel canisters (3 BWR assemblies per canister, or 1 PWR assembly per canister). Failed assemblies (expected to occur at 2% frequency) are placed in similar canisters, followed by overpacking to provide double encapsulation. After inspection for helium leakage the packaged fuel is sent to the repository for disposal.

Secondary wastes generated at the SFPF are primarily combustible trash and decontamination solutions from the receiving and loadout stations, and water treatment system wastes. Small quantities of tools and failed equipment are also produced. The facility is assumed to be dismantled at the end of its useful life, with small quantities of contaminated material being sent to the repository. The SFPF wastes are characterized in Table 10.

FUEL REPROCESSING PLANT

The FRP consists of five integrated facilities: the spent fuel storage basin, the fuel dissolution and solvent extraction facility (the main plant), the plutonium conversion facility, the UF_6 facility, and the waste management facility. Each facility has operations that are unique in the fuel cycle; therefore, the waste streams from the FRP are the most diverse of any facility in the post-fission LWR-MOX fuel cycle.

Of the several waste streams generated in the FRP, the two with the highest specific radioactivity are HLLW and fuel residues. HLLW is the concentrated raffinate from the first-cycle extractor combined with dissolver sludge. It contains 99% of the fission products and actinides other than uranium and plutonium (0.5% loss assumed) that are originally in the spent fuel. In addition, significant quantities of reprocessing chemicals are present in varying concentrations, depending upon the particular flowsheet selected. This paper assumes the reference HLLW composition given in Reference 3; the waste is composed of 52 kg total oxides per MTHM (including

TABLE 10. Estimated Waste Volumes and Activities from the Reference Spent Fuel Packaging Facility[a]

Waste Stream	Volume, m^3/GWe·yr		Activity, Ci/GWe·yr[c]	
	As Generated	As Shipped[b]	Activation Products	Fission Products
Operating Waste				
General trash	17	4.3	4.7E-1	5.0E1
Wet waste	0.2	0.3	4.7E-1	5.0E1
Scrap	0.01	0.01	2.5E-3	2.6E-1
Total operating wastes	17.2	4.6	9.4E-1	1.0E2
Maintenance Waste[d]				
General trash	0.5	0.1	4.7E-3	5.0E-1
Scrap	1.8	1.8	4.7E-1	5.0E1
Total maintenance wastes	2.3	1.9	4.7E-1	5.1E1
Decommissioning Waste[e]				
General trash	0.03	0.01	NS	4.7E-3
Wet waste	0.01	0.02	NS	7.1E-3
Scrap	0.83	0.83	NS	7.1E-3
Total decommissioning wastes	0.87	0.86	NS	1.9E-2
Total packaging facility wastes (excluding fuel)	20.4	7.4	1.4E0	1.5E2

Waste Stream	Volume, m^3/GWe·yr		Activity, Ci/GWe·yr[c]			
	As Generated	As Shipped[b]	AP and FP[g]	U	Pu	Other Actinides
Spent Fuel	15	35[f]	AP:6.8E4 FP:9.9E6	8.6E1 (3.6E7g)	2.6E6 (2.9E5g)	1.2E5

(a) Spent fuel is received at 9 yr out of reactor. The SFPF has a 2000 MTHM/yr capacity and a 30-yr lifetime, 36.8 MTHM/GWe·yr.
(b) As-shipped volume assumes general trash is compacted, wet wastes are immobilized in cement, and scrap is packaged directly.
(c) Activity is at 10 yr out of reactor.
(d) Includes failed equipment and ventilation filters.
(e) Decommissioning alternative is dismantlement immediately upon shutdown.
(f) Assumes cylindrical canisters:
PWR - 0.32 m dia x 4.9 m (1 assembly each)
BWR - 0.41 m dia x 4.9 m (3 assemblies each).
(g) AP: activation products; FP: fission products.

32 kg of fission product oxides). This waste is combined with glass-forming additives to produce a borosilicate glass cast in stainless steel canisters. To meet the WG.7 criterion of 9 wt% fission product oxides in glass, a waste loading of 15 wt% HLW oxides is specified. Table 11 indicates the resulting HLW glass volume; the total packaged volume is about 5.4 m^3/GWe·yr.

The fuel residues include hulls and assembly hardware resulting from fuel disassembly, shearing, and dissolution operations. The radioactivity in the assembly hardware is from neutron activation of the constituent metals. The activity of the hulls includes activation products plus actinides and fission products from undissolved residual fuel (0.05% loss assumed). The fuel residues are assumed to be mixed with cement and packaged in suitable canisters for disposal. The resulting waste characteristics, shown in Table 11, are based upon the assumption that waste loading in cement is equal to that achievable by pouring uncompacted residues into the canister with sand added as an inert filler.[3] Comparison of these characteristics with Reference 8 reveals that a more conservative assumption could have been used; that is, cement immobilization may increase the bulk volume of fuel residues by 70%. Reference 8 also assumes that a larger fraction of the spent fuel remains undissolved with the fuel residues.

If irradiated UO_2 and MOX fuel assemblies are processed through the FRP separately, then it is conceptually possible to isolate uranium recovered from MOX fuel and discard it as waste. This analysis did not assume separate processing of the two kinds of fuel, and therefore does not present an independent estimate of the waste generated. However, some 11 MTU/GWe·yr[8] of depleted uranium will be recovered. If this is disposed of as UO_2, and assuming 50% of theoretical density, about 2.3 m^3/GWe·yr of packaged waste would result.

Other FRP wastes arising from routine operations include solvent cleanup wash solutions, second- and subsequent-cycle solvent extraction raffinates, ion-exchange resins and bead resins from storage basin water cleanup. Main plant and storage basin combustible trash and main plant noncombustible scrap are also significant in volume. Maintenance wastes comprise a smaller volume but contain considerable activity, especially in the case of main plant and

TABLE 11. Estimated Waste[a] Volumes and Activities from the Reference Fuel Reprocessing Plant[b]

Waste Stream	Volume, m^3/GWe·yr		Activity, Ci/GWe·yr[d]			
	As Generated	As Shipped[c]	Fission Products	U	Pu	Other Activities
Operating Waste						
Noble gases[e]	-	0.1	2.7E5	NS	NS	NS
General trash	83	17	5.8E2	1.0E-1 (1.8E4g)	4.1E3 (2.7E2g)	4.2E0
Wet waste	9	15	3.4E4	7.6E-1 (1.4E5g)	6.8E3 (4.4E2g)	2.0E1
Scrap	17	17	1.2E2	2.0E-2 (3.6E3g)	6.5E2 (4.4E1g)	2.1E0
Total non-high level operating wastes	109	49	3.0E5	8.8E-1 (1.6E5g)	1.2E4 (7.5E2g)	2.6E1
High-level liquid waste	22	4.3[f]	9.7E6	7.3E-1 (1.8E5g)	2.4E4 (2.2E3g)	1.8E5
Fuel residues	12	12[g]	AP:[h] 8.7E5 FP: 6.2E4	1.0E-1 (1.8E4g)	3.5E3 (2.2E2g)	9.8E2
Total operating waste	143	65	AP: 8.7E5 FP: 1.1E7	1.7E0 (3.6E5g)	4.0E4 (3.2E3g)	1.8E5
Maintenance Waste[i]						
General trash	6	2	1.2E3	4.0E-3 (6.1E2g)	1.3E4 (8.8E2g)	2.0E1
Scrap	9	9	1.2E2	2.2E-3 (4.0E2g)	7.0E2 (4.4E1g)	2.0E0
Total maintenance waste	15	11	1.3E3	6.2E-3 (1.0E3g)	1.4E4 (9.2E2g)	2.2E1
Decommissioning Waste[j]						
General trash[k]	0.6	0.7	7.4E-1	2.8E-5 (4.8E1g)	4.2E-1 (1.9E-1g)	1.1E-1
Wet waste	0.3	0.4	9.0E-1	7.5E-6 (1.3E1g)	1.1E-1 (4.9E-2g)	3.0E-2
Scrap	5.0	5.0	2.4E0	3.5E-5 (5.8E1g)	5.2E-1 (2.3E-1g)	1.4E-1
Total decommissioning waste	5.9	6.1	4.0E0	7.1E-5 (1.2E2g)	1.1E0 (4.7E-1g)	2.8E-1
Total fuel reprocessing plant wastes	160	82	AP: 8.7E5 FP: 1.1E7	1.7E0 (3.6E5g)	5.4E4 (4.1E3g)	1.8E5

(a) Includes transuranic and nontransuranic wastes.
(b) The fuel reprocessing plant is assumed to be of conventional design based on the PUREX flowsheet, with a nominal throughput of 2000 MTHM/yr, 36.4 MTHM/GWe·yr, 30-yr lifetime.
(c) As-shipped volume assumes combustibles are incinerated and immobilized in cement, compactables are compacted, wet wastes are immobilized in cement, and scrap wastes are packaged directly.
(d) Activity at 0.5 yr after reactor discharge, except for certain PuO_2 conversion wastes (1.5 yr), high-level liquid waste (10 yr), and decommissioning wastes (shutdown + 30 yr).
(e) Assumes fractional distillation, yielding a mixture, 80% of which is krypton; gas cylinder storage at 34 atm (500 psi).
(f) Volume of waste glass only; packaged volume is greater by 1.25X, i.e., 5.4 m^3/GWe·yr.
(g) Fuel residues as-shipped volume assumes cementation of uncompacted hulls and hardware.
(h) AP: activation products; FP: fission products.
(i) Includes HEPA filters and failed equipment from the main reprocessing plant, the PuO_2 conversion facility, and portions of the UF_6 conversion facility.
(j) Decommissioning alternative is 30-yr protective storage (to reduce exposure levels) followed by facility dismantlement.
(k) HEPA filters are packaged without compaction, thereby increasing the final shipping volume.

PuO_2 conversion facility ventilation filters. Wastes in these categories are treated as described above and packaged in 200-ℓ drums.

Decommissioning of the FRP involves placing the facility into a 30-yr protective storage mode before dismantlement. Operations include chemical and mechanical decontamination and fixation of residual decontamination, deactivation of equipment, isolation of contaminated areas, and final interim storage preparations such as sealing doors and installing security systems and radiation detection equipment. At the end of the protective storage period, normal dismantling activities are undertaken. Waste treatment systems installed at the FRP are used to treat decommissioning wastes to the extent possible. Other wastes are packaged for shipment to another treatment facility and subsequently are sent to the geologic repository.

Table 11 summarizes FRP wastes according to operating, maintenance, and decommissioning categories, for which additional detail is provided in Appendix Tables A-4 through A-6. The Working Group 7 report structure distinguishes between medium-level and low-level operating wastes as well, using a package surface dose rate of 0.2 R/hr as the distinguishing characteristic. Using data provided in Reference 6, Appendix 10, the operating wastes shown in Table 11 of this report have been restructured to indicate the distribution between dose rate classes, and are presented in Table 12. The only significant FRP wastes likely to occur in the lower class are the incinerator scrubber solution, most UF_6 plant wastes, and PuO_2 conversion plant glove box wastes.

TABLE 12. Summary of Operating Wastes from the Reference Fuel Reprocessing Plant by Package Dose Rate[a]

	No Shielding Required		Shielding Required[c]	
Waste Category	Volume, m^3/GWe·yr	Activity, Ci/GWe·yr	Volume, m^3/GWe·yr	Activity, Ci/GWe·yr
General trash	7	1.1E1	10	4.7E3
Wet waste	-	-	15	4.1E4
Scrap	2	1.9E-1	15	7.7E2
Total	9	1.1E1	40	4.7E4

(a) Distribution of wastes between the two dose rate categories was estimated from Reference 8.
(b) Surface dose rate <0.2 R/hr.
(c) Surface dose rate ≥0.2 R/hr.

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APPENDIX

DETAILS OF ESTIMATED WASTE VOLUMES AND ACTIVITIES FOR THE LWR U/Pu RECYCLE FUEL CYCLE

TABLE A-1. Estimated Operating Waste Volumes and Activities from the Reference Nuclear Power Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[c]	
				As Generated	As Shipped[b]	Activation Products	Fission Products
General trash	Combustible trash	Paper	23	190	48	5.8E-1	2.8E0
		Plastic	67				
		Rubber	6				
		Wood	3				
		Cloth	1				
Wet waste	Bead resins	Polystyrene	50	27	43	1.7E2	3.9E3
		H_2O	50				
	Powdered resins	Polystyrene	50	27	43	3.5E2	8.0E1
		H_2O	50				
	Filter precoat sludge	Filter aids	80	32	51	1.7E1	1.2E1
		H_2O	20				
	Sulfate concentrate	Na_2SO_4	25	240	380	4.9E2	1.6E1
		H_2O	75				
	Borate concentrate	$Na_2B_4O_7$	10	4	6	5.6E0	4.0E0
		H_2O	90				
Scrap	Noncombustible trash	Metal	90	38	38	1.7E-1	8.0E-1
		Glass	10				
	Control rods	Ferrous alloys	100	6	7	1.9E5	1.2E0

(a) LWR, at equilibrium operation, 2/3 PWR - 1/3 BWR, 1200 MW_e generating capacity, 70% load factor, 30 year lifetime, 30,000 MWd/MTHM average fuel exposure, 32% thermal-to-electric conversion efficiency, 36.4 $MTHM/GW_e$ yr, approximately one-third of fuel is assumed to be mixed-oxide.

(b) As-shipped volume assumes the following treatments:
- general trash - compaction
- wet wastes - cement immobilization
- scrap - direct packaging.

(c) Activities are at 0.5 year.

TABLE A-2. Estimated Maintenance Waste Volumes and Activities from the Reference Nuclear Power Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[c]	
				As Generated	As Shipped[b]	Activation Products	Fission Products
General trash	HEPA filters	Glass	40	5	1.3	4.2E0	3.2E0
		Wood	60				
Wet waste	Cartridge filters	Filter media	80	5	7.5	3.5E2	2.0E0
		H_2O	20				

(a) See Table A-1, footnote (a).
(b) See Table A-1, footnote (b).
(c) Activities are at 0.5 year.

TABLE A-3. Estimated Waste Volumes and Activities for Entombment of the Reference Nuclear Power Plant[a]

Waste Stream	Volume[b] m^3/power plant AIF[c]	NUREG[d]	Average	m^3/GWe·yr, Average	Activity, Ci/GWe·yr[e]
Miscellaneous combustible and wet wastes[f]	280	620	450	18	1.9E3
Contaminated metals and other solid wastes	2000	2200	2100	83	4.0E1

(a) See Table A-1, footnote (a).
(b) Volumes presented assume that combustible wastes are compacted, wet wastes are immobilized in cement, and solid wastes are packaged directly.
(c) Estimated from data presented in Reference 11.
(d) Estimated from data presented in Reference 10, specifically, from Table G.4-2, It was assumed that 50% of the "contaminated metals and misc." and all of the "radioactive wastes" are packaged and shipped to the repository. The other wastes are assumed to be deposited within the entombment structure.
(e) Estimated from Reference 10. Activities are at time of shutdown, and are primarily activation products.
(f) E.g., decontamination wastes, ion exchange resins, cartridge filters, evaporator bottoms.

TABLE A-4. Estimated Operating Waste Volumes and Activities from the Reference Fuel Reprocessing Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[c]			
				As Generated	As Shipped[b]	Fission Products	U	Pu	Other Actinides
TRU									
General trash	Main plant combustible trash	Paper/rags	40	58	12	1.2E2	2.0E-4 (3.6E1g)	6.8E0 (4.4E-1g)	2.0E0
		PVC	20						
		Neoprene	11						
		Polyethylene	14						
		Latex	11						
		Wood	4						
	PuO_2 conversion combustible trash	Same as above		1.1	0.2	NS	NS	3.3E3* (2.2E2g)	NS
	Ion exchange bead resins	Polystyrene	50	0.2	0.05	3.4E2	2.0E-3 (3.6E2g)	6.8E1 (4.4E0g)	2.0E-1
		H_2O	50						
	Degraded extractant	TBP	30(vol)	0.3	0.08	1.2E2	2.0E-4 (3.6E1g)	6.8E2 (4.4E1g)	2.0E0
		n-dodecane	70(vol)						
Wet waste	Main plant ILLW	$NaNO_3$	18	4.0	6.4	3.4E4	2.0E-1 (3.6E4g)	6.8E3 (4.4E2g)	2.0E1
		Na_3PO_4	8						
		Misc. salts	4						
		H_2O	70						
	Main plant silica gel	SiO_2	70	0.2	0.3	1.9E0	NS	6.8E-1 (4.4E-2g)	NS
		H_2O	30						
	UF_6 plant fluorinator bed residues	Al_2O_3	100	0.2	0.3	1.7E0	1.2E-3 (2.2E2g)	1.3E0 (8.8E-2g)	NS
	UF_6 plant fluorinator fines	Al_2O_3	50	1.1	1.8	1.7E1	3.0E-1 (5.3E4g)	6.8E0 (4.4E-1g)	NS
		CaF_2	46						
		Uranium fluorides	4						
Scrap	Main plant noncombustible trash	Ferrous alloys	90	15	15	1.2E2	2.0E-4 (3.6E1g)	6.8E0 (4.4E-1g)	2.1E0
		Glass	10						
	UF_6 plant noncombustible trash	Same as above		0.4	0.4	NS	2.0E-2 (3.6E3g)	NS	NS
	PuO_2 conversion noncombustible trash	Same as above		0.2	0.2	NS	NS	6.4E2* (4.4E1g)	NS

TABLE A-4. (contd)

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$ As Generated	Volume, $m^3/GW_e \cdot yr$ As Shipped[b]	Activity, $Ci/GW_e \cdot yr$[c] Fission Products	U	Pu	Other Actinides
High-level liquid waste	Raffinate from first-cycle extractor and dissolver sludge	Nitrate salts	15	22	4.3[d]	9.7E6**	7.3E-1** (1.8E5g)	2.4E4** (2.2E3g)	1.8E5**
		HNO_3	10						
		H_2O	75						
Fuel residues	Hardware	Fe	57	2.0	2.0	AP:[e] 4.7E5	NS	NS	NS
		Ni	17						
		Cr	17						
		Cu	5						
		Other metals	4						
	Hulls	Zr	98	10	10.2	AP: 4.0E5	1.0E-1	3.5E3	9.8E2
		Sn	1			FP: 6.2E4	(1.8E4g)	(2.2E2g)	
		Other metals	1						
NON-TRU									
General trash	Storage basin combustible trash	Paper/rags	40	22	4.4	6.8E-1	NS	NS	NS
		PVC	20						
		Neoprene	11						
		Polyethylene	14						
		Latex	11						
		Wood	4						
	UF_6 plant combustible trash	Same as above		1.8	0.4	NS	1.0E-1 (1.8E4g)	NS	NS
Wet waste	Storage basin bead resin	Resin	50	0.1	0.2	2.9E-1	NS	NS	NS
		H_2O	50						
	Storage basin filter precoat sludge	Sludge	40	0.3	0.5	2.9E1	NS	NS	NS
		H_2O	60						
	Storage basin sulfate concentrate	Na_2SO_4	25	0.2	0.3	2.9E1	NS	NS	NS
		H_2O	75						
	Storage basin miscellaneous solutions	Salts	25	0.4	0.6	3.9E1	NS	NS	NS
		H_2O	75						

TABLE A-4. (contd)

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$ As Generated	Volume, $m^3/GW_e \cdot yr$ As Shipped[b]	Activity, $Ci/GW_e \cdot yr$[c] Fission Products	U	Pu	Other Actinides
	UF_6 plant K_2UO_4 mud	KOH	3	2.6	4.2	NS	2.6E-1 (4.6E4g)	NS	NS
		KF	4						
		K_2UO_4	3						
		$Fe(OH)_2$	18						
		Misc. salts	1						
		H_2O	71						
Scrap	Storage basin noncombustible trash	Ferrous alloys	90	1.8	1.8	AP:[e] 9.9E-3 FP: 4.8E-2	NS	NS	NS
		Glass	10						

(a) The fuel reprocessing plant is assumed to be of conventional design based on the PUREX flowsheet, with a nominal throughput of 2000 MTHM/yr, 36.4 $MTHM/GW_e \cdot yr$, 30 year lifetime.
(b) See Table A-1, footnote (b). Additionally, high-level liquid waste as-shipped volume assumes vitrification and fuel residues as-shipped volume assumes cementation of uncompacted hull and hardware.
(c) Activities are at 0.5 year except as noted: *indicates 1.5 years; **indicates 10 years.
(d) Volume of waste glass only; packaged volume is greater by 1.25X.
(e) AP: activation products; FP: fission products.

TABLE A-5. Estimated Maintenance Waste Volumes and Activities from the Reference Fuel Reprocessing Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$ As Generated	Volume, $m^3/GW_e \cdot yr$ As Shipped[b]	Activity, $Ci/GW_e \cdot yr$[c] Fission Products	U	Pu	Other Actinides
TRU									
General trash	Main plant ventilation filters	Wood Glass	60 40	5.1	1.3	1.2E3	2.0E-3 (3.5E2g)	6.9E1 (4.4E0g)	2.0E1
	PuO_2 conversion ventilation filters	Metal Glass	60 40	0.7	0.2	NS	NS	1.3E4* (8.8E2g)	NS
Scrap	Main plant failed equipment	Ferrous alloys	100	7.3	7.3	1.2E2	2.0E-4 (3.6E1g)	6.9E0 (4.4E-1g)	2.0E0
	UF_6 plant failed equipment	Same as above		0.4	0.4	NS	2.0E-3 (3.6E2g)	NS	NS
	PuO_2 conversion failed equipment	Same as above		0.8	0.8	NS	NS	6.9E2* (4.4E1g)	NS
NON-TRU									
General trash	Storage basin ventilation filters	Wood Glass	60 40	0.4	0.1	2.6E1	NS	NS	NS
	UF_6 plant ventilation filters	Same as above		0.2	0.05	NS	2.0E-3 (3.6E2g)	NS	NS
Scrap	Storage basin failed equipment	Ferrous alloys	100	0.4	0.4	AP:[d] 6.3E-3 FP: 3.0E-2	NS	NS	NS

(a) See Table A-4, footnote (a).
(b) See Table A-1, footnote (b).
(c) Activities are at 0.5 year except as noted: *indicates 1.5 years.
(d) AP: activation products; FP: fission products.

TABLE A-6. Estimated Waste Volumes and Activities for Protective Storage/ Dismantlement of the Reference Fuel Reprocessing Plant[a]

Waste Stream	Waste Description	Decommissioning Phase[b]	Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[d]			
			As Generated	As Shipped[c]	Fission Products	U	Pu	Other Actinides
TRU								
General trash	Combustible trash	PS	0.06	0.02	8.3E-4	1.3E-8 (2.2E-2g)	2.0E-4 (8.4E-5g)	5.2E-5
	Combustible trash	D	0.08	0.02	4.6E-3*	5.8E-8* (4.6E-2g)	1.6E-3* (1.9E-4g)	1.4E-4*
	HEPA filters	PS	0.10	0.27	5.8E-1	9.1E-6 (1.6E1g)	1.4E-1 (5.9E-2g)	3.6E-2
	HEPA filters	PS	0.02	0.05	NS	1.6E-5 (2.8E1g)	2.4E-1 (1.1E-1g)	6.5E-2
	HEPA filters	D	0.10	0.27	5.8E-2	9.1E-7 (1.6E0g)	1.4E-2 (5.9E-3g)	3.6E-3
	HEPA filters	D	0.02	0.05	NS	1.6E-6 (2.8E0g)	2.4E-2 (1.1E-2g)	6.5E-3
Wet waste	Noncombustible wet wastes	PS	0.14	0.22	4.8E-1	7.5E-6 (1.3E1g)	1.1E-1 (4.9E-2g)	3.0E-2
Scrap	Equipment and structural materials	D	0.11	0.11	1.3E0	2.0E-5 (3.3E1g)	2.9E-1 (1.3E-1g)	7.8E-2
	Equipment and structural materials	D	0.47	0.47	5.4E-1	8.4E-6 (1.4E1g)	1.3E-1 (5.5E-2g)	3.4E-2
	Equipment and structural materials	D	0.73	0.73	4.2E-1	6.5E-6 (1.1E1g)	9.7E-2 (4.2E-2g)	2.6E-2
NON-TRU								
General trash	Combustible trash	PS	0.04	0.01	5.0E-4	NS	NS	NS
	Combustible trash	PS	0.07	0.02	9.9E-4*	NS	NS	NS
	Combustible trash	D	0.06	0.01	1.2E-3	NS	NS	NS
	HEPA filters	PS	0.02	0.01	8.3E-2	NS	NS	NS
	HEPA filters	D	0.02	0.01	8.3E-3	NS	NS	NS

TABLE A-6. (contd)

Waste Stream	Waste Description	Decommissioning Phase[b]	Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[d]			
			As Generated	As Shipped[c]	Fission Products	U	Pu	Other Actinides
Wet waste	Combustible wet wastes	PS	0.08	0.13	2.9E-1	NS	NS	NS
	Noncombustible wet wastes	PS	0.04	0.06	1.3E-1	NS	NS	NS
Scrap	Equipment and structural materials	D	0.11	0.11	6.2E-2	NS	NS	NS
	Equipment and structural materials	D	3.6	3.6	8.3E-2	NS	NS	NS

(a) See Table A-4, footnote (a); the facility is placed in 30-year protective storage prior to dismantlement.
(b) Indicates decommissioning phase during which the waste is generated; P: protective storage; D: dismantlement.
(c) See Table A-1, footnote (b).
(d) Activities are at time of shutdown + 30 years except as noted: *indicates activity at shutdown.

TABLE A-7. Estimated Operating Waste Volumes and Activities from the Reference MOX Fuel Fabrication Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$ As Generated	Volume, $m^3/GW_e \cdot yr$ As Shipped[b]	Activity, $Ci/GW_e \cdot yr$[c] U	Activity, $Ci/GW_e \cdot yr$[c] Pu	Activity, $Ci/GW_e \cdot yr$[c] Other Actinides
TRU								
General trash	Combustible trash	PVC	33	5.9	5.9	5.6E-2 (3.4E3g)	2.1E3 (1.5E2g)	3.5E1
		Cellulosics	30					
		Polyethylene	18					
		Latex	9					
		Neoprene	9					
		Styrene	1					
Wet waste	Process solutions	$Al(NO_3)_3$	16	0.24	0.38	1.8E-3 (1.1E2g)	6.9E1 (5.0E0g)	1.1E0
		$Ca(NO_3)_2$	6					
		CaF_2	0.2					
		H_2O	78					
	Scrap recovery solutions	$Al(NO_3)_3$	2	4.1	6.6	1.8E-2 (1.1E3g)	6.9E2 (5.0E1g)	2.3E2
		$Ca(NO_3)_2$	11					
		AlF_3	0.4					
		NH_4NO_3	7					
		$NaNO_3$	7					
		H_2O	73					
Scrap	Noncombustible trash	Metal	90	2.4	2.4	1.8E-3 (1.1E2g)	6.9E1 (5.0E0g)	1.1E0
		Glass	10					

(a) The MOX Fuel Fabrication Plant is assumed to be operated and maintained by contact means, with a nominal throughput of 400 MTHM/yr, 11.8 $MTHM/GW_e \cdot yr$, 30-year lifetime.
(b) All wastes are immobilized in concrete.
(c) Activities are at 2.5 years after reactor discharge.

TABLE A-8. Estimated Maintenance Waste Volumes and Activities from the Reference MOX Fuel Fabrication Plant[a]

Waste Stream	Waste Description	Composition, wt%		Volume, $m^3/GW_e \cdot yr$ As Generated	Volume, $m^3/GW_e \cdot yr$ As Shipped[b]	Activity, $Ci/GW_e \cdot yr$[c] U	Activity, $Ci/GW_e \cdot yr$[c] Pu	Activity, $Ci/GW_e \cdot yr$[c] Other Actinides
TRU								
General trash	HEPA filters	Metal	60	1.2	1.2	1.3E-1 (7.8E3g)	4.9E3 (3.3E2g)	8.0E1
		Glass	40					
Scrap	Failed equipment	Metal	80	2.4	2.4	1.8E-3 (1.1E2g)	6.9E1 (5.0E0g)	1.1E0
		Insulating brick	20					

(a) See Table A-7, footnote (a).
(b) All wastes are immobilized in concrete.
(c) Activities are at 2.5 years after reactor discharge.

TABLE A-9. Estimated Waste Volumes and Activities from Dismantlement of the Reference MOX Fuel Fabrication Plant[a]

Waste Stream	Waste Description	Decommissioning Phase[b]	Volume, $m^3/GW_e \cdot yr$		Activity, $Ci/GW_e \cdot yr$[d]		
			As Generated	As Shipped[c]	U	Pu	Other Actinides
TRU							
General trash	Combustible trash	D	9.8E-2	1.5E-2	7.6E-5 (6.5E0g)	2.5E0 (2.7E-1g)	5.4E-2
	HEPA filters	D	2.4E-2	6.4E-2	2.8E-3 (2.4E2g)	9.2E1 (1.0E1g)	1.9E0
Wet waste	Combustible wet wastes	D	2.0E-1	3.1E-2	1.1E-3 (9.6E1g)	3.7E1 (4.0E0g)	7.8E-1
	Noncombustible wet wastes	D	9.8E-2	1.6E-1	6.9E-6 (5.9E-1g)	2.3E-1 (2.5E-2g)	4.9E-3
Scrap	Equipment and structural materials	D	2.9E-1	2.9E-1	1.4E-3 (1.2E2g)	4.6E1 (5.0E0g)	9.8E-1
	Equipment and structural materials	D	1.8E0	1.8E0	1.4E-3 (1.3E2g)	4.8E1 (5.2E0g)	1.0E0
	Equipment and structural materials	D	2.9E-1	2.9E-1	1.4E-4 (1.2E1g)	4.6E0 (5.0E-1g)	9.8E-2

(a) See Table A-7, footnote (a); the facility is dismantled upon shutdown.
(b) See Table A-3, footnote (b).
(c) See Table A-1, footnote (b).
(d) Activities are at time of shipment from site.

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