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COMMERCIAL HIGH-LEVEL-WASTE MANAGEMENT

OPTIONS AND ECONOMICS:

A COMPARATIVE ANALYSIS OF THE
CERAMIC AND GLASS WASTE FORMS

DOE Research and Development Report

*Prepared for the United States
Department of Energy,
Savannah River Operations Office
under Contract Number DE-AC09-79ET41900*

Rockwell International
Energy Systems Group

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OPTIONS AND ECONOMICS:**

**A COMPARATIVE ANALYSIS OF THE
CERAMIC AND GLASS WASTE FORMS**

By

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ABSTRACT

The results of an estimate of the waste management costs of the commercial high-level waste from a 3000 metric ton per year reprocessing plant show that the judicious use of the ceramic waste form can save about \$2 billion during a 20-year operating campaign relative to the use of the glass waste form. This assumes PWR fuel is processed and the waste is encapsulated in 0.305-m (12-in.) diameter canisters with ultimate emplacement in a BWIP-type horizontal-borehole repository. The estimated total cost (capital and operating) of the management in the ceramic form is \$2.0 billion, and that of the glass form is \$4.0 billion.

Waste loading and waste form density are the driving factors in that the low-waste loading (25%) and relatively low density (3.1 g/cm^3) characteristic of the glass form requires several times as many canisters to handle a given waste throughput than is needed for the ceramic waste form whose waste loading capability exceeds 60% and whose waste density is nominally 5.2 g/cm^3 . The consequence of the difference in the number of canisters is that the repository costs, which are assumed to be proportional to the number of canisters emplaced, are several times higher for the glass form and dominate the total costs. With fewer canisters for the ceramic waste form, the nominally constant immobilization facility costs are found to be the major factor, with a decreasing contribution from the repository costs as the waste loading is increased.

Canisters with higher loading have higher heat generation rates. In some of the scenarios considered here, the canisters must be stored before emplacement to prevent the generation of unacceptably high temperatures in the repository. The minimum-cost ceramic waste form has a 60 wt. % waste loading of commercial high-level waste (CHLW) and requires 25 years' storage before emplacement in basalt with delayed backfill.

In addition to the finding of this study that high-waste loadings are economically advantageous, it was also found that a cost saving can be realized by early reprocessing and immobilizing, followed by (dry) canister storage.

It was also found that, because of the process flexibility allowed by the availability of the high-waste loading of the ceramic form, the intermediate-level liquid waste stream can be mixed with the high-level liquid waste stream (mixed waste) and economically processed and emplaced. The cost is greater by \$0.3 billion than that of the best high-level liquid waste handling process sequence (\$2.3 billion vs \$2.0 billion), but this difference is less than the cost of the separate disposal of the intermediate-level liquid waste.

This document on system economics is one of three documents being published on the waste form, the process plant design, and the system economics, for the application of ceramics to the management of High-Level Waste.

I. SUMMARY

A comparative study has been made of the waste management costs for the crystalline ceramic waste form and the borosilicate glass waste form for immobilizing the waste from a commercial reprocessing plant for pressurized water reactor (PWR) fuel. The results show that the least expensive process sequence involving the standard glass waste form* has an estimated total cost (capital and operating) of \$4.0 billion for the plant operating 20 years at a fuel reprocessing rate of 3000 metric tons of uranium (MTU) per year.[†] The least expensive process sequence involving the ceramic waste form has an estimated total cost of \$2.0 billion for the plant operating 20 years at the same fuel reprocessing rate. Thus, the ceramic waste option offers a saving of 50% relative to the estimated cost of the reference glass process.

This study included the effects on costs of variations in the waste composition, the waste form, the waste loading, the age of the waste at the time of emplacement, and repository backfill options. The high waste-loadings attainable in the ceramic waste form (60 wt. %)[§] result in the ceramic canisters having a higher heat generation rate than do the glass canisters which are limited by the chemistry of the glass to a waste loading of about 25 wt. %. The currently described repositories are designed for the thermal characteristics of the glass waste form. The consequence of the emplacement of high heat release rate canisters is that the local temperatures of the waste form, the canister, the backfill, or the repository may exceed the allowables unless the canister emplacement sites are well separated. In this study, a modified TAP (Thermal Analysis Program) code has been used to evaluate the temperatures in the repository and to determine the allowable canister emplacement density. The heat generation rates of the waste materials are based on ORIGEN code evaluations of a PWR reactor core.

*The "standard" waste form package used as the basis for economic evaluation in this report is a nominal 0.305-m (12-in.) diameter, 3.05-m (10-ft) long canister as described in much of the current waste management literature.

[†]This corresponds to the processing rate for one fully implemented AGNS fuel reprocessing plant. All cost figures reported here are based on this processing rate.

[§]Higher waste loadings are practical. This value was chosen as a reference value.

For borosilicate glass, the waste form was assumed to contain 25 wt. % waste and to have a density of 3.1 g/cm^3 . Each canister contains an amount of waste equivalent to 2 MTU (1000 kg), and generates 1.95 kW when the waste is 10 years old.* Seventeen (the maximum number of spaces available in the repository borehole) of these canisters can be emplaced in the horizontal emplacement repository (Figure A-1) and immediately backfilled with a 25% bentonite-75% basalt mixture.

For ceramic, the waste form was assumed to contain 60 wt. % waste and to have a density of 5.2 g/cm^3 . The canister contains three smaller cans containing hot isostatically pressed (HIPped) product. The canister has a waste content equivalent to 7.39 MTU and generates 7.2 kW when the waste is 10 years old.* Because of the high heat loading, only three of these canisters can be placed in a single repository borehole, and then only if the backfill emplacement is delayed. By storing these canisters 25 years to allow the heat generation rate to decrease, it is found that the maximum of 17 canisters can be emplaced (30-year-old waste), with delayed backfill.

If immediate basalt backfill is used, the 60 wt. % waste-loaded canister must be stored for 45 years before emplacement is allowed at 17 canisters per borehole. If the backfill material is 25% bentonite-75% basalt, the waste must be stored for 65 years before emplacement. The estimated costs of these three waste management options range from \$2.0 billion to \$2.2 billion, with the higher costs corresponding to the longer storage times. Although these estimated costs are among the lowest found in the study, a lower estimated cost of \$1.9 billion was found for the management scenario in which the ceramic HIP (hot isostatic press) forms were encapsulated in a heavy-walled self-shielded canister. The difference of \$0.1 billion in the 20-year total is smaller than the uncertainty in the estimated costs, so that, for practical purposes, these four cases have nominally the same estimated cost. The important difference is that these costs for the ceramic waste form are in the low \$2 billion range, while the costs for the best standard canister glass waste form are about \$4 billion.

*As used in this report, the waste age is the time after fuel element is discharged from the reactor.

In addition to examining the effects of aging and backfill options on ceramics, a parallel series of studies was carried out on the use of a mixed waste consisting of combining the high-level liquid waste (HLLW) and the intermediate-level liquid waste (ILLW) streams from a Purex plant to obtain the feed mixture for a ceramic waste form package. The intermediate-level waste is primarily inert and does not contribute an appreciable heat generation component into the mixed waste. As a result, the mixed waste has a lower canister heat generation rate.

Canisters of ceramic waste with 60 wt. % of mixed waste can be emplaced at maximum density when the waste is 15 years old and backfilling is delayed. If the canisters are immediately backfilled using 100% basalt, the waste must be 30 years old. The estimated costs for these two alternatives are \$2.2 billion and \$2.3 billion, respectively. Again, these differences are only \$0.1 billion, and the values are in the low \$2.0 billion range, which may be characteristic of ceramic waste forms that are emplaced at the optimum repository density of 17 canisters per borehole.

By reducing the waste loading of mixed waste to 53 wt. %, the canisters can be emplaced with delayed backfill when the waste is 10 years old, with an estimated cost of \$2.3 billion. This combination is attractive even though the cost is \$0.3 billion greater than that of the lowest standard ceramic waste form. It does dispose of the ILLW stream, and at a very low incremental cost compared with setting up a separate processing and disposal line. It also allows an earlier emplacement of the waste.

A disposal option was investigated using a fractionated waste (90% of the cesium and strontium and their daughters removed). At a 60% waste loading, 17 canisters can be emplaced per borehole even if 25% bentonite-75% basalt backfill is immediately installed. The estimated cost for this option is \$2.5 billion, which includes a \$0.6 billion allowance for the capital and 20-year operating costs of the fractionation plant. No credit is taken for the cesium and strontium values because the uses of these materials are highly specialized and their values are very difficult to establish.

On the other hand, the "fractionation plant" could also be designed to remove other elements from the waste stream. Rhodium (at \$70/g) and palladium (at \$30/g) are present in the waste at 390 g/MTU and 12 g/MTU, respectively. The combined potential value of these noble metals, then, is about \$200 million per year (for only one 3000-MTU/year reprocessing plant). This is a strong financial incentive, and the payoff from such a plant would be very high, even if the price of the metals were to drop substantially. No credit was taken in this analysis for the potential value of these metals.

In summary, this comparative cost study has identified several waste management scenarios involving the use of the crystalline ceramic waste form and commercial high-level waste, mixed waste, or 90% fractionated waste whose estimated capital and 20-year operation costs are in the \$2 to \$2.4 billion range. The lowest estimated cost scenarios require the use of delayed backfill, but this is not a new concept. It has been suggested as a means of providing relatively easy retrieval of the canisters. If immediate backfill is required, then the ceramic waste canisters must be stored up to 65 years to achieve a minimum cost of emplacement.

An additional cost reduction (approximately \$0.1 billion) may be achieved by the use of a self-shielded canister in conjunction with the ceramic waste form.

The waste management scenarios using the standard borosilicate glass canister allow immediate 25% bentonite-75% basalt backfill, but the total estimated capital plus 20-year operation costs are \$4.0 billion. If the glass canister diameter were to be increased from 12 to 17 in., however, the cost would be reduced to \$2.8 billion because of the marked decrease in the number of canisters required.

This optimization of the glass canister size results in a reduction of about \$1.2 billion relative to the standard canister. However, the use of the ceramic mixed waste form is still more advantageous by \$0.5 billion, and the

60 wt. % CHLW form by \$0.8 billion, per-3000 MTU/year reprocessing plant. For steady-state operation in the year 2000, seven reprocessing plants at 3000 MTU/year are projected to be required. Thus, the total rate of savings attainable by the use of the ceramic waste form compared with this optimized glass form could range from \$175 million to \$280 million per year (\$3.5 to \$5.6 billion in 20 years), depending on the ceramic system chosen.

Therefore, in view of the more advantageous costs and with the additional consideration of having a higher leach resistance, the crystalline ceramic waste form appears as a strong candidate for the management of commercial high-level waste.

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II. INTRODUCTION

Nuclear plants have been producing commercial amounts of power for the last decade, and it is anticipated that they will produce an ever-increasing fraction of the nation's energy needs. The rate of expansion will be less than that originally expected, but even at a low expansion rate, the amount of power produced is sizable. This expectation produces the continuing problem of the disposal of the spent fuel. Policies in force during the last several years have resulted in the accumulation of spent fuel elements at reactor sites, and this problem will worsen until a procedure for nuclear waste disposal is adopted and implemented. One solution that has been under serious study is to directly encapsulate the fuel pins in suitable canisters and to place them in an engineered repository. It has the disadvantage of making the contained fuel values more inaccessible, although the requirement for retrievability mitigates the problem.

A second solution, which is the basis of the study reported herein, is to reprocess the fuel elements and recover their uranium and plutonium. The reprocessing plant's effluent nuclear waste would, either immediately or at a planned later date, be immobilized in a solid waste form that is suitable for emplacement in an engineered repository. This approach has at least two advantages in that valuable nuclear fuel material can be conserved, and the waste material can be put in a chemically stable, highly leach-resistant form. This satisfies the essential need of any nuclear waste disposal process, i.e., that the nuclear waste as emplaced will remain in situ such that none of the nuclear products will enter the biosphere and become a hazard to man.

It is also of interest to note that several of the fission product decay chains produce valuable materials. This leads to a third advantage of reprocessing the spent fuel, that is, of having the option of recovering valuable noble metals, such as rhodium and palladium, as well as those with heat source or radiation use potential, such as strontium and cesium.

During the past 10 years, a substantial effort has been carried out to find a waste form that is economically producible, chemically stable, and highly leach resistant. The bulk of this effort has been directed toward the development of a borosilicate glass. Recently, an effort was mounted to investigate other waste forms as alternatives to glass. A number of candidates were evaluated, with the result that waste elements that are contained as primary constituents of crystalline phases have been shown to have superior leach resistance, higher allowable waste loadings, and higher densities than the standard borosilicate glass forms. These properties make it possible to load more waste into a given-sized canister, with the result that the overall cost of disposing of the waste can presumably be reduced.

Concurrently, during the past 2 years, the glass process has been improved and simplified so that fewer process operations are required to produce the glass product. A similar improvement has been accomplished in the process studies of the crystalline ceramic process so that the two processes are now comparable in complexity. As a result, the conclusions reached in earlier reports⁽¹⁻⁹⁾ are no longer valid because the crystalline form process was heavily penalized for complexity and early-stage development. Even then, it was recognized that the crystalline form's higher waste-loading potential would result in markedly reduced costs of transporting, packaging, and emplacement of waste canisters.

This study evaluates the costs of several waste disposal scenarios involving glass and crystalline waste forms in reference-sized canisters, using a variety of processing alternatives, waste storage options, and repository/emplacement options in an effort to find a viable waste disposal process and handling sequence that offers the minimum total waste disposal cost for reprocessed commercial high-level nuclear waste.

III. THE CERAMIC WASTE FORM

Ceramics are crystalline-phase assemblages with the same or similar phases as natural minerals that have endured geologic conditions for millions of years, often under high temperatures and high pressures. Thus, ceramic waste forms should be capable of isolating the waste radionuclides from the environment for similarly long periods under the geologic conditions of a repository. The Department of Energy has conducted a survey of naturally occurring minerals that have maintained their integrity for geologic times by resisting weathering or dissolution and that occur naturally in igneous, sedimentary, metamorphic, or placer deposits. These minerals are potential hosts for radionuclides. In general, several different minerals can be used to immobilize radionuclides for biosphere isolation. This has led to different mineral assemblages for different nuclear wastes. In general, the Synroc ceramics developed by the Australian Atomic Energy Agency and Lawrence Livermore National Laboratory consist of titanium-based minerals, while the mineral assemblages proposed by Rockwell are iron-aluminum-based ceramics.

A. DEFENSE AND COMMERCIAL WASTE COMPOSITIONS

In the Rockwell approach, the host phases for radionuclides are determined by the major components of the waste, which in general are the nonradioactive chemicals added during reprocessing. The variation in chemical composition of defense high-level radioactive wastes is illustrated in Table 1, where the composition of major elements in Savannah River Plant (SRP) waste is given with and without alumina removal. Partial sodium and alumina removal is planned in the glassification program. Except for uranium, the radioactive portion of the waste is less than 1%; the major components are reprocessing and neutralization chemicals.

TABLE 1
TYPICAL COMPOSITIONS OF SAVANNAH RIVER PLANT DEFENSE WASTE CALCINES⁽¹⁰⁾

Component	Major Elements Only					
	Without Al Removal (wt. %)			With Al Removal (wt. %)		
	High Fe	Composite	High Al	High Fe	Composite	High Al
Fe ₂ O ₃	57.17	36.13	5.32	55.90	47.16	14.80
Al ₂ O ₃	4.89	28.26	76.05	1.29	9.24	50.77
MnO ₂	3.56	9.94	4.37	3.74	12.98	12.16
U ₃ O ₈	12.34	3.26	1.28	12.98	4.25	3.57
CaO	3.62	2.69	0.35	3.80	3.51	0.97
NiO	9.08	4.47	0.78	9.54	5.84	2.17
SiO ₂	0.40	0.85	0.56	<0.40	1.12	1.57
Na ₂ O	4.52	5.08	1.96	4.75	6.63	5.41
Na ₂ SO ₄	<0.50	0.93	<0.50	<0.50	1.21	<0.50
Ion-Siv IE-95*	8.82	8.93	9.33	8.00	8.05	8.58

*Mixture of CaAl₂Si₄O₁₂·6H₂O and (NaKCa)₃Al₃Si₈O₂₄·8H₂O

Similarly, the major component of commercial waste is the soluble nuclear poison gadolinium. Anticipated liquid waste compositions and volumes from the reprocessing of spent commercial PWR fuels with 33,000-MWd/MTU burnup, 3.84 MW/MTU specific power, and 3.1% enrichment, and after 5-years' decay, are given in Table 2.

B. CERAMIC PHASE ASSEMBLAGES

Rockwell's approach to the design of the ceramic form was to base the final ceramic phase assemblage on those naturally occurring stable phases that the waste elements, including the nonradioactive components, most readily form. This

TABLE 2
COMMERCIAL HIGH-LEVEL LIQUID AND INTERMEDIATE-LEVEL
LIQUID WASTE COMPOSITIONS

	HLLW		ILLW
	Nominal	Minimum	
Fission products less I (g/l)	67.67	45.07	
Iodine at 0.5% (g/l)	0.0032	0.0022	0.0043
Uranium at 0.5% loss (g/l)	12.69	8.45	16.91
Plutonium at 0.5% loss (g/l)	0.117	0.076	0.152
Other actinides (g/l)	1.75	1.17	0.0035
Soluble poison (g/l)	64.22	42.77	
Nitric acid (M)	4-7	4-7	2.5
Total nitrate at max. HNO_3	10.54	9.25	3.5
Phosphate (g/l)	0.45	0.30	23.0
Shear fines (g/l)	0.66	0.44	
Corrosion products (g/l)	0.65	0.43	0.17
Chloride (g/l)	0.053	0.035	0.32
Sodium [potassium] (g/l)			17.64 [0.36]
Manganese (g/l)			0.5
Sulfate (g/l)			0.11
Decay heat (watts/l)	3.13	2.51	0.012
Est. insoluble solids (g/l)	14.6	9.7	2.0

approach increased the waste loading available in the ceramic while significantly simplifying the required processing control. An example of this approach was the "high alumina" ceramic form produced from simulated Savannah River Plant "high Al composition" waste. The ceramic was composed of 90 wt. % waste oxide components and consisted of only three natural phases: uraninite, hercynite spinel, and magnetoplumbite, all natural minerals. This material showed the best overall leach and mechanical impact resistance of all waste forms tested in the 1981 Alternate Waste Form Peer Review Panel evaluation.⁽⁷⁾ This same approach, when

applied to the SRP "high Fe" and "composite" waste compositions, produced a form able to accommodate 50 to 70 wt. % waste at a density of 4 g/cm^3 with only four phases: nepheline, spinel (hercynite-magnetite), uraninite, and magnetoplumbite.

Similar results were obtained in Synroc ceramics by modifying the original Synroc assemblage as the waste dictated. The final Synroc-D form contained two of the Rockwell phases, nepheline and spinel, and two of the original Synroc phases, perovskite and a modified zirconolite, also at a waste loading of about 60 wt. %.

The final phase assemblage for defense waste represents the best combination of the Rockwell and Synroc forms. It has demonstrated a leach resistance 100 to 1,000 times superior to borosilicate glass for uranium and has three times the waste loading in the waste form.⁽¹¹⁾ Moreover, it was demonstrated that great flexibility in redox control and consolidation conditions greatly reduces the process complexity. The leach resistance of the ceramic forms and their dissolution mechanisms have also been studied in depth at Rockwell Science Center.⁽¹²⁾ The findings indicate that the ceramic forms would have actinide retention over geologic time scales even under hydrothermal conditions.

Rockwell has been applying this same approach in ceramic design to commercial waste compositions. In contrast to the Australian efforts in which only fission products are incorporated into the Synroc forms, Rockwell has designed and is testing a ceramic form for the reference Barnwell AGNS reprocessed waste stream. This waste stream consists of about 48 wt. % nonradioactive material such as oxides (Gd_2O_3 , Na_2O , P_2O_5 , etc.) in addition to the fission products and actinide elements. The current Rockwell form contains only three major phases, rutile, pyrochlore, and perovskite, and uses titanium as a main additive. This waste form is capable of extremely high waste loadings (about 70 wt. %) and densities of 5.0 to 5.4 g/cm^3 and is exhibiting superior leach resistance in current laboratory testing for radionuclides.

C. ACID WASTE CERAMIC FLOW DIAGRAM AND PROCESS LAYOUT

Most of the high-level waste in the United States has been neutralized to permit storage in carbon steel tanks until a waste immobilization process and permanent repository are developed. Eventually, high-level waste streams will be processed directly without neutralization and storage. Since the high-level waste stream coming from the reprocessing plant is highly acidic (approximately 2 M HNO_3), a waste immobilization process capable of handling acid wastes will be required. Therefore, an acid CHLW ceramic flowsheet and layout were developed.

1. Design Parameters

The acid waste for a typical Purex 3000-MTU/year reprocessing plant was used for this design. This will be the capacity of the Allied General Nuclear Services plant at Barnwell, South Carolina, when it is in full operation. The projected waste stream composition from this plant, as described in PNL 3838,⁽¹³⁾ was used. The design criteria are given in Table 3:

TABLE 3
DESIGN VALUES USED FOR GLASS AND CERAMIC PLANTS IMMOBILIZING WASTE FROM A
3000-MTU/YEAR COMMERCIAL REPROCESSING PLANT*

	HLLW		HLLW + ILLW	
	Glass	Ceramic	Glass	Ceramic
Waste oxide production rate (kg/day)	658	658	869	869
Added tailoring agents (kg/day)	1974	439	2607	579
Total oxide (kg/day)	2632	1097	3476	1448
Canister capacity (kg)	525	810	525	810
Canister production rate (canisters/day)	5.00	1.35	6.62	1.79
Waste per canister (MTU/canister)	2.0	7.4	1.5	5.6
Heat per canister, 5-yr decay (kW/canister)	3.2	12.0	2.4	9.0
Heat per canister, 10-yr decay (kW/canister)	1.9	7.2	1.4	5.4

*Immobilization in the standard 0.305-m (12-in.) ID by 3.05-m (10-ft) long canister.

2. Process Flow Diagram

As shown in Figure 1, the high-level waste and tailoring additives are mixed directly and fed to the fluidized-bed calciner. The larger calcined granules are withdrawn from the fluidized bed into the HIP canister and compacted by vibration of the HIP can and connecting tube. The vibrapacked HIP cans are heated, evacuated, and sealed by crimping and welding the fill-and-evacuation tubes.

The sealed HIP cans are decontaminated by a high-pressure water spray wash, dried, and smeared to verify decontamination. The decontaminated HIP cans are then transferred to the transfer cell. All activity is sealed within these HIP cans so that subsequent processing will not generate off gas or allow the spread of contamination.

The HIP cans are transferred to the HIP cell. Three of them are placed into each of two HIP unit baskets. Two baskets are placed in each HIP unit, one above the other. The HIP units are sealed, pressurized to $1.27\text{E}7 \text{ N/m}^2$ (2500 psi), and heated to 1100°C . The increased temperature causes the HIPping pressure to rise well above the desired $6.89\text{E}7 \text{ N/m}^2$ (10,000 psi). The cans are maintained at 1100°C and $6.89\text{E}7 \text{ N/m}^2$ (10,000 psi) for about 15 to 30 min and are allowed to cool. When the temperature reaches approximately 300°C , the pressure is released and the HIP units are opened. The HIPped cans are transferred to the QA area. Dual HIP units are provided to allow adequate heatup and cooldown times.

The HIPped cans are measured to assure that the required density has been obtained. The cans are placed three deep in an external canister, which is sealed, decontaminated by a high-pressure water spray, dried, and smeared to assure decontamination. The sealed canisters are then placed in the transfer cell and transferred to storage.

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Figure 1. Flow Diagram for Ceramic Preparation of Acid Wastes

3. Process Layout

The ceramic process layout for acid waste is given in Figure 2 and consists of five major cells: (1) processing cell, (2) decontamination cell, (3) maintenance cell, (4) HIPping cell, and (5) HIP gas recovery cell. The overall dimensions of the processing canyon are 45.7 m (150 ft) long by 11.6 m (38 ft) wide, including the 1.22-m (4-ft) thick canyon walls, for a total area of 530 m² (5700 ft²). The off-gas processing system is identical to that given for the modified ceramic layout for neutralized defense waste (see Figures 3 and 4) and requires 233 m² (2508 ft²). In addition, the HIP gas recovery system requires an area of about 50 m² (532 ft²). The total area required is thus 813 m² (8740 ft²).

4. Off-Gas Process and Cell Layout

The off-gas from the fluidized-bed calciner is quenched and water scrubbed. The off-gas then passes through a condenser, an evaporator, a demister, a gas preheater, and a sintered metal filter prior to leaving the high-level canyon (see Figure 3). The off-gas is transferred to the off-gas processing cell for further decontamination prior to release to the atmosphere. The scrubber slurry and the evaporator still bottoms are returned to the recycle feed tank for subsequent recycle to the calciner.

In the low-level, contact maintenance, off-gas processing cell, the gas passes through a condenser, an evaporator, a demister, a gas heater, prefilters, ruthenium and iodine traps, and HEPA filters. The decontaminated gas is then forced through a heated, catalyzed NO_x destruction bed prior to dilution with ventilation air and release to the stack.

The off-gas processing cell layout is shown in Figure 4. The cell is designed so that it can be contact maintained. Redundant prefilter-HEPA filter systems and blowers are provided to permit continuous operation during maintenance of the other systems. Including the 0.61-m (2-ft) thick concrete shielding, the cell is 20.12 m (66 ft) long by 11.58 m (38 ft) wide, or 233 m² (2508 ft²).

Figure 2. Layout of Ceramic Process for Commercial (Acid) Wastes

Figure 3. Flowsheet for Modified Ceramic Process Off-Gas System

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Figure 4. Layout of Off-Gas System

D. NEUTRALIZED WASTE CERAMIC PROCESS

The ceramic process for neutralized waste is essentially the same as that for acid waste except for some additional preprocessing steps. The preprocessing steps would vary with the waste being processed. As an example, the Savannah River Plant waste has been neutralized and contains mercury, sand, and molecular sieve particles. One method of processing this waste would be to incorporate a washing step to remove a large fraction of the sodium, a reduction step to reduce the mercury to the metallic state (for purification and recovery), and a mill to reduce the size of the sand and sieve particles. Alternatively, these sand and HIP particles could be added directly to a HIP can without size reduction and processed into a nepheline ceramic phase. This system is described in detail by Grantham et al.⁽¹¹⁾

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IV. WASTE MANAGEMENT OPTIONS

A. IMPACT OF LEACH RATE ON RADIONUCLIDE RELEASE TO THE BIOSPHERE

Immobilization and burial in a deep geologic repository is an attractive method for disposal of high-level radioactive wastes.⁽¹⁴⁾ Candidate repositories include granite, bedded salt, basalt, shale, and tuff.⁽¹⁵⁾ Sites with these minerologies will be selected with minimal present and projected future water content, ground water flow, tectonic activity, and economic value (to minimize human intrusion).

A disposal system embodying the multiple-barrier concept⁽¹⁶⁾ calls for an engineered barrier surrounding the waste form in the repository to prevent or delay attack by ground water, to modify the ground water to minimize waste form dissolution, and to retard transport of radionuclides into the repository by the ground water. Such a concept is desirable since there will remain some degree of uncertainty in the capacity of the repository itself as well as of the barrier and of the waste form to function as projected, especially when such projections involve a million years.⁽¹⁵⁾

Waste form requirements^(4,7) generally include (1) immobilization of the radionuclides of concern, (2) stability toward mechanical, thermal, radiation, and transmutation process stresses, and (3) stability toward release of radionuclides through reaction with any repository ground water, host rock, or engineered barrier material. Benefits from a superior waste form are enhanced safety (in regard to preventing radionuclide release) in transportation to and emplacement in a repository, and lower radionuclide release rates during geologic storage. The effect of this release rate on radionuclide release to the biosphere is considered below.

1. Transport of Radionuclides to the Biosphere

The most likely path for radionuclide release to the biosphere is by ground water flow through the repository where it contacts the waste form.⁽¹⁷⁾ Future

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intrusion by man, drilling of wells, mining of minerals, or exploration may occur, permitting direct release of the radionuclide-containing solids or exposure of these solids to waters used for consumption.⁽¹⁸⁾ Natural geologic events, such as earthquakes or volcanic eruptions, could likewise result in exposure of the waste solids. Proper site selection can minimize, but never eliminate, the danger of such sudden radionuclide release. A high-integrity waste form will minimize the hazards attendant on such release.

Although repositories will be selected in areas where there is little, if any, ground water flow through the region in which the waste form packages (form plus engineered barriers) are emplaced, such ground water flow must be considered as possible at some time in the period of concern (up to 10^6 years). While some specialists⁽¹⁴⁾ discount any significant delay offered by the engineered barrier to ground water contact with the waste form, most experts assume,^(18,19,20) and the NRC may require, that the barrier does delay contact for a thousand years (Draft 10 CFR 60).

The inevitable contact will result in leaching of the radionuclides from the form in a potentially complex process involving the ground water, the form, the barrier, and the host rocks. The radionuclides ending up in solution enter the repository; solubility limitations, sorption, and dispersion (axial and transverse) may occur, delaying and modifying the radionuclide's exit from the repository. During this time, the radionuclides will decay, with some TRUs producing radioactive daughters of concern.

The radionuclides potentially of concern include fission products, TRUs, and decay products.^(18,20) Short-lived fission products (e.g., Cs-137 and Sr-90) will have decayed to such a low level during the 10^3 -year isolation period that they do not present an appreciable hazard. Radionuclides that decay by beta or alpha emissions are particularly hazardous to man because they cause a large amount of ionization in a few cells of the body. Long-lived fission products and other light species (Tc-90, I-129, C-14), TRUs (U-234, Np-237, Pu-239, Am-241), and decay products (Th-230, Ra-226, Ra-225) pose potential hazards.

The hazards from these radionuclides are based on their quantity, toxicity, and release rate from the repository.⁽¹⁸⁾ A specific measure incorporating these parameters is the "Water Dilution Rate," which is the rate of discharge (expected or actual) of the radionuclide divided by its maximum permissible drinking water concentration.⁽²⁰⁾ Others⁽²¹⁾ use 10 CFR 20 rather than drinking water standards but with the same general results.

2. Modeling

There are three major barriers to the transport of the radionuclides from the buried waste form to the biosphere:

- 1) The waste package itself (form plus engineered barrier)
- 2) The actual ground water flow rate, which can be rather low
- 3) Release rates from the waste form, solubility limits in the ground water, and sorption of the radionuclide by the repository rock (or soil).

In order to predict the behavior of the system over the million-year period of concern, each "barrier" process is evaluated to determine the barrier mechanism(s) involved. Models are developed which describe transport and retention phenomena. Waste form leaching mechanisms and corresponding modeling efforts are under study under the guidance of the MCC (Materials Characterization Center) for the DOE.⁽²²⁾ Repository modeling has been widely done with considerable degrees of sophistication.^(18,21,23) In all cases, simplifying assumptions are made, e.g., release rate patterns (constant or otherwise) are assumed, ground water flow rates are generally held constant, and the effects of jointing and bedding with interlayers of other mineralogy are not included. In one case, repository failures leading to radionuclide flow into a fast-moving aquifer were considered,⁽²¹⁾ but few such studies have been reported. This modeling effort is of great value, even essential, to estimate the potential future hazard involved. However, an irreducible level of uncertainty will remain. This level of uncertainty will be greater for the repository subsystem, which cannot be fully and completely investigated, than for the waste form or the engineered barrier, which can be fully characterized for real-time periods.

Repository models do not account for intrusion and catastrophies, which are unlikely, but possible. Under these scenarios, the best assurance of waste isolation is a well-designed waste form and waste barriers.

a. Effects of Decay Chains

Even with separation of uranium and plutonium during reprocessing, about 0.5% of these, including Pu-238 and U-234, remain along with all the Am and Cm. Am-242 decays to Cm-242, which in turn yields Pu-238 and then U-234. U-238 yields U-234, then Th-230, and then Ra-226. Because of its high toxicity and low sorption, Ra-226 constitutes one of the relatively major long-term hazards. Np-237, which yields U-233, then Th-229, and then Ra-225, is also a hazard for similar reasons. These radium isotopes, being generated continuously, show parametric behavior different from most hazardous radionuclides (see below).

b. Effect of Isolation Distance Time Delay in Dissolution and Dissolution Rate

For the leach time and water velocity shown, Pigford⁽²⁰⁾ has evaluated peak water dilution rates (WDRs) for hazardous radionuclides from HLLW for various migration distances as shown in Figure 5. It is seen that, for distances beyond one kilometer, the peak water dilution rates are constant with that of I-129 > Np-237 > Ra-226 > Tc-99 > Ra-225.

Figure 5 also shows the effect of a 1000-year delay in dissolution compared with immediate start of dissolution. While the effect is noticeable for some of these hazardous species near the waste form, it is negligible at ~1 km and beyond.

For a water travel time (migration distance x water velocity) of 100 years, the effect of leach period (reciprocal of dissolution rate) on the water dilution rate for hazardous species is shown in Figure 6. For radionuclides that are not decay daughters, the water dilution rate is proportional to the (assumed uniform) leach time. Only for leach times of $\sim 10^5$ years or longer does the hazard (water dilution rate) from a decay daughter exceed those from waste-contained radionuclides.

Figure 5. Peak Water Dilution Rates from High-Level Waste⁽²⁰⁾

Some species are of such low solubility that even their saturated solutions meet drinking water standards. For a neutral pH water with negligible CO_2 and O_2 , Np solubility is about 10^{-11} M. This corresponds to about $1.7 \times 10^{-9} \text{ Ci/m}^3$ of Np-237, compared with the allowed $3 \times 10^{-6} \text{ Ci/m}^3$.

Some species are so strongly sorbed by repository media (rock or soil) that they decay to harmless levels before they migrate from the repository. Pu-239, with a 24,400-year half-life and a permissible concentration of $5 \times 10^{-6} \text{ Ci/m}^3$, but with a sorption constant (water flow velocity/species migration velocity) of $\sim 10^4$ and low solubility, poses a relatively low hazard.

Figure 6. Effect of Dissolution Time

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3. Conclusions

Within the system — waste form, engineered barrier, repository — the form leach rate does show a direct impact on the projected biological hazard. With careful site selection, the repository medium, by excluding ground water or permitting it only at low-flow velocities and by sorption of many radionuclides, can provide a substantial barrier to transport to the biosphere. However, the modeling projections do not take into account many repository "defects" (jointing, bedding, etc.), and completely ignore hazards from intrusion and catastrophes. Accordingly, with the resulting uncertainties, an increased burden is placed on the waste form plus engineered barrier.

Based on these and other factors, the effort to develop a superior waste form is warranted. The cost to develop such a superior form would be only a small part of the overall system development cost. Such a form would add to the technical basis for confidence in the disposal system. It would also find public acceptance, which depends on using the best available form.

B. DESCRIPTION OF THE WASTE MANAGEMENT OPTIONS

The higher waste loading (up to 90 wt. %) and density (up to 5.6 g/cm^3) of ceramic nuclear waste forms provide many waste management options not available to the borosilicate glass reference waste form, which is limited to densities of about 3.2 g/cm^3 and waste loadings of about 30 wt. % to avoid separate phase formation during vitrification. This permits the evaluation of ceramic waste management options that would not be cost effective or not available for glass waste forms.

To evaluate the economic options available for ceramic waste management, typical ceramic and glass waste loadings and densities were chosen, namely, up to 60 wt. % and 5.2 g/cm^3 for ceramics, and 25 wt. % and 3.1 g/cm^3 for glass. Management of the waste produced by a typical large fuel reprocessing plant (3000 MTU/year) for the 20-year life of a well-built and maintained chemical processing plant was selected for this evaluation. PWR fuel, having 32,700 MWd/MTU burnup as described in PNL 3838,⁽¹³⁾ was used for this evaluation. It was assumed that all fuel was stored at the reactor site for 5 years before these waste management options applied. The latest BWIP repository design of 3.05-m (10-ft) high by 6.1-m (20-ft) wide drifts, 61 m (200 ft) apart, with horizontal emplacement of canisters in holes drilled 32.6 m (107 ft) apart between the drifts was used. Normally, these boreholes would contain 17 canisters of glass. The repository thermal limitations for various emplacement arrays of canisters of ceramic were evaluated, and the number of canisters of ceramic that could be placed in these holes without exceeding the repository thermal limitations was calculated using the TAP (Thermal Analysis Program) code. Optional strategies for reducing heat loading in the ceramic to acceptable repository levels were developed using AFR storage, HLLW storage, near-surface canister storage, waste fractionation, and dilution. The waste management options and canister loadings in the repository were then used as the basis for calculating waste management costs.

A summary of the scenarios evaluated is given in Table 4. The first column lists the case number that will be used in the waste management scenarios to graphically illustrate the waste management option being evaluated and is used in the economics section (Section VII) to describe the costs associated with the waste management options.

The second column in Table 4 lists the waste form used in the evaluation, i.e., glass or ceramic. The third column lists the type of waste, i.e., commercial high-level waste, mixed high-level liquid waste and intermediate-level liquid waste, and fractionated waste with 90% of the cesium and strontium isotopes removed. Fractionated waste was studied because removal of strontium and cesium removes a large fraction of the short-term decay heat and provides these isotopes for beneficial use, such as gamma radiation sources and thermal-electric batteries. High-level liquid waste is defined as that raffinate produced in the extraction of uranium and plutonium from 32,700-MWd/MTU burnup fuel concentrated to 378.5 liters/MTU. Intermediate-level waste is the raffinate produced in the cleanup of the extractant and solvent for recycle.

The fourth column gives the waste loadings in wt. % of the final waste form. For glass only, the upper value of 25 wt. % was studied. For ceramic, the upper value of 60 wt. % was used in Cases 5 through 10, 15 through 27, and 29 through 33. In the other ceramic cases evaluated, lowered waste loadings were considered.

The type of storage used in each evaluation is shown in the sixth column. Spent fuel element (SFE) storage, high-level liquid waste (HLLW) storage in stainless steel tanks, and near-surface storage of canisters are the storage methods considered. The age of the waste (decay time after removal from the reactor) when the waste is emplaced in the repository is given in the seventh column in Table 4. The repository backfill (D = delayed backfill, B/B = 25% bentonite-75% basalt, and B = 100% basalt) is given in Column 8. The amount of waste from the specified number of MTU in spent fuel contained in each canister is given in Column 9. The number of canisters per year, which are produced at a 3000-MTU/year reprocessing plant rate and which would have to be emplaced in the repository annually without accumulating canisters in storage, is shown in

TABLE 4
SUMMARY OF SCENARIOS EVALUATED

Case	Waste Form	Waste Material	Waste Loading (%)	Time in Storage ^a (year)	Stor. Med.	Age at Burial	Backfill ^b	MTU per Can	Cans per Year	Cans per Hole	MTU per Hole	Initial kW per Hole
1	Glass	CHLW	25	0	NA	5	D	2	1,500	17	34	55
2	Glass	CHLW	25	5	SFE	10	B/B	2	1,500	17	34	33
3	Glass	CHLW	25	5	Can	10	B/B	2	1,500	17	34	33
4	Glass	CHLW	25	5	HLLW	10	B/B	2	1,500	17	34	33
5	Ceramic	CHLW	60	5	SFE	10	D	7.39	406	<4 ^d	<30	<29
6	Ceramic	CHLW	60	5	Can	10	D	7.39	406	<4 ^d	<30	<29
7	Ceramic	CHLW	60	5	HLLW	10	D	7.39	406	<4 ^d	<30	<29
8	Ceramic	CHLW	60	15	Can	20	D	7.39	406	8	59	42
9	Ceramic	CHLW	60	20	Can	25	D	7.39	406	13	96	60
10	Ceramic	CHLW	60	25	Can	30	D	7.39	406	17	126	69
11	Ceramic	CHLW	48	5	Can	10	D	5.91	507	4	24	23
12	Ceramic	CHLW	45	5	Can	10	D	5.54	541	10	55	54
13	Ceramic	CHLW	40	5	Can	10	D	4.93	609	17	84	82
14	Ceramic	CHLW	35	5	Can	10	D	4.31	696	17	73	71
15	Ceramic	CHLW	60	25	Can	30	B	7.39	406	<4 ^d	<30	<16
16	Ceramic	CHLW	60	35	Can	40	B	7.39	406	13	96	42
17	Ceramic	CHLW	60	45	Can	50	B	7.39	406	17	126	44
18	Ceramic	CHLW	60	45	Can	50	B/B	7.39	406	<4 ^d	<30	<11
19	Ceramic	CHLW	60	55	Can	60	B/B	7.39	406	13	96	27
20	Ceramic	CHLW	60	65	Can	70	B/B	7.39	406	17	126	29

TABLE 4
SUMMARY OF SCENARIOS EVALUATED
(Continued)

Case	Waste Form	Waste Material	Waste Loading (%)	Time in Storage ^a (year)	Stor. Med.	Age at Burial	Backfill ^b	MTU per Can	Cans per Year	Cans per Hole	MTU per Hole	Initial kW per Hole
21	Ceramic	Mixed	60	5	Can	10	D	5.60	537	8	45	44
22	Ceramic	Mixed	55	5	Can	10	D	5.12	585	14	72	70
23	Ceramic	Mixed	53	5	Can	10	D	4.94	608	17	84	81
24	Ceramic	Mixed	60	10	Can	15	D	5.60	537	17	95	77
25	Ceramic	Mixed	60	15	Can	20	B	5.60	537	<4 ^d	<22	<16
26	Ceramic	Mixed	60	20	Can	25	B	5.60	537	8	45	28
27	Ceramic	Mixed	60	25	Can	30	B	5.60	537	17	95	52
28	Glass	Mixed	25	5	Can	10	B/B	1.51	1,983	17	26	25
29	Ceramic	Mixed	60	35	Can	40	B/B	5.60	537	<4 ^d	<22	<10
30	Ceramic	Mixed	60	40	Can	45	B/B	5.60	537	5	28	11
31	Ceramic	Mixed	60	45	Can	50	B/B	5.60	537	17	95	33
32	Ceramic	90%	60	5	Can	10	B/B	7.82	384	17	133	31
33	Ceramic	CHLW ^c	60	25	Can	30	D	7.39	406	17	126	69
34	Glass	CHLW	25 ^e	5	Can	10	D	4.00	750	17	68	66

^aTime in Storage — Fuel elements are stored 5 years at the reactor. This time is the additional time of storage in a separate facility.

^bBackfill — D = delayed; B/B = 25% bentonite-75% basalt; B = 100% basalt.

^cSelf-shielded canister.

^dThermal calculations showed 4 canisters/hole to exceed the allowable limitations. Cost evaluations have been made using 3 canisters/hole.

^eOptimized canister size, 17-in. waste form diameter.

Column 10. The number of canisters that are emplaced per hole without exceeding any of the thermal limitations given in Appendix A is given in Column 11. The waste from the specified MTU that is placed in each repository hole is given in the next to last column, and the amount of heat (kW) in the waste that is placed in each repository hole when initially emplaced is given in the last column in Table 4.

For example, in Case 5, commercial high-level waste immobilized in ceramic at 60 wt. % waste loading that has been stored for 10 years (five at the reactor site and five away from the reactor site) as spent fuel elements before immobilization was placed in the repository at <4 canisters, <30 MTU, or <29 kW per hole with delayed backfill. Case 2 is the same as Case 5, except glass is the waste form, and the canisters are emplaced at 17 canisters, 34 MTU, or 33 kW per hole, and the hole is backfilled with 25% bentonite-75% basalt at emplacement.

C. GRAPHICAL PRESENTATION OF WASTE MANAGEMENT SCENARIOS

Graphical presentations of the waste management scenarios are given in Figures 7 through 13. The arrows joining the boxes describe the general waste management route from reactor spent fuel element storage to repository emplacement for the scenarios listed below each figure. The listings show the case number and the particulars of each processing step. For reprocessing, the waste age and the waste product are shown. For immobilization, the waste age, the waste form, and the waste loading are shown. For canister packaging, the waste age is shown. For emplacement, the waste age, the type of backfill, the number of canisters placed per borehole, and the number of MTU per borehole are shown. For the fractionation process, the waste age and the degree of Cs and Sr removal are shown. For the interim storage steps, the waste age at entry and at discharge are shown. The backfill conditions are designated as D for delayed backfill, i.e., the canister is emplaced without backfill and will remain until some later date.* The symbol B represents an immediate backfill with crushed basalt, and the symbol B/B represents an immediate backfill with a 25% bentonite-75% basalt mixture.

*One of the advantages of delayed backfill is the ease of canister retrievability. The method for accomplishing the backfill at the later time is not yet specified. In reality, it may be difficult to backfill without leaving voids. In boreholes having several (up to 17) canisters, no penalty for delayed backfill has been assessed in this cost analysis.

CASE	REPROCESSING		IMMOBILIZATION			PACKAGING	EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE (YR)	WASTE AGE (YR)	BACKFILL	CANS PER HOLE	MTU PER HOLE
1	5	CHLW	5	GLASS	25	5	5	D	17	34

Figure 7. Direct Glassification Scenario

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Figure 8. AFR Storage Scenarios

CASE	REPROCESSING		IMMOBILIZATION			STORAGE		PACKAGING	EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE ENTRY (YR)	WASTE AGE DIS-CHARGE (YR)	WASTE AGE (YR)	WASTE AGE (YR)	BACK-FILL	CANS PER HOLE	MTU PER HOLE
3	5	CHLW	5	GLASS	25	5	10	10	10	B/B	17	34
6	5	CHLW	5	CERAMIC	60	5	10	10	10	D	3	22
8	5	CHLW	5	CERAMIC	60	5	20	20	20	D	8	59
9	5	CHLW	5	CERAMIC	60	5	25	25	25	D	13	96
10	5	CHLW	5	CERAMIC	60	5	30	30	30	D	17	126
11	5	CHLW	5	CERAMIC	48	5	10	10	10	D	4	24
12	5	CHLW	5	CERAMIC	45	5	10	10	10	D	10	55
13	5	CHLW	5	CERAMIC	40	5	10	10	10	D	17	84
14	5	CHLW	5	CERAMIC	35	5	10	10	10	D	17	73
15	5	CHLW	5	CERAMIC	60	5	30	30	30	B	3	22
16	5	CHLW	5	CERAMIC	60	5	40	40	40	B	13	96
17	5	CHLW	5	CERAMIC	60	5	50	50	50	B	17	126
18	5	CHLW	5	CERAMIC	60	5	50	50	50	B/B	3	22
19	5	CHLW	5	CERAMIC	60	5	60	60	60	B/B	13	96
20	5	CHLW	5	CERAMIC	60	5	70	70	70	B/B	17	126
34	5	CHLW	5	GLASS*	25	5	10	10	10	D	17	68

*CANISTER DIAMETER, 17 INCHES ID

9441-25

Figure 9. Near-Surface Storage Scenarios – CHLW

CASE	REPROCESSING		STORAGE		IMMOBILIZATION			PACKAGING	EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE ENTRY (YR)	WASTE AGE DIS-CHARGE (YR)	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE (YR)	WASTE AGE (YR)	BACK-FILL	CANS PER HOLE	MTU PER HOLE
4	5	CHLW	5	10	10	GLASS	25	10	10	B/B	17	34
7	5	CHLW	5	10	10	CERAMIC	60	10	10	D	3	22

Figure 10. HLLW Storage Scenarios

9441-26

CASE	REPROCESSING		IMMOBILIZATION			STORAGE		PACKAGING	EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE ENTRY (YR)	WASTE AGE DIS-CHARGE (YR)	WASTE AGE (YR)	WASTE AGE (YR)	BACK-FILL	CANS PER HOLE	MTU PER HOLE
21	5	MIXED	5	CERAMIC	60	5	10	10	10	D	8	45
22	5	MIXED	5	CERAMIC	55	5	10	10	10	D	14	72
23	5	MIXED	5	CERAMIC	53	5	10	10	10	D	17	84
24	5	MIXED	5	CERAMIC	60	5	15	15	15	D	17	95
25	5	MIXED	5	CERAMIC	60	5	20	20	20	B	3	16
26	5	MIXED	5	CERAMIC	60	5	25	25	25	B	8	45
27	5	MIXED	5	CERAMIC	60	5	30	30	30	B	17	95
28	5	MIXED	5	GLASS	25	5	10	10	10	B/B	17	26
29	5	MIXED	5	CERAMIC	60	5	40	40	40	B/B	3	16
30	5	MIXED	5	CERAMIC	60	5	45	45	45	B/B	5	28
31	5	MIXED	5	CERAMIC	60	5	50	50	50	B/B	17	95

Figure 11. Near-Surface Storage Scenarios — Mixed Waste

9441-27

CASE	REPROCESSING		FRACTIONATION		IMMOBILIZATION			STORAGE		PACKAGING	EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE ENTRY (YR)	WASTE AGE DIS-CHARGE (YR)	WASTE AGE (YR)	WASTE AGE (YR)	BACK-FILL	CANS PER HOLE	MTU PER HOLE
32	5	CHLW	5	90%	5	CERAMIC	60	5	10	10	10	B/B	17	133

Figure 12. Fractionation Scenario

CASE	REPROCESSING		IMMOBILIZATION			PACKAGING	STORAGE		EMPLACEMENT			
	WASTE AGE (YR)	WASTE PRODUCT	WASTE AGE (YR)	WASTE FORM	WASTE LOADING (%)	WASTE AGE (YR)	WASTE AGE ENTRY (YR)	WASTE AGE DIS-CHARGE (YR)	WASTE AGE (YR)	BACK-FILL	CANS PER HOLE	MTU PER HOLE
33	5	CHLW	5	CERAMIC	5	5	5	30	30	D	17	126

Figure 13. Self-Shielded Canister Scenario

9441-29

V. REPOSITORY LIMITATIONS

The ceramic waste form, with its high density (5.2 g/cm^3) and high-waste loading (60 wt. %) can contain nearly four times as much waste per unit volume as the reference borosilicate glass form (at 3.1 g/cm^3 and 25 wt. %). It also has nearly four times the heat generation rate, which poses a potential temperature problem in the repository. One way of accommodating concentrated heat sources in the repository is to increase their separation. However, even this approach will fail when the individual canister heat generation rate is so high that some temperature in the region of the canister will exceed the allowable for the materials involved. These maxima are: for glass, 500°C ; for ceramic, 1000°C ; for stainless steel (SSTL), 430°C ; for mild steel (C-STL), 430°C ; for basalt, 450°C ; and for the 25% bentonite-75% basalt overpack mixture, 300°C (based on bentonite stability).

The configuration of the horizontal emplacement repository is shown in Figure A-1. The shapes, sizes, and spacings of the tunnels and boreholes have been designed to maintain the rock stress at a level that will prevent collapse of the tunnels.⁽²⁴⁾ For this repository, 17 canisters can be physically located in each borehole, and each may have a 2-kW heat generation rate. Under these conditions, the temperature pattern in the repository is acceptable with the boreholes being immediately filled with the 25% bentonite-75% basalt (B/B) back-fill mixture. This heat load is essentially that of a standard 0.305-m (12-in.) by 3.05-m (10-ft) long canister, filled with a glass at 25% waste loading with 10-year-old commercial high-level waste. The heat generation rate of a ceramic waste canister at a 60% waste loading of 10-year-old CHLW, is 7.2 kW.

An alternate waste material is a mixture of the high-level liquid waste stream and the intermediate-level liquid stream in the proportions generated in the reprocessing plant. A standard canister containing a 60% waste loading of 10-year-old mixed waste has a heat generation rate of 5.4 kW.

Another alternate waste material consists of a "fractionated" waste stream, that is, one which has had a portion (say, 90%) of its cesium and strontium removed in addition to the standard removal of 99% of the uranium and plutonium. A standard canister containing a 60% waste loading of 10-year-old 90% fractionated waste has a heat generation rate of 1.8 kW. A full borehole loading of 17 of these canisters would be acceptable for immediate B/B backfill.

In order to evaluate the various scenarios by which one might consider waste management in the ceramic waste form, the unsteady-state thermal patterns generated by various borehole loadings of ceramic waste forms having varying waste loadings and waste ages were calculated, and the maximum allowable borehole canister loadings were determined. The details of the thermal analysis are given in Appendix A.

The input data for the calculation are the heat rate decay curves for the waste materials and the compositions of the waste streams. The heat-rate values were developed using the data reported by Slate⁽¹³⁾ for the products of a 32,700 MWd/MTU exposure of a 3.1% enriched uranium PWR fuel element. Because the mixing of the ILLW stream into the HLLW stream to form the mixed waste does not introduce an appreciable heating effect, the heat-rate values for CHLW can be used on a per-MTU basis for mixed waste as well. The values for the 90% fractionated waste were derived from the CHLW values, adjusting for the fraction of cesium, strontium, and their daughters removed. These data are shown in Table 5.

The composition of the CHLW stream was taken from Mendel,⁽²⁵⁾ who reported the expected concentrations of the fission products, transuranics, and process inerts for a commercial PWR reprocessing plant. Values for the fractionated waste were derived from the CHLW composition.

The composition of the mixed waste stream was taken from Hall,⁽²⁶⁾ who reported the expected concentrations of the fission products, the transuranics, and the processing inerts for the AGNS plant.

TABLE 5
HEAT GENERATION RATES FOR COMMERCIAL HIGH-LEVEL WASTE MATERIALS

Waste Age (years)	CHLW (W/MTU)	CHLW, 90% Fractionated* (W/MTU)	Waste Age (years)	CHLW (W/MTU)	CHLW, 90% Fractionated* (W/MTU)
5	1622	588	80	190	54.1
6	1358	403	90	156	49.4
7	1197	318	100	129	45.8
8	1095	275	150	111	35.9
9	1024	250	200	95.7	30.8
10	971	233	250	82.4	27.1
15	810	185	300	71.0	24.1
20	704	157	350	61.1	21.6
25	620	137	400	52.6	19.4
30	549	121	450	45.3	17.6
35	489	108	500	39.1	16.1
40	437	96.9	600	29.0	13.7
45	391	88.0	700	21.5	11.9
50	351	80.5	800	15.9	10.6
60	284	68.8	900	11.8	9.57
70	232	60.3	1,000	8.77	8.77

*CHLW with 90% of the Cs and Sr and their daughters removed.

Table 6 summarizes these waste stream composition data as used in this study.

In addition to the consideration of maximum allowable temperatures for the materials in the waste packages and the repository, there is a consideration of the maximum allowable areal heat loading for the repository. This latter concern is related to the expansion forces generated by the average increase in temperature of the repository structure, with the limitation that the mine shafts, tunnels, rooms, and boreholes must not collapse during the active repository life. Values of areal loading expressed as watts per square meter or kW/acre have been reported.^(27,28,29,30) These are summarized in Table 7. As shown, the quoted local areal values range from 7.8 to 18.8 W/m² (31.6 to 76.1 kW/acre). The average areal heat loadings, which account for the inactive regions needed for shafts, etc., are about 2/3 as large, and would range from 21 to 51 kW/acre. However, these values are simply the calculated results derived from the particular combinations of waste loading, canister size, waste age at emplacement, and the spacing in the repository. Thus they are features of the indicated designs, but they are not limitations imposed by the repository rock (basalt). This is a point of emphasis, because the misinterpretation of these areal heat loads can lead to false limitations being imposed on the repository design.

The areal heat loading should be derived from a rock mechanism analysis. A somewhat specific evaluation of the required rock stress safety factors for a basalt repository gives the data shown in Table 8.⁽³¹⁾ The conditions imposed on this repository system were that each canister contain the spent elements from three PWR fuel assemblies, the waste fuel is emplaced at 10 years of age (1.74 kW/canister), and with an areal heat loading of 13 W/m². Table 9 shows the results of the calculated rock stress safety factors. A comparison of the Table 9 data with that of Table 8 shows the rock stress safety factor for the 13-W/m² (52.6 kW/acre) areal heat loading to be well above the minimum requirement, with the strong implication that 52 kW/acre is a conservative areal heat

TABLE 6
WASTE COMPOSITION SUMMARY

Component	CHLW (wt. % as oxide)	CHLW, 90% Fractionated (wt. % as oxide)	Mixed HLLW and ILLW (wt. % as oxide)
Fission Products	55.05	52.45	37.81
Transuranics	19.59	20.72	14.30
Process Inerts	<u>25.36</u>	<u>26.83</u>	<u>47.89</u>
Total	100.00	100.00	100.00
Specific Weight of Waste, <u>Kg oxide</u> MTU	65.75	62.16	86.87

TABLE 7
REPOSITORY AREAL HEAT LOAD SUMMARY

Waste Description Emplacement in Basalt	Thermal Loading at Emplacement*		Ref.
	Local	Average	
	W/m ²	W/m ²	
PWR Spent Fuel Elements	13.0		28
BWR Spent Fuel Elements	10.1		28
Commercial High-Level Waste	16.3		28
Defense High-Level Waste	14.0		28
Reference Spent Fuel Case	12.3	8.2	29, 30
Commercial High-Level Waste	12.3	8.2	29, 30
Spent Fuel — SF2 Package	7.8		27
Self-Shielded Package — Spent Fuel	15.2		27
Commercial High-Level Waste	5.8		27
Self-Shielded Package — CHLW	16.0		27
Defense High-Level Waste (24 in. Ø)	9.8		27
Self-Shielded Package — DHLW (24 in. Ø)	10.3		27
Defense High-Level Waste (32 in. Ø)	10.3		27
Self-Shielded Package — DHLW (32 in. Ø)	18.8		27

*Values in kW/acre are nominally four times those in W/m².

TABLE 8
REQUIRED ROCK STRESS SAFETY FACTORS⁽³¹⁾

Location in Basalt	Required Safety Factor		
	Operational Phase	Retrieval Storage Phase	Thermal Storage Phase
Canister Hole	1.5	1.0	1.0
Room and Pillar	2.0	1.25	1.0
Entries and Shafts	2.0	1.5	1.0

TABLE 9
CALCULATED ROCK STRESS SAFETY FACTORS⁽³¹⁾

Location in Basalt	Required Safety Factor		
	Operational Phase	Retrieval Storage Phase	Thermal Storage Phase ^c
Canister Hole	4.1	2.0 ^a	2.4
Room and Pillar	2.7	2.1 ^b	2.0
Entries and Shafts	2.7	2.1 ^b	2.0

^a5 years after initial storage, when this factor is at a minimum (peak temperature period)

^b25 years after initial storage

^c50 years after initial storage

load value for a basalt repository. However, the study⁽³¹⁾ did not address the problem of defining the maximum allowable areal heat loading.

The following evaluations (Section VII) develop values of kW/borehole for the horizontal borehole repository configuration used in this report. Local areal heat loads in W/m^2 are 0.503 times the kW/hole values.

VI. METHODOLOGY OF THE ECONOMIC ANALYSIS

The goal of the economic analysis undertaken in this study was to determine which, if any, scenarios for the disposal of commercial high-level waste by the use of the crystalline ceramic waste form may be economically feasible. The impetus for the belief that the use of the ceramic waste form may offer an economic advantage over the glass waste form arises from results of the development work on the form and from the findings that not only are high-waste loadings and high densities attainable, but also that the stability of the form as measured by leach resistance is excellent. Since the initiation of the research and development of the ceramic waste form about 3 years ago, the complexity of the process sequence has been steadily decreasing such that the simplicity of the present ceramic process design is quite comparable to that of the glass process (which has also undergone significant improvements in the last several years).

Earlier cost comparisons have been made for the immobilization plants producing glass and ceramic forms,^(9,32) with the conclusion that the glass process was favored, particularly because of the then-identified complexity of the ceramic process and because of the fact that the glass process had been tested at larger scale and in more detail. Although the latter situation continues to be a factor, the former one is no longer applicable. Further, the leach resistance of the ceramic form is significantly greater than that of glass so that its overall performance as a trap for the radioactive nuclides in a repository environment is superior to that of glass. No credit has been given the ceramic waste form because of its better leach resistance, i.e., no modification of repository design or simplification of the engineered barrier.

In view of these recent advances in ceramic waste immobilization technology, it is appropriate to re-examine, in an order-of-magnitude way, the economics of the exploitation of the ceramic waste form. That is the goal of this study.

The approach taken herein is to use, as a source, published data or estimates of the costs of each of the process blocks making up the overall waste handling sequence (i.e., from the liquid waste product of the reprocessing plant to final emplacement in a repository). These data are evaluated, where possible, in terms of the specific processes to which they apply to establish a basis upon which they could be used to evaluate the scenarios used in this study. Values were adjusted to 1981 based on the Chemical Engineering Plant Cost Index. Adjustments for plant size or capacity have been made using the well-established 0.6-power relationship. Operating costs are best estimated using actual operating data. However, for most of the process blocks of present interest, no data are available. Operating costs have therefore been estimated by evaluating the individual steps involved and assigning a working crew with backup workers as appropriate for hot-cell-type operations. Four-shift-per-week operation for part of the staff, and one-shift operation for others, has been considered, as well as an allowance for the "realization factor," the fact that a worker only works 90% of the total hours in the year because of vacation, holidays, etc.

Maintenance and supplies are included in the estimation of annual operating costs as a percentage of the labor estimate. In addition, an annual replacement and repair allowance for the equipment is evaluated based on the expected severity of service and the equipment capital value.

Cost comparisons between scenarios or cases are made on a 20-year basis. Capital costs for all process blocks except the repository are directly used in the total. Because the repository capacity greatly exceeds the 20-year production rate of ceramic waste forms at the reference process rate of 3000 MTU/year, the "capital" cost is based on the fraction of the repository utilized in a 20-year period. Operating costs for 20 years for each process plant, for canister use and for shipping operations, are also directly included in the totals.

The details of the cost and operating estimates for the individual waste management processes involved in the 34 scenarios described above in Section IV.C are given in Appendices B through K. Appendix L summarizes the cost estimate figures developed.

VII. ECONOMIC COMPARISONS, COMMERCIAL WASTE OPTIONS

A. GENERAL

Cost estimates for each of the commercial high-level waste management scenarios described in Section IV have been made. The details of the calculations are presented in Appendices B through K. Table 10 is a listing of the least costly scenario of each type examined and shows the 20-year estimated cost of the ceramic waste form process sequences to be in the range of \$1.9 to \$2.5 billion and the standard 0.305-m (12-in.) glass waste form costs to be in the range of \$3.9 to \$5.0 billion. The least expensive glass form estimate (No. 34)* is \$2.8 billion, compared with the least expensive ceramic form estimates (Nos. 10 and 33) of \$2.0 and \$1.9 billion. Although the cost estimate figures as developed have a relatively large uncertainty, it does appear that there is a significant difference in the costs of disposal for the two waste forms. Table 10 shows that the least expensive scenarios are invariably those in which the waste has aged so that the thermal restrictions will allow a full repository borehole loading of 17 canisters. Also, as expected, the delayed backfill cases show lower costs, because the heat transfer capability of a bare canister in an open channel is superior to that of a canister packed with a granular material backfill. Further, the use of the 25% bentonite-75% basalt (BEN/BAS) backfill further restricts the thermal effects because of the lower allowable temperature for the bentonite.

The lowest estimated cost figure of \$1.9 billion was found for a case (No. 33) in which a self-shielded cask is used. As evaluated in Appendix J, the cost of the heavy-walled cask is more than offset by reductions in handling and repository costs. However, this particular estimated cost has a greater uncertainty than the others, so that a more detailed study of the comparison between standard and self-shielded cases will be required to validate the difference.

*For a 0.43-m (17-in.) diameter canister which is the maximum size that can be emplaced with delayed backfill at 25 wt. % waste loading.

TABLE 10
COST ESTIMATE
SUMMARY OF "BEST" VARIATIONS^a

Case No.	Form	Waste ^b	Waste Age At Burial (years)	Waste Loading (%)	Backfill ^c	Cans Per Hole	MTU Per Hole	Est. ^g Cost (10 ⁹ \$)
28	Glass	Mixed	10	25	BEN/BAS	17	26	4.8
3	Glass	CHLW	10	25	BEN/BAS	17	34	4.9
31	Ceramic	Mixed	50	60	BEN/BAS	17	95	2.4
32	Ceramic	90%	10	60	BEN/BAS	17	133	2.5
20	Ceramic	CHLW	70	60	BEN/BAS	17	126	2.2
27	Ceramic	Mixed	30	60	Basalt	17	95	2.3
17	Ceramic	CHLW	50	60	Basalt	17	126	2.1
1	Glass	CHLW	5	25	Delayed	17	34	3.8
13	Ceramic	CHLW	10	40	Delayed	17	84	2.3
23	Ceramic	Mixed	10	53	Delayed	17	84	2.3
24	Ceramic	Mixed	15	60	Delayed	17	95	2.2
10	Ceramic	CHLW	30	60	Delayed	17	126	2.0
33	Ceramic	CHLW	30	60	Delayed ^d	17	126	1.9
34	Glass	CHLW	10	25 ^e	Delayed	17	68	2.8

^aReference canister: 0.305-m (12-in.) ID, and 3.05 m (10 ft) long, containing a net 0.156 m³ (5.50 ft³) of ceramic waste form, or a net 0.169 m³ (5.98 ft³) of glass waste form.

^bWaste Materials: CHLW, commercial high-level waste (99% of U and Pu removed 90%); fractionated waste (99% of U and Pu, and 90% of Cs, Sr, and daughters removed); mixed, mixed HLLW and ILLW from reprocessing.

^cBackfill: BEN/BAS indicates an immediate backfill with a 25% bentonite-75% basalt mixture; Basalt indicates an immediate backfill with 100% basalt; and Delayed indicates no backfill for an extended period after emplacement.

^dSelf-shielded cask - storage and burial.

^eNonstandard canister, 0.43-m (17-in.) ID.

The several scenarios described in Section IV were chosen to evaluate not only the differences in costs of basic approaches but also to identify the trends of costs within the basic approach scenario groups. Discussions of these scenarios and their estimated costs follow.

B. GLASS FORM SCENARIOS

Table 11 shows a listing of the glass form cases studied. Case 28 shows the highest estimated cost of any of the scenarios evaluated. This is primarily due to the lower amount (MTU) of waste in the canisters, and in the borehole, even with the full complement of 17 canisters. The additional handling costs accumulate through the process sequence.

TABLE 11
SUMMARY OF SCENARIOS FOR GLASS FORMS

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kW Per Hole ^d	MTU Per Hole	Est. Cost (10 ⁹ \$)
28	Mixed	10 ^c	25	BEN/BAS	17/26	26	4.8
2	CHLW	10 ^a	25	BEN/BAS	17/33	34	4.5
4	CHLW	10 ^b	25	BEN/BAS	17/33	34	4.0
3	CHLW	10 ^c	25	BEN/BAS	17/33	34	4.0
1	CHLW	5	25	Delayed	17/55	34	3.8
34	CHLW	10	25 ^e	Delayed	17/66	68	2.8

^a5 years' SFE storage

^b5 years' HLLW storage

^c5 years' canister storage

^dInitial kW/hole value

^eFor a 0.43-m (17-in.) canister instead of the standard 0.305-m (12-in.) size.

Cases 2, 3, and 4 show the effects of the method of waste storage on the overall cost. Case 2, for which 5 years' storage as spent fuel elements (SFE) in a water pool away from the reactor, is significantly more expensive than is storage as HLLW or as dry, cooled, sealed canisters.

Although the rounded-off values for Cases 3 and 4 are the same in Table 11, the source values in Table L-1 shows Case 3 to be less expensive. Further, a review of the cost estimate pattern for storage periods greater than 5 years shows that the cost differences will more greatly favor the dry canister storage. A similar relation was found for the storage method comparison of the ceramic forms. All other storage costs were based on a convection-cooled, dry canister storage facility.

Table 11 indicates the estimated cost of the least expensive standard 0.305-m (12-in.) glass-form case to be \$3.9 billion. This is achieved by using the somewhat unrealistic case of placement of 5-year-old waste in the repository. At this age, the heat generation rate of the waste is high enough that it cannot be backfilled with either 25% bentonite-75% basalt or with 100% basalt. However, after a nonbackfilled delay in the repository of 5 years, the 10-year-old waste could be backfilled, if desired.

Case 34 shows an estimated cost of \$2.8 billion. This option uses a non-standard canister size, 0.43-m (17-in.) ID, for which diameter, using a 25 wt. % waste loading, the centerline temperature reaches the 500°C glass temperature limit in a basalt repository, with delayed backfill. For this case, immobilization occurs at 5 years, and the canister is stored for an additional 5 years before emplacement. The marked reduction in the cost is due to halving the number of glass canisters and the consequent major saving in repository costs. This is clearly the least expensive glass option, but its estimated 20-year cost is still almost a billion dollars more (per 3000-MTU/year reprocessing plant rate) than the best ceramic case, as shown in Table 11.

C. CERAMIC FORM SCENARIOS — STORAGE METHOD VARIATIONS

Table 12 shows a listing of the cases in which the three different storage methods were compared for a storage period of 5 years. As in the glass-case comparison, the net costs showed the convection-cooled, dry canister method to be least expensive. The estimated costs here are high because the 10-year-old waste has a high heat generation rate. This limits the number of canisters per hole, mainly because the individual canisters have a heat rate that causes their temperatures — even without the additive effect of the general temperature increase of the field — to approach the limits of the canister material (430°C). Then, compared to being able to load 17 canisters per borehole, the cost of having only three raises the repository capital cost by the factor (17/3). Thus, this cost becomes dominant, as can be seen in Table L-1.

TABLE 12
SUMMARY OF SCENARIOS FOR CERAMIC FORMS
STORAGE METHOD VARIATIONS

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kW Per Hole ^d	MTU Per Hole	Est. Cost (10 ⁹ \$)
5	CHLW	10 ^a	60	Delayed	3/21	22	3.7
7	CHLW	10 ^b	60	Delayed	3/21	22	3.2
6	CHLW	10 ^c	60	Delayed	3/21	22	3.1

^a5 years' SFE storage

^b5 years' HLLW storage

^c5 years' canister storage

^dInitial kW/hole value

D. CERAMIC FORM SCENARIOS — WASTE AGE VARIATIONS

Table 13 shows a listing of the cases in which the age of the waste has been varied, with a constant 60% waste loading, to ultimately permit the emplacement of 17 canisters per borehole. As expected, the interim storage times required for the heat generation rate to drop to values that permit full loadings in the boreholes increase as the heat transfer conditions within the borehole worsen from the delayed backfill option to the immediate backfill with the 25% bentonite-75% basalt mixture.

TABLE 13
SUMMARY OF SCENARIOS FOR CERAMIC FORMS
CHLW WASTE AGE VARIATIONS^a

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kw Per Hole ^b	MTU Per Hole	Est. Cost (10 ⁹ \$)
6	CHLW	10	60	Delayed	3/21	22	3.1
8	CHLW	20	60	Delayed	8/42	59	2.3
9	CHLW	25	60	Delayed	13/60	96	2.1
10	CHLW	30	60	Delayed	17/69	126	2.0
15	CHLW	30	60	Basalt	3/12	22	3.2
16	CHLW	40	60	Basalt	13/42	96	2.2
17	CHLW	50	60	Basalt	17/44	126	2.1
18	CHLW	50	60	BEN/BAS	3/9	22	3.3
19	CHLW	60	60	BEN/BAS	13/27	96	2.2
20	CHLW	70	60	BEN/BAS	17/29	126	2.2

^aAll cases use canister storage

^bInitial kw/hole value

Figures 14, 15, and 16 show the details of the cost totals and clearly illustrate the very dominant effects of the allowable number of canisters that can be placed in a borehole on the cost of the waste management option. In each of the three groups, the estimated total costs decrease with increased storage time so that the minimum cost is found for the condition that 17 canisters be acceptable per borehole. Cases 10, 17, and 20 show cost increments of \$0.1 billion, but the uncertainty of any of these totals is at least \$0.5 billion, so that all of the cases for which as few as 13 canisters are placed per borehole could be considered cost-equivalent. However, it is evident that in order that the cost advantages of a high-waste loading and high-density waste form be realizable, the waste must be stored for several decades.

E. CERAMIC FORM SCENARIOS — WASTE LOADING VARIATIONS

Table 14 shows a listing of the cases in which the waste loading of the ceramic form has been varied, with a constant waste age at burial of 10 years. As the waste loading is decreased, the number of canisters required to handle the 3000-MTU/year production rate increases, as is shown in Table 4. The result of the combination of reduced canister heat load, which increases the number of canisters allowed per borehole, and the increased number of canisters to be processed results in a minimum in the estimated cost. This occurs when the allowable number of canisters per borehole reaches 17. Figure 17 shows the details of the cost components for this series of options and again shows the dominance of the repository costs on the total. A reduction of the waste loading below the value allowing full borehole density results in an increase in the estimated cost, as seen in Case 14. It is of interest that this minimum estimated cost is only 14% larger than the lowest value found — and well within the uncertainty range of these estimates. Case 13 is, therefore, suggested as an option for significant savings, if waste storage is not acceptable as an element of a waste management scenario.

Figure 14. Estimated Costs vs Waste Age: CHLW Immobilized in Ceramic, 60% Waste Loading, Delayed Backfill

Figure 15. Estimated Costs vs Waste Age: CHLW Immobilized in Ceramic, 60% Waste Loading, Immediate Basalt Backfill

Figure 16. Estimated Costs vs Waste Age: CHLW Immobilized in Ceramic, 60% Waste Loading, Immediate Bentonite-Basalt Backfill

Figure 17. Estimated Costs vs Waste Loading: CHLW Immobilized in Ceramic, Buried at 10 Years of Age, Delayed Backfill

TABLE 14
SUMMARY OF SCENARIOS FOR CERAMIC FORMS
CHLW WASTE LOADING VARIATIONS^a

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kW Per Hole	MTU Per Hole	Est. Cost (10 ⁹ \$)
6	CHLW	10	60	Delayed	3/21	22	3.1
11	CHLW	10	48	Delayed	4/23	24	3.2
12	CHLW	10	45	Delayed	10/54	55	2.4
13	CHLW	10	40	Delayed	17/82	84	2.3
14	CHLW	10	35	Delayed	17/71	73	2.5

^aAll cases use canister storage.

F. CERAMIC FORM SCENARIOS — MIXED WASTE VARIATIONS

Table 15 shows a listing of the cases in which mixed waste is used to produce a ceramic waste form. The concept of using a mixed waste is attractive from the point of view that both the high-level and the intermediate-level waste from a reprocessing plant can be effectively accommodated. The mixture consists of using the HLLW and ILLW waste streams in proportion to their generation rates. The effect of this is to dilute the HLLW waste by about 32% with the ILLW stream, which contains a negligible amount of heat-generating isotopes. The result is that about 30% more canisters with about 75% as large a heat load are required to handle a given MTU production rate.

In the first three cases in Table 15, the waste loading is varied with a constant waste age of 10 years at burial. Case 23 shows that for mixed waste, a waste loading of 53% provides enough dilution to permit the emplacement of 10-year-old waste with delayed backfill. This corresponds to a waste loading of 40% for CHLW in Case 13 (Table 14). As we would expect, the difference in loading is about 32%, which means that the amounts of waste in the canisters of

TABLE 15
SUMMARY OF SCENARIOS FOR CERAMIC FORMS
MIXED WASTE VARIATIONS

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kW Per Hole	MTU Per Hole	Est. Cost (10 ⁹ \$)
21	Mixed	10	60	Delayed	8/44	45	2.6
22	Mixed	10	55	Delayed	14/70	72	2.4
23	Mixed	10	53	Delayed	17/81	84	2.3
24	Mixed	15	60	Delayed	17/77	95	2.2
25	Mixed	20	60	Basalt	3/12	17	3.8
26	Mixed	25	60	Basalt	8/28	45	2.7
27	Mixed	30	60	Basalt	17/52	95	2.3

Case 13 and Case 23 are equal. Figure 18 shows the details of the cost components for this group of options. The repository costs are seen to control the total because the other costs are changing so slowly with waste loading.

Case 24 examines the effect of storing the waste an additional 5 years to provide a 15-year emplacement age with a 60% waste loading. This option appears to be slightly less expensive than the others and uses the least amount of repository space for a mixed waste form, with 95 MTU being emplaced per borehole.

Cases 25, 26, and 27 were evaluated to determine the effects of an immediate basalt backfill on the waste management cost estimate. The pattern of an increased number of canisters per borehole, as the storage time is increased, is evident, with the maximum 17-canister loading corresponding to a total estimated cost of \$2.3 billion. This is larger than the minimum value found, but, as is seen for several other options, the difference is less than the uncertainty of the individual estimated cost values. Figure 19 shows the details of the cost components for this group of options. The repository costs are seen to dominate,

Figure 18. Estimated Costs vs Waste Loading: Mixed Waste Immobilized in Ceramic, Buried at 10 Years of Age, Delayed Backfill

Figure 19. Estimated Costs vs Waste Age: Mixed Waste Immobilized in Ceramic, 60% Waste Loading, Immediate Basalt Backfill

and the minimum occurs at the earliest time at which 17 canisters can be placed in each borehole. This is because the cost per site for unfilled sites is much greater than the cost of canister storage for several years, so it is less costly to wait.

Again, one can either decrease the waste loading or provide convection-cooled, dry canister storage for a few years to obtain an equal minimum estimated cost for the waste management of mixed waste at the rate of 3000 MTU/year. This minimum is 14% greater than the minimum found for CHLW waste.

G. CERAMIC FORM SCENARIOS — MISCELLANEOUS CASES

Table 16 shows two scenario summaries. Case 33 is analogous to Case 10, except that (as per Appendix J) the hot isostatically pressed ceramic forms are loaded into a heavy-walled self-shielded canister. The predicted reduction in the costs of handling 25-year dry storage, and the elimination of overpack, results in an estimated 20-year cost of \$1.9 billion compared with \$2.0 billion for the standard canister. The difference in these estimates as developed is not significant; if anything, the Case 33 estimate is the more uncertain, but a suggestion remains that a more detailed study of the cost elements of a self-shielded canister with a ceramic waste form may show an increased difference, and with more confidence in the values.

TABLE 16
SUMMARY OF SCENARIOS FOR CERAMIC FORMS
MISCELLANEOUS

Case No.	Waste	Waste Age At Burial (years)	Waste Loading (%)	Backfill	Cans/kW Per Hole	MTU Per Hole	Est. Cost (10 ⁹ \$)
33	CHLW ^a	30	60	Delayed	17/69	126	1.9
32	90% ^b	10	60	BEN/BAS	17/31	133	2.5

^aStorage in self-shielded cask

^bFractionated waste, 90% Sr and Cs removed

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Case 32 was evaluated to examine the effect of the rather substantial reduction in the heat generation rate of 90% fractionated waste. (90% fractionated waste as used herein is commercial high-level waste from which 90% of the cesium and strontium and their daughters has been removed following reprocessing.) As is indicated in the table, a 60% waste-loaded ceramic waste form can be emplaced, when the waste age is 10 years, at 17 canisters per borehole, and immediately backfilled with the 25% bentonite-75% basalt mixture. The initial heat load in the borehole is 31 kW, as compared with 33 kW for 10-year-old glass (Case 3, Table 11). The estimated cost for this option is \$2.5 billion, of which an estimated \$0.6 billion have been assigned as the 20-year cost of operating the fractionation plant. The remainder, \$1.9 billion, is lower than the cost of the other CHLW forms because fewer canisters are required.

Fractionation, or material recovery/removal, is an area that warrants further work. The value of strontium, as a heat source, or cesium, as an irradiation source, may be difficult to assess (and to recover), but there are substantial amounts of noble metals in the waste stream and the value of these materials as chemical process catalysts is considerable. In fact, it appears that the presently estimated cost of the fractionation plant could be recovered several times over from the value of the rhodium and the palladium in the CHLW.

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VIII. ECONOMIC COMPARISON, MANAGEMENT OF FRENCH WASTE

The French have initiated a program of waste management that involves immobilization in borosilicate glass followed by canister storage for 50 years. This program will safely immobilize the waste in the near term and allow an adequate time to resolve the problems of selecting and building a repository.

The glass process used produces a waste form having a waste loading of 15 wt. %. One 0.5-m (~20-in.) diameter by 1.0-m (~40-in.) canister is produced per day, or 300 canisters per year. It is of interest to compare the estimated cost of the glass process and a ceramic process having the same waste-handling rate. The one 15 wt. % loaded glass canister per day contains the equivalent of 1.2 MTU of waste. One 60 wt. % loaded ceramic canister contains the equivalent of 7.39 MTU, so that the ceramic canister production rate is $(1.2/7.39)$ or 0.16 per day, or about one every 6 days, or about one HIP can every second day. Although this is an impractically low rate of ceramic production, it has been considered as a steady, continuous rate.

The bases for the cost estimate evaluations of the several process plants and operations involved are described in the appendices. Table K-1 shows a summary of the cost components for the two waste forms. The ceramic could produce a reduction in the estimated annual cost of \$33.3E6/year, with the 20-year total estimated cost for the ceramic form of \$916E6, compared with \$1581E6 for the glass form. About half of the difference is seen to originate in the costs at the repository, whose effects are emphasized in this comparison in which the glass waste loading is much lower than that used for the reference glass designed for U.S. wastes.

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IX. DISCUSSION

The goal of this study was to determine if there are waste management options by which the cost of handling commercial high-level waste might be minimized. The reference waste form is borosilicate glass, which can contain up to 25 wt. % waste. The best alternative form, which has been under study in recent years, is the crystalline ceramic waste form, which can contain more than 60 wt. % waste. Further, the density of the ceramic waste form is about 5.2 g/cm³ (with 0.156 m³/canister), compared with a 3.1-g/cm³ density for glass (with 0.169 m³/canister). The combination of these effects results in the ceramic form's waste loading being about 3.7 times that of the glass form. This suggests that an economy might be found in the fact that fewer canisters are needed for a given amount of waste if the ceramic form is used. The ratio of the number of canisters is given by the expression

$$N_c/N_g \cong \frac{(\text{density})_c}{(\text{density})_g} \cdot \frac{(\text{waste loading})_c}{(\text{waste loading})_g} \cdot \frac{V_c}{V_g}$$

This study involved examining six glass form scenarios, 26 corresponding ceramic form scenarios, and two other specialized ceramic form scenarios. Variations in waste age at burial, waste loading, waste composition, and backfill condition in a basalt repository were examined. A summary of the commercial waste handling management cost results is shown in Table 17. The derivations of the listed data are given in Appendices B-J, and a discussion of the listed options follows.

A. COMMERCIAL HIGH-LEVEL WASTE (CHLW)

The reference case is based on a representative high-quality borosilicate glass form made from CHLW and having a high-waste loading and a high density. The cost basis is the sum of the capital costs of the component waste management process plants, plus a 20-year total of operating costs.* On this basis, the estimated cost of the reference case is \$4.0 billion (\$200 million/year). This

*These costs are developed for the waste generated from one 3000-MTU/year reprocessing plant. Seven such plants are projected to be needed to maintain steady-state processing of commercial waste in the year 2000.

TABLE 17
SUMMARY OF COMMERCIAL WASTE MANAGEMENT OPTIONS

Case No.	Form	Waste ^a	Waste Age at Burial (years)	Waste Loading (%)	Backfill	Estimated Cost ^c (\$ Billion)
3 ^b	Glass	CHLW	10	25	BEN/BAS	4.0
1	Glass	CHLW	5	25	Delayed	3.8
10	Ceramic	CHLW	30	60	Delayed	2.0
17	Ceramic	CHLW	50	60	Basalt	2.1
20	Ceramic	CHLW	70	60	BEN/BAS	2.2
13	Ceramic	CHLW	10	40	Delayed	2.3
24	Ceramic	Mixed	15	60	Delayed	2.2
27	Ceramic	Mixed	30	60	Basalt	2.3
23	Ceramic	Mixed	10	53	Delayed	2.3
32	Ceramic	90%	10	60	BEN/BAS	2.5
33	Ceramic	CHLW	30	60	Delayed ^d	1.9
34	Glass	CHLW	10	25 ^e	Delayed	2.8

^aWaste Materials: CHLW, commercial high-level waste (99% of U and Pu removed); 90%, fractionated waste (99% of U and Pu, and 90% of Cs, Sr, and daughters removed); mixed, mixed HLLW and ILLW from reprocessing.

^bReference case.

^cEstimated cost is based on the sum of plant capital costs plus 20 years of operating costs for a 3000-MTU/year waste management process rate.

^dSelf-shielded cask — storage and burial.

^eNon-standard canister, 17-in. ID.

scenario involves 5 years of storage in a dry convection-cooled canister storage facility. If the canister storage were to be eliminated in the process sequence (Case 1), the waste could be emplaced, but a delayed backfill would be required. The estimated cost of Case 1 is \$3.8 billion (\$190 million/year).

A 60 wt. %, 5.2 g/cm^3 ceramic waste form made from 10-year-old waste (Case 10) can be immediately emplaced in a basalt repository, but the thermal effects severely restrict the canister placement density. The optimum scenario for waste management of this waste material requires a 25-year storage period to allow the heat generation rate to decay. Even then, delayed backfill is required. The estimated cost of Case 10 is \$2.0 billion (\$100 million/year). If immediate backfill using 100% basalt is required, then the optimum storage time for this CHLW canister is 45 years, which, plus the 5 years' time spent at the reactor site, totals 50 years at emplacement (Case 17). The estimated cost of this scenario is \$2.1 billion (\$105 million/year). Further, if immediate backfill using the 25% bentonite-75% basalt mixture is required, then the optimum storage time for this CHLW canister becomes 65 years (Case 20). The estimated cost for this scenario is \$2.2 billion (\$110 million/year).

This sequence shows the effect of the backfill specification on both the storage time requirement and on total cost. However, it is of interest to note that even for the long storage times (which may be undesirable on other accounts), the total cost of waste management using a high-waste-loaded ceramic form is expected to be much less than that for a high-quality glass waste form.

Although the potential of making a high-waste-loaded form is attractive, these studies show that the thermal considerations then mandate the use of long storage times, which may be an undesirable aspect of the waste management concept. The idea of the storage of waste for several decades, even storage of dry, sealed canisters, may be distasteful. However, the French and the Swedish waste management programs do include, by choice, dry canister storage for periods up to 50 years. Further, decades-long waste storage has been accomplished at

the Hanford Works and at the Savannah River Plant with the storage of high-level liquid waste and with the certainty that additional storage time will be required.

In view of the long-term storage question, a study of waste loading variation for the emplacement of 10-year-old waste was carried out, with the result that a 40 wt. % waste loading of CHLW in a ceramic form can be emplaced at the optimum repository placement density (Case 13). The estimated cost of this scenario is \$2.3 billion (\$115 million/year).

B. MIXED WASTE

A reprocessing plant produces an intermediate-level liquid waste stream derived from the regeneration of the process chemicals. The amount of radioactivity in this stream is small, but it must be disposed of. One way of handling its disposal is to mix the ILLW with the HLLW stream. The mixture has about 30% more material to be handled but has only 75% as much heat generation per canister. It therefore appears that the ceramic waste form, with its higher waste loading capability, might provide an answer to the waste management of a mixed CHLW stream. Case 24 represents the optimum storage time (10 years) of a 60 wt. % loaded ceramic waste form based on mixed waste, emplaced with delayed backfill. The estimated cost is \$2.2 billion (\$110 million/year). If an immediate basalt backfill is required at the repository, the 60 wt. % loaded ceramic waste must be stored for 25 years before being emplaced at the maximum repository placement density. The estimated cost is \$2.3 billion (\$115 million/year).

However, in order that 10-year-old mixed waste be emplaceable at maximum repository placement density, it must be diluted to produce a 53 wt. % loading in the ceramic waste form. This value is compatible with the required 40 wt. % loading of CHLW (Case 13). The estimated cost is \$2.3 billion (\$115 million/year).

Thus, this approach provides a means of disposing of the ILLW, and the cost increment of \$0.3 billion for the 20-year operation may well be less than it would cost to process the ILLW stream separately.

C. FRACTIONATED WASTE

The separation of the strontium and the cesium from the reprocessing plant effluent waste stream is called fractionation. For the present study, this separation process removes 90% of the cesium and 90% of the strontium and 90% of their daughters. The cesium and the strontium are handled separately, and no cost benefit was taken for these products. With the fractionation plant cost penalty, the estimated cost of waste management of 10-year-old mixed waste is \$2.5 billion (\$125 million/year).

D. SELF-SHIELDED CANISTER

A self-shielded canister concept uses a heavy-walled vessel as the outer component. If a ceramic waste form were to be used, three of the condensed HIP forms would be loaded directly into the self-shielded canister and sealed. Subsequent handling and packaging costs would be reduced. The estimated cost of this approach (Case 33) is \$1.9 billion (\$95 million/year). Although this estimate has a very large uncertainty, this study indicates that the self-shielded canister concept is a competitor and may be the least expensive of those scenarios by which the waste management of CHLW can be economically accomplished.

E. OPTIMIZED CANISTER SIZE — BOROSILICATE GLASS WASTE FORM

In order to take full advantage of the delayed backfill concept for the management of waste in the borosilicate glass form, the canister diameter was optimized. The standard 0.305-m (12-in.) diameter, loaded with 25 wt. % borosilicate glass, emplaced at 17 canisters per borehole, can be immediately back-filled with 25% bentonite-75% basalt. The bentonite temperature limit is approached. By using delayed backfill, the glass-filled canister diameter can be increased until the next temperature limitation is reached with 17 canisters per borehole. Case 34 shows this condition, which occurs for a 0.43-m (17-in.) ID canister. The number of canisters is halved, and, as a consequence, the estimated cost is reduced to \$2.8 billion (\$140 million/year).

This is, of course, the most favorable borosilicate glass waste form scenario and is about \$1.2 billion less than the reference (standard canister size) case (No. 3). However, the estimated cost is still substantially more (\$0.8 billion) than the least expensive standard-canister crystalline ceramic case (No. 10).

F. WASTE FORM STABILITY

The stability of a waste form is reflected in the leach rates of its constituents. Although both glass and the crystalline ceramic materials have very low leach rates for the species studied, the rates from the ceramics are at least an order of magnitude lower than those of glass. However, as noted above in Section IV.A, the determination of the leach rates of those few specific long-lived radioactive species of greatest hazard to man have not been addressed in either the glass or the ceramic programs. Because the rates that have been measured are virtually all below the allowable thresholds, there may be a tendency to assume that either material will be satisfactory and that the deleterious constituents will remain in place as predicted. This may well be true. However, the fact that some particularly noxious isotopes have been identified (with the direct measurement of their rates in a test program being impractical), casts a different light on the importance of waste form stability. It appears only prudent, in view of the long-term potential hazard of these isotopes, that the waste form of choice should be the one of the greatest observable stability having the lowest leach rate for analogous species. The ceramic form thus appears to be a better choice.

G. THE WASTE FRACTIONATION PROCESS

Section C above addressed the cost considerations of fractionating the effluent process stream from a Purex plant to remove strontium and cesium, with no credit being taken for their value. This value is difficult to assess because they are, in effect, specialty materials. Strontium has been used in

capsules as a nominal zero-maintenance, long-lived heat source for use in remote areas. Its practical use as a heat source in other than remote locations is unlikely because of the cost of preparing capsules and because other heating methods are available. Cesium has been considered as an irradiation source suitable for the treatment of sludge; but, again, the value of the treatment is expected to be less than the cost of recovering and packaging the cesium for use. Therefore, the principal impetus for fractionation is the marked reduction in the heat generation of the fractionated waste.

Fractionation of other elements is another possibility, not because of any concomitant change in the heat generation rate, but rather because of the value of the materials themselves. The elements of major interest are palladium and rhodium. The amounts of these elements in the commercial high-level waste from a single 3000-MTU/year Purex plant handling 5-year-old waste are 3840 kg/year and 1170 kg/year, respectively. The estimated value of these materials is nearly \$200,000/year. This poses a strong financial incentive for their separation.

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X. CONCLUSION AND RECOMMENDATIONS

Based on the results of this study, the ceramic waste form, with its high waste loading and high density compared with the borosilicate glass form, offers the possibility of a major reduction in the cost of the waste management of commercial waste. The minimum estimated cost of waste management based on the borosilicate glass technology involves the use of a 0.43-m (17-in.) diameter canister and is found to be \$2.8 billion over a 20-year period. The minimum estimated cost of waste management based on the crystalline ceramic technology and using a standard 0.305-m (12-in.) diameter canister is found to be \$2.0 billion over a 20-year period. The projected savings are \$0.8 billion over the 20-year period, or \$40 million/year.

It is recommended that the crystalline ceramic waste management concept be pursued in further detail. The immediate needs are to (1) establish the limitations of the ceramic waste form for waste composition variation and for waste loading, (2) demonstrate the performance of the key process equipment such as the fluid bed calciner and the HIP unit in pilot scale, (3) refine the process description and update the process cost estimates to ensure that the process under study is the optimum one, and (4) re-evaluate comparative costs as more accurate evaluations of site-specific repository costs become available. (At the present level of overall waste management cost estimate developments, repository costs are major components of the total.)

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APPENDIX A

REPOSITORY HEAT TRANSFER MODEL

A finite difference model of the waste repository was prepared to calculate repository temperatures as a function of the amount of waste emplaced in the repository. The model used for these calculations is much coarser than the currently used HEATING 5 model,* but comparable results were obtained (for the reference glass case, the maximum canister surface temperature being $\sim 10^{\circ}\text{C}$ (18°F) higher than that for the RH0 calculation, which would be expected from the approximations used here).

The reference repository configuration is shown in Figure A-1.⁽³³⁾ The main tunnels are spaced 67 m (220 ft) apart. Horizontal shafts (boreholes), in which waste canisters will be emplaced, are drilled between the main tunnels, 32.6 m (107 ft) apart. For the reference glass case, 17 glass canisters are emplaced in each horizontal shaft. Each glass canister contains 2.0 MTU (25 wt. % waste loading) of 10-year-cooled waste. Backfill with bentonite/crushed basalt is delayed in order to meet the retrievability criterion, although the canisters could be immediately backfilled without exceeding any of the temperature limits.

The reference glass and ceramic canisters are shown in Figure A-2. For this analysis, the overall ceramic canister dimensions are the same as those for the reference glass canister. Optimization of the canister and repository configurations for the ceramic waste form was beyond the scope of the present work.

Table A-1 lists the node numbers and slab thicknesses for a vertical section through the repository for the TAP analysis. Nodes are placed in the center of each slab. The repository is at the level corresponding to Node 20 [-1029 m (-3375 ft)]. The vertical adiabatic surfaces assumed in this work are:

*Used at Rockwell Hanford Operations (RH0)

REFERENCE 17 GLASS CANISTERS,
10-YEAR COOLED,
DELAYED BACKFILL

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Figure A-1. Repository Configuration

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a) GLASS CANISTER

b) CERAMIC CANISTER

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Figure A-2. Emplacement Geometry

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TABLE A-1
 NODE LOCATIONS, TAP CODE
 (Nodes Located at Center of Slab)

Node Number	Slab Thickness [m (ft)]	Note
1	303 (994)	Isothermal for transient models
2	195 (640)	
3	195 (640)	
4	195 (640)	
5	97.5 (320)	
6	97.5 (320)	
7	48.8 (160)	
8	48.8 (160)	
9	24.4 (80)	
10	24.4 (80)	
11	12.2 (40)	
12	12.2 (40)	
13	6.1 (20)	Isothermal for steady-state model
14	6.1 (20)	
15	3.05 (10)	
16	3.05 (10)	
17	3.05 (10)	
18	1.22 (4)	
19	0.67 (2.2)	Fine grid for 3D models
20	0.67 (2.2)	
21	0.67 (2.2)	
22	1.22 (4)	
23	3.05 (10)	
24	3.05 (10)	
25	3.05 (10)	
26	6.1 (20)	
27	6.1 (20)	Isothermal for steady-state model
28	12.2 (40)	

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TABLE A-1
 NODE LOCATIONS, TAP CODE
 (Nodes Located at Center of Slab)
 (Continued)

Node Number	Slab Thickness [m (ft)]	Note
29	12.2 (40)	
30	24.4 (80)	
31	24.4 (80)	
32	48.8 (160)	
33	48.8 (160)	
34	97.5 (320)	
35	97.5 (320)	
36	195 (640)	
37	195 (640)	
38	390 (1280)	
39	480 (1576)	
		Isothermal for transient models

(1) through the centerline of the waste canisters, (2) through the center of the main tunnel, (3) a line midway between the horizontal shafts, and (4) a line midway between main tunnels. For the one-dimensional (1-D) transient model, there is no fine structure within each slab. Temperatures of Nodes 1 [0 m (0 ft)] and 39 [-2438 m (-8000 ft)] are held constant at 20 and 117⁰C (68 and 243⁰F), respectively.

For the three-dimensional (3-D) steady-state model, levels corresponding to Nodes 17 to 23, inclusive, have a fine structure as shown in Figure A-3. Temperatures of Nodes 13 and 27 are held constant at the values calculated by the 1-D transient analysis.

For the 3-D transient model, levels corresponding to Nodes 17 to 23, inclusive, also have a fine structure as shown in Figure A-3. Temperatures of Nodes 1 and 39 are held constant at 20 and 117⁰C (68 and 243⁰F), respectively. The starting temperatures for all nodes are either the initial field temperatures (prior to emplacement) or the temperatures calculated from the 3-D steady-state model for nodes in the levels corresponding to Nodes 13 to 27, inclusive, and from the 1-D transient model for the other nodes. The use of these models will be discussed below.

A Rockwell International version of the Thermal Analysis Program (TAP) code was used for these calculations. Running times were long, even with the relatively small number of nodes and connectors (285 nodes and 716 connectors, maximum). Therefore, rather than use Euler's method, a modified Dufort-Frankel method was used to calculate time steps in the TAP code. Running time was reduced by a factor of 5, but an instability can occur with the modified Dufort-Frankel method if the material properties change too rapidly with successive iterations. To check for this problem, the results from the TAP code using the modified Dufort-Frankel method were compared with results from the TAP code using Euler's method. The results (Table A-2) indicate that no significant instability exists for this network when the modified Dufort-Frankel method is used.

Figure A-3. Fine Structure of Horizontal Section of Repository

TABLE A-2
COMPARISON OF FINE-GRID, 3-D, TRANSIT SOLUTION
USING MODIFIED DUFORT-FRANKEL METHOD AND
EULER'S METHOD*

Time (Years After Emplacement)	Error in Modified Dufort-Frankel Method (°C)
0.5	-1.7
1.0	-1.2
1.5	-1.0

*Glass waste form, 10-year cooling prior to emplacement. Reported error is the error in temperature at surface of canister in the central location.

The purpose of these calculations was to determine, for different cooling times and waste locations, how many waste canisters (or how much waste) could be emplaced without exceeding temperature criteria (Table A-3). In order to do this, it was necessary to run a number of cases parameterizing cooling times, number of canisters per hole, waste source (unfractionated, 90% fractionated, or mixed), and waste loading. Runs with the 3-D transient code became prohibitively long unless peak canister temperatures were reached relatively soon after emplacement (less than ~10 years). For short-cooled waste, peak canister temperatures were indeed reached in a few years. For long-cooled or fractionated waste, peak canister temperatures occur a considerable time after emplacement. The approach taken then for long-cooled or fractionated waste was to first run the coarse-grid, 1-D code to estimate approximately when peak canister temperatures might be encountered. At some time prior to the estimated peak temperature time, the fine-grid, 3-D steady-state code was used to calculate the temperature distribution for the near-field. Selection of what constituted the near-field was based on an estimate of the error in the radial component of the temperature distribution when assuming isothermal slabs at the ends of the field. The maximum estimated error for the geometry used was 5°C. The temperature distribution for the steady-state near-field and the transient, 1-D far-field temperatures were then used as input to the 3-D transient code. The

success of this approach depends on the selected near-field region being well within the thermal wave. With the slowly decreasing heat generation rate of the waste forms, the longer the emplacement period, the less the error. The amount of error was assessed by comparing this route for the solution of the problem to a run with the 3-D transient code using initial field temperatures. The results (Table A-4) indicate that the error associated with this calculational approach is acceptably small for times greater than 20 years after emplacement.

TABLE A-3
LIMITATIONS ON REPOSITORY NEAR-FIELD TEMPERATURES

Glass centerline temperature	500 ^o C
Ceramic centerline temperature	1000 ^o C
Canister surface temperature	430 ^o C
Basalt (backfill or undisturbed) temperature	450 ^o C
Basalt/bentonite backfill temperature	300 ^o C

TABLE A-4
COMPARISON OF THE COARSE-GRID TRANSIENT — FINE-GRID
STEADY-STATE SOLUTION TO THE FINE-GRID
TRANSIENT ANALYSIS*

Steady-State Time (Years After Emplacement)	Error in Steady-State Solution (^o C)
5	+27.3
10	+14.4
20	+3.3
30	-0.8

*Glass waste form, 10-year cooling prior to emplacement. Reported error is the error in the temperature at the surface of the canister in the central location.

A node was not placed at the surface of the canisters because this would have resulted in significantly longer computer running times. Instead, the temperatures at the outer surface of the backfill region (surface of the hole) were calculated from the temperature nodes adjacent to, immediately above, and immediately below the waste nodes, assuming steady-state conditions with the heat load being proportioned according to the heat transfer areas. No heat transfer was assumed along the axis of the canisters. The three temperatures thus obtained were averaged and the canister surface temperature was calculated, assuming steady-state cylindrical symmetry and taking no credit for axial heat transfer in the canisters themselves. For the delayed backfill case, it was assumed that radiation was the only mode of heat transfer between the canister and the undisturbed basalt.* Waste form centerline temperatures were calculated assuming steady-state cylindrical symmetry, taking no credit for axial heat transfer. No overpack was assumed, i.e., for the glass waste form, all heat transfer within the canister was by conduction; for the ceramic form, one radiation barrier was assumed. With overpack, the glass waste form would have two radiation barriers, and the ceramic waste form, three. With overpack significantly higher glass centerline temperatures would be calculated. Waste form centerline calculations for all ceramic cases and for the reference glass case (i.e., 12-in.-diameter canister) indicated that under no emplacement condition assumed here would the centerline temperature criteria be exceeded.

Results from these calculations are presented in Tables A-5, A-6, A-7, and A-8. The most restrictive emplacement condition is with immediate bentonite/basalt backfill. The least restrictive emplacement condition is with delayed backfill. Therefore, if a particular configuration meets the temperature criterion for immediate bentonite/basalt backfill, it also meets the temperature criteria for immediate basalt backfill and for delayed backfill. If a particular configuration meets the temperature criterion for immediate basalt backfill, it also meets the temperature criterion for delayed backfill.

*RHO has recently added a convective heat transfer term to the heat transfer term for delayed backfill cases. If included in the analysis provided here, the addition of the convective term would increase the amount of waste that could be emplaced for the delayed backfill option.

TABLE A-5
ALLOWABLE WASTE BURIAL CONFIGURATIONS
HIGH-LEVEL WASTE

- 60 wt. % Waste Loading (ceramic)
- 25 wt. % Waste Loading (glass)

Except as noted, waste unfractionated

Case No.	Form	Cooling Time Prior to Emplacement (year)	Number of Canisters Per Hole	Waste Buried Per Hole (MTU)	Heat Generation Per Hole at Time of Emplacement (kW)
<u>Bentonite/Basalt Backfill (Temperature limit at can surface = 300°C)</u>					
2,3,4	Glass	10	17	34	33
18	Ceramic	50	<4	<30	<11
19	Ceramic	60	13	96	27
20	Ceramic	70	17	126	29
32	Ceramic ^a	10	17	133	31
<u>Basalt Backfill (Temperature limit at can surface = 430°C)</u>					
15,33	Ceramic	30	<4	<30	<16
16	Ceramic	40	13	96	42
17	Ceramic	50	17	126	44
<u>Delayed Backfill (Temperature limit at can surface = 430°C)</u>					
3	Glass ^b	10	17	34	33
5,6,7	Ceramic	10	<4	<30	<29
8	Ceramic	20	8	59	42
9	Ceramic	25	13	96	60
10	Ceramic	30	17	126	69

^a90% Cs and Sr removal

^bReference configuration

TABLE A-6
ALLOWABLE WASTE BURIAL CONFIGURATIONS
MIXED WASTE

- 60 wt. % Waste Loading (ceramic)
- 25 wt. % Waste Loading (glass)

Case No.	Form	Cooling Time Prior to Emplacement (year)	Number of Canisters Per Hole	Waste Buried Per Hole (MTU)	Heat Generation Per Hole at Time of Emplacement (kW)
Bentonite/Basalt Backfill (Temperature limit at can surface = 300°C)					
28	Glass	10	17	26	25
29	Ceramic	40	<4	<22	<10
30	Ceramic	45	5	28	11
31	Ceramic	50	17	95	33
Basalt Backfill (Temperature limit at can surface = 430°C)					
25	Ceramic	20	<4	<22	<16
26	Ceramic	25	8	45	28
27	Ceramic	30	17	95	52
Delayed Backfill (Temperature limit at can surface = 430°C)					
21	Ceramic	10	8	45	44
24	Ceramic	15	17	95	77

TABLE A-7
ALLOWABLE WASTE BURIAL CONFIGURATIONS
(Unfractionated, 10-Year-Cooled Waste)

Case No.	Waste Loading (wt. %)	Number of Canisters Per Hole	Waste Buried Per Hole (MTU)	Heat Generation Per Hole At Time of Emplacement (kW)
<u>High-Level Waste</u>				
Bentonite/Basalt Backfill (temperature limit at can surface = 300°C)				
-	19.5	3	7	7
-	19.0	7	16	16
-	18.5	12	27	27
-	18.0	15	33	32
-	17.9	17	37	36
Basalt Backfill (temperature limit at can surface = 430°C)				
-	30.0	4	15	14
-	29.5	6	22	21
-	29.0	9	32	31
-	28.5	11	39	37
-	28.0	14	48	47
-	27.5	17	58	56
Delayed Backfill (temperature limit at can surface = 430°C)				
11	48	4	24	23
12	45	10	55	54
13	40	17	84	81
<u>Mixed High- and Intermediate-Level Waste</u>				
Delayed Backfill (temperature limit at can surface = 430°C)				
21	60	8	45	44
22	55	14	72	70
23	53	17	84	82

TABLE A-8
ALLOWABLE WASTE BURIAL CONFIGURATIONS
(Unfractionated, 30-Year-Cooled, High-Level Waste)

Waste Loading (wt. %)	Number of Canisters Per Hole	Waste Buried Per Hole (MTU)	Heat Generation Per Hole At Time of Emplacement (kW)
<u>High-Level Waste</u>			
Bentonite/Basalt Backfill (temperature limit at can surface = 300°C)			
34.2*	1	4	2
34.0*	2	8	5
33.2	4	16	9
32.0	8	32	17
30.8	12	46	25
29.2	17	61	34
Basalt Backfill (temperature limit at can surface = 430°C)			
53.2*	1	7	4
53.0*	2	13	7
52.0	4	26	14
50.0	8	49	27
48.0	12	71	39
45.4	17	95	52
Delayed Backfill (temperature limit at can surface = 430°C)			
85*	1	10	6
84*	2	21	11
81	4	40	22
75	8	74	41
70	12	103	57
65	17	136	75

*Extrapolated

Calculations were made to optimize the glass canister diameter for the delayed backfill case. For 10-year-old waste and a glass canister with no overpack, the maximum allowable glass temperature 500⁰C (at centerline) occurs with a canister diameter of 17 in. With an overpacked canister, the maximum allowable glass temperature occurs at a waste form diameter slightly over the nominal value of 12 in.

The temperature of the waste form was calculated after 1000 years in the repository. For the standard glass case (no overpack), a temperature of 95⁰ was calculated (with a glass temperature limit of 100⁰C at 1000 years). For the worst ceramic case (17 cans, 60% waste loading, 10-year-old waste), a waste form centerline temperature of 180⁰C was calculated. (While not yet specified, this value is well within the capability of the ceramic waste form.)

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APPENDIX B

IMMOBILIZATION FACILITY COST ESTIMATE

A. CAPITAL COST ESTIMATE

The capital cost estimate for the immobilization facility is based on the estimate for the Savannah River Laboratory's Defense Waste Processing Facility (SRL-DWPF) given by McDonnell⁽⁹⁾ and based on the plant layout given by Dunson.⁽³³⁾ McDonnell's value includes separate costs for the basic structure, the process equipment, a canister shipment facility, and a local canister storage area. The estimated cost of the canyon structure used in the present report is based on the cost per square foot of the SRL-DWPF structure.

The crystalline ceramic plant as presently conceived involves three areas. The first houses the equipment in which the waste materials are handled and is, therefore, a hot canyon [1.22-m (4-ft) shielding wall] similar to the DWPF. The second area houses the HIPping gas recovery tankage and appurtenances. The third area houses the off-gas system, except for the first filter, which is within the hot canyon area. Figures 2 and 4 show the resulting CHLW immobilization plant plot plan used in this study. The off-gas system shown in Figure 4 becomes an extension of the ceramic process layout shown in Figure 2.

This concept was also applied to the glass plant to establish a parallel design for both waste form systems. Further, it was judged that less tankage would be required for a glass plant using acid CHLW, so that the CHLW plant area should be smaller than that of the DWPF. Figure B-1 shows the plant plot plan used for this study. The unit cost for the hot canyon area was based on McDonnell's analyses as follows: DWPF cost estimate,⁽⁹⁾ \$625E6 (1981 \$). This included a \$94E6 contingency and a \$26E6 allowance for a storage function, leaving \$505E6 as the cost of the basic plant. Of this, \$50E6 is assigned to equipment costs, leaving the DWPF structural base hot-canyon cost at \$455E6. The area of the DWPF plant is 1,093 m² (11,764 ft²). The basic structure cost of a plant of a different size was scaled using the 0.6 power dependence on the area ratio.

Figure B-1. Layout of Glass Production Canyon
for Commercial (Acid) Waste

DOE/ET/41900-17
(ESG-DOE-13391)

The process equipment cost was used uniformly at \$50E6. The canister shipment facility cost (which was a separate item in McDonnell's analysis) was used uniformly at \$25E6.

The local storage area cost (\$26E6) used by McDonnell was for 1000 units. At the base rate used in this study, this represents a 2/3-year storage for the glass plant and is considered adequate. For the ceramic plant systems, for which canister production rates are lower, the facility cost was scaled to the 1000-unit base using the 0.6 power of the annual production rate to provide a 1-year storage capability.

Table B-1 shows a summary of the components of the capital cost estimate for the immobilization plants.

B. OPERATING COST ESTIMATE

The operating costs for CHLW plants are based in part on an evaluation and an estimate of the work stations that must be manned for each plant. A four-shift-per-week schedule has been taken in both plants for all operations in the hot canyon, as well as for some maintenance and QA support. An additional maintenance, QA, and engineering staff working on a one-shift-per-week basis is included.

In the glass plant, the HLLW feed, the frit feed, and the melter stations have duplicate operators. The four-shift operation has 28 direct men per shift, and the one-shift operation has 18 men. This totals 130 EP, which, at a realization factor of 90%, gives a total direct staff of 145 men.

In the ceramic plant, the feed monitor, the calciner, and the HIP units have duplicate operators. The four-shift operation has 26 direct men per shift, and the one-shift operation has 19 men. This totals 123 EP, which, at a realization factor of 90%, gives a total direct staff of 137 men.

TABLE B-1
IMMOBILIZATION PLANT CAPITAL COST ESTIMATE DETAIL

Cases	Waste Form	Total Plant Area [m ² (ft ²)]	Cans per Year	Est. Cost Basic Structure (10 ⁶ \$)	Est. Cost Process Equipment (10 ⁶ \$)	Est. Cost Can. Ship Facility (10 ⁶ \$)	Est. Cost Can. Stor. Facility (10 ⁶ \$)	Est. Total Plant Cost (10 ⁶ \$)
1,2,3,4	Glass	876 (9424)	1500	398	50	25	26	499
5,6,7,8, 9,10,15, 16,17,18, 19,20,33	Ceramic	763 (8740)	406	380	50	25	15	470
11	Ceramic	763 (8740)	507	380	50	25	17	472
12	Ceramic	763 (8740)	541	380	50	25	18	473
13	Ceramic	763 (8740)	609	380	50	25	19	474
14	Ceramic	763 (8740)	696	380	50	25	21	476
21,24,25, 26,27,29, 30,31	Ceramic	763 (8740)	537	380	50	25	18	473
22	Ceramic	763 (8740)	585	380	50	25	19	474
23	Ceramic	763 (8740)	608	380	50	25	19	474
28	Glass	876 (9424)	1983	398	50	25	26	499
32	Ceramic	763 (8740)	384	380	50	25	15	470
34	Glass	876 (9424)	750	398	50	25	22	495

A staff increment of two men is assigned to ceramic plant scenarios for which more than 500 canisters per year are produced, and an increment of four men is assigned to ceramic plant scenarios for which more than 575 canisters per year are produced.

A second component of the operating cost are materials and supplies, which are estimated to be 50% of the labor cost.

The third component of the operating cost is the allowance for capital repair and maintenance. Based on the expected service life spans of the major equipment items, an allowance of 30% per year of the equipment capital is used for the glass plant; and an allowance of 20% per year of the equipment capital is used for the ceramic plant.

Table B-2 shows the summary of the components of the operating cost estimate for the immobilization plants.

TABLE B-2

IMMOBILIZATION PLANT OPERATING COST ESTIMATE DETAIL

Cases	Waste Form	Cans per Year	Labor Cost* (10 ⁶ \$/yr)	Materials & Supplies (10 ⁶ \$/yr)	Capital Repair/ Maint. (10 ⁶ \$/yr)	Total Estimated Cost (10 ⁶ \$/yr)	Total Estimated Cost (10 ⁶ \$/20 yr)
1,2,3,4	Glass	1500	11.6	5.8	15	32.4	648
5,6,7,8, 9,10,15, 16,17,18, 19,20,33	Ceramic	406	11.0	5.5	10	26.5	530
11	Ceramic	507	11.1	5.6	10	26.7	534
12	Ceramic	541	11.1	5.6	10	26.7	534
13	Ceramic	609	11.3	5.6	10	26.9	538
14	Ceramic	696	11.3	5.6	10	26.9	538
21,24,25 26,27,29, 30,31	Ceramic	537	11.1	5.6	10	26.7	534
22	Ceramic	585	11.3	5.6	10	26.9	538
23	Ceramic	608	11.3	5.6	10	26.9	538
28	Glass	1983	11.6	5.8	15	32.4	648
32	Ceramic	384	11.0	5.5	10	26.5	530
34	Glass	750	11.2	5.6	15	31.8	636

*Labor at \$80,000/man-year.

APPENDIX C CANISTER COST ESTIMATE

McDonell⁽⁹⁾ estimates the cost of a 0.61-m (24-in.) diameter by 3.05-m (10-ft) long canister to be \$10,000. The CHLW canister is 0.305 m (12 in.) in diameter by 3.05 m (10 ft) long and is made of Schedule 40S pipe (0.95-cm or 0.375-in. wall). A 3.05-m (10-ft) length weighs 225 kg (496 lb). The estimated cost of the external canister is:

Cylindrical section at \$11/kg (\$5/lb)	\$2,500
End caps (2)	2,000
Welding, QA cost	<u>1,000</u>
Total	\$5,500

The cost of the 0.41-m (16-in.) diameter by 1.07-m (3.5-ft) long Schedule 5 wall HIP can, whose wall weighs 44.5 kg (98 lb), is:

Cylindrical section at \$11/kg (\$5/lb)	\$ 500
End caps (2)	1,500
Welding, QA cost	<u>1,000</u>
Total	\$3,000

The estimated costs for the 0.305-m (12-in.) canisters used in this study are:

External canister	\$5,500
Ceramic canister assembly containing three HIP cans in the external canister	\$14,500

The estimated cost for the 0.43-m (17-in.) (glass) canister (Case 34) was scaled on a direct diameter ratio (17/12), to be \$7,790.

Table C-1 shows a summary of the estimates for the canister costs.

TABLE C-1
CANISTER COST ESTIMATE DETAIL

Case	Waste Form	Cans per Year	Total Estimated Cost (10 ⁶ \$/yr)	Total Estimated Cost (10 ⁶ \$/20 yr)
1, 2, 3, 4	Glass	1500	8.25	165
5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20	Ceramic	406	5.89	118
11	Ceramic	507	7.35	147
12	Ceramic	541	7.84	157
13	Ceramic	609	8.83	177
14	Ceramic	696	10.09	202
21, 24, 25, 26, 27, 29, 30, 31	Ceramic	537	7.79	156
22	Ceramic	585	8.48	170
23	Ceramic	608	8.82	176
28	Glass	1983	10.91	218
32	Ceramic	384	5.57	111
34	Glass	750	5.84	117

APPENDIX D

CANISTER TRANSPORTATION COST ESTIMATE

The estimation of the cost of transporting canisters to the repository is based on the assumption that the immobilization plant will be located about 2,400 km (1,500 miles) from the repository. This corresponds with the round-trip mileage assumed by McDonell⁽⁹⁾ for his estimate of \$10,000 per canister for truck transport. Transport by rail is about 70% as expensive, but rail shipment of CHLW canisters may not be allowed unless rail routes can be selected to avoid population centers.

Only one CHLW canister with its shielding (about 10,300 kg, or 50,000 lb, in total) can be handled by a tractor-semitrailer combination.

The canister transport estimate used in this study is \$10,000/canister. Table D-1 shows the summary of the estimates for the shipping costs.

TABLE D-1
SHIPPING COST ESTIMATE DETAIL

Case	Waste Form	Cans per Year	Total Estimated Cost (10 ⁶ \$/yr)	Total Estimated Cost (10 ⁶ \$/20 yr)
1, 2, 3, 4	Glass	1500	15.0	300
5, 6, 7, 8, 9, 10, 15, 16, 17, 18, 19, 20, 33	Ceramic	406	4.06	81
11	Ceramic	507	5.07	101
12	Ceramic	541	5.41	108
13	Ceramic	609	6.09	112
14	Ceramic	696	6.96	139
21, 24, 25, 26, 27, 29, 30, 31	Ceramic	537	5.37	107
22	Ceramic	585	5.85	117
23	Ceramic	608	6.08	122
28	Glass	1983	19.83	397
32	Ceramic	384	3.84	77
34	Glass	750	7.50	150

APPENDIX E
SPENT FUEL ELEMENT STORAGE FACILITY COST ESTIMATE

A. CAPITAL COST ESTIMATE

DOE/ET-0055⁽³⁴⁾ gives an estimated cost for a storage facility that can accommodate 5000 MTU of spent fuel elements as \$200E6 in 1978 dollars. It also gives an estimated cost for expansion of the facility in increments of 1000-MTU storage capacity at \$20E6 in 1978 dollars. The Chemical Engineering Plant Cost Index was used to escalate these costs to 1981 values, with a ratio of (297/218.8), or 1.36, so that the 5000-MTU unit cost is \$272E6, and the 1000-MTU additions are at \$27.2E6 each.

In this study, this type of waste storage was found to be more expensive than the cooled, dry storage of canisters, so that only Cases 2 and 5, which require 5 years' storage beyond the standard 5 years at the reactor site, involve SFE storage.

The capital cost for a 5-year capacity facility (15,000 MTU) is \$272E6 for the first 5000 MTU plus (10)(\$27.2E6) for the remaining 10,000 MTU. The total estimated capital cost is thus \$544E6 (Cases 2 and 5).

B. OPERATING COST ESTIMATE

DOE/ET-0055⁽³⁴⁾ gives an operating cost for a storage facility that handles 2000 MTU/year of spent fuel elements as \$6E6/year in 1978 dollars. The chemical engineering common labor rate ratio for 1981 rates vs 1978 rates shows a (2.05/1.75) = 1.17 escalation factor. An allowance of 25% is made to account for the 3000-MTU/year rate for the present study relative to the reference 2000-MTU/year rate. This assumes that one-half of the operating cost is fixed and the other one-half is proportional to the canister handling rate.

On these bases, the operating cost for the scenarios of Cases 2 and 5 are:

$$(\$6E6)(1.17)(1.25) = \$8.8E6/\text{year}.$$

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APPENDIX F
HIGH-LEVEL LIQUID WASTE STORAGE FACILITY

A. CAPITAL COST ESTIMATE

McDonnell⁽³⁵⁾ estimates the installed cost of a 3785-m^3 (1,000,000-gal) Savannah River Laboratory high-level liquid waste storage tank to be \$16E6 in 1981 dollars. This tank is carbon steel and suitable for the containment of neutralized waste. For containment of CHLW, which is acid waste, a stainless steel tank is required. Cost ratios for 316 SSTL vs C-STL tankage are given in the cost data compilation of Chilton.⁽³⁶⁾ Ratios of 4.7 and 4.8 are given for 379-m^3 (100,000-gal) tanks, and the ratio for a 1500-m^3 (400,000-gal) tank is about 5. For the present study, 4.8 is used, so the estimated cost of a 3785-m^3 (1E6-gal) SSTL tank for CHLW is \$76.8E6.

In this study, this type of waste storage was found to be slightly more expensive than the cooled, dry storage of canisters so that only Cases 4 and 7, which require 5-year storage beyond the standard 5 years at the reactor rate, involve HLLW storage.

A storage facility in which 3000 MTU equivalent per year of commercial HLLW can be stored for 5 years will require three 3785-m^3 (1E6-gal) tanks. One MTU of this waste is contained in 378 liters of HLLW so that one 3785-m^3 (1E6-gal) tank can be filled in $(1E6)(3.785)/(378)(3000) = 3.3$ years. At this time, the waste is 1.65 years old on the average. After the second tank is filled, 3.3 years later, the average age of the waste in the first tank will be 4.95 or 5 years, and its processing can begin. However, a third tank is now required to accept the next increment of HLLW.

The estimated capital cost of a 5-year HLLW storage facility is therefore $(3)(\$76E6)$, or \$228E6.

B. OPERATING COST ESTIMATE

McDonnell⁽³⁵⁾ estimates the operating cost of an HLLW storage tank to be \$600,000 per year. However, this includes the costs of operation of the cooling system, which is sized to handle 15- to 20-year-old defense waste. Five-year-old CHLW will have about 15 times as great a heat generation rate,⁽³⁷⁾ and will require an appropriately larger cooling system. If 10% of the total operating costs represent direct costs of cooling, then an incremental cost of about \$250,000 per year is indicated. Therefore, the operating costs for Cases 4 and 7 become $(3)(0.85E6) = \$2.55E6/\text{year}$ and \$51E6 for 20 years.

APPENDIX G

CONVECTION-COOLED DRY CANISTER STORAGE FACILITY COST ESTIMATE

A. CAPITAL COST ESTIMATE

McDonell⁽⁹⁾ gives an estimated cost for a dry canister storage facility with the capacity of 1,030 0.61-m (24-in.) canisters. The total cost of \$26E6 (1981 dollars) is divided among three components: (1) a fixed cost (\$10E6), which includes the end walls and other items that are not a function of the size, (2) a component cost (\$2E6), which includes the cost of heat transfer/ventilation equipment and is a function of the facility heat load, and (3) a space cost (\$14E6), which accounts for the size of the facility (walls, floors, etc.) and is a function of the number of canisters in storage. McDonell visualized a smaller structure than is needed to accommodate the storage times and volumes need in some of the scenarios described herein. The basic structure is therefore visualized as having a decontamination area adjacent to a hot maintenance area, with the storage areas located to either side as required. The maximum storage area unit is that required to accommodate 7,500 canisters.

The estimated fixed cost used in the present study is then \$10E6 per 7,500-canister storage unit.

The component cost for a facility is obtained by using the 0.6 power dependence of the heat load. The basic DWPF 0.61-m (24-in.) glass-filled canister heat load is 420 W⁽⁹⁾.

The estimated component cost is thus equal to:

$$\left[\frac{(\text{Number of canisters})}{1,030} \times \frac{(\text{average heat load, watts})}{420} \right]^{0.6} (\$2\text{E}6).$$

The space cost for a facility is obtained by using the 0.6 power dependence of the facility capacity. The reference building accommodates 1,030 canisters.⁽⁹⁾

The estimated space cost is thus equal to:

$$\left[\frac{(\text{Number of canisters})}{1,030} \right]^{0.6} (\$14\text{E}6).$$

Table G-1 summarizes the components of the capital cost of the canister storage facility for the scenarios used in this study.

B. OPERATING COST ESTIMATE

The operating costs for the canister storage facility are based on an evaluation of the staff required to handle the canisters and to maintain the facility. Canister handling must be a remote operation, and, even if no irregularities were to occur, several hours will be required to transfer a canister in the facility. Part of the staff would be on a four-shift-per-week basis, with the remainder on a one-shift basis. The work and guard crew per shift on the four-shift-per-week crews handling 1,500 or more canisters per year would have seven men, with an additional four men on a one-shift basis, for a total of 32 EP. The work and guard crew per shift on the four-shift per week crews handling up to 600 canisters per year would have 4 men, with an additional 7 men on a one-shift basis, for a total of 23 EP. For canister handling loads in the 600-750 per year, the crew would total 26 EP.

With a 90% realization factor, these facility staffs would number 36, 26, and 29 men.

A second component of operating costs is materials and supplies, which are estimated at 10% of the labor cost. The third component is the repair and replacement cost, which is estimated to be 5% of the capital cost per year.

Table G-2 summarizes the components of the operating costs for the canister storage facility.

TABLE G-1
CANISTER STORAGE CAPITAL COST ESTIMATE DETAIL

Case No.	Waste Form	Waste	Cans per Year	Storage Period (year)	Capacity Needed (Cans)	Heat Load (Watts/Can)	Est. Fixed Cost (10 ⁶ \$)	Est. Comp Cost (10 ⁶ \$)	Est. Space Cost (10 ⁶ \$)	Total Est. Cost (10 ⁶ \$)
1	Glass	CHLW	1,500	0	0	0	0	0	0	0
3	Glass	CHLW	1,500	5	7,500	3,240	10	22	46	78
6	Ceramic	CHLW	406	5	2,300	11,990	10	22	21	53
8	Ceramic	CHLW	406	15	6,090	7,160	10	32	41	83
9	Ceramic	CHLW	406	20	8,120	6,600	20	36	48	104
10, 15	Ceramic	CHLW	406	25	10,150	6,140	20	39	55	114
11	Ceramic	CHLW	507	5	2,535	9,590	10	22	24	56
12	Ceramic	CHLW	541	5	2,705	8,990	10	22	25	57
13	Ceramic	CHLW	609	5	3,045	8,000	10	22	27	59
14	Ceramic	CHLW	696	5	3,480	6,990	10	22	29	61
16	Ceramic	CHLW	406	35	14,210	5,420	20	45	67	132
17, 18	Ceramic	CHLW	406	45	18,270	4,860	30	49	79	158
19	Ceramic	CHLW	406	55	22,330	4,410	30	52	89	171
20	Ceramic	CHLW	406	65	26,390	4,020	40	54	98	192
21	Ceramic	Mixed	537	5	2,685	9,070	10	22	25	57
22	Ceramic	Mixed	585	5	2,925	8,310	10	22	26	58
23	Ceramic	Mixed	608	5	3,040	8,010	10	22	27	59
24	Ceramic	Mixed	537	10	5,370	9,080	10	34	38	82
25	Ceramic	Mixed	537	15	8,055	5,600	20	33	48	101
26	Ceramic	Mixed	537	20	10,740	5,320	20	37	57	114

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TABLE G-1
CANISTER STORAGE CAPITAL COST ESTIMATE DETAIL
(Continued)

Case No.	Waste Form	Waste	Cans per Year	Storage Period (year)	Capacity Needed (Cans)	Heat Load (Watts/Can)	Est. Fixed Cost (10 ⁶ \$)	Est. Comp Cost (10 ⁶ \$)	Est. Space Cost (10 ⁶ \$)	Total Est. Cost (10 ⁶ \$)
27	Ceramic	Mixed	537	25	12,425	4,650	20	39	65	124
28	Glass	Mixed	1,983	5	9,915	2,450	20	22	54	96
29	Ceramic	Mixed	537	35	18,795	4,100	30	45	80	155
30	Ceramic	Mixed	537	40	21,480	3,890	30	47	87	164
31	Ceramic	Mixed	537	45	24,165	3,670	40	49	93	182
32	Ceramic	90%	384	5	1,920	4,600	10	12	20	42
34	Glass	CHLW	750	5	3,750	6,490	10	22	30	62

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TABLE G-2
CANISTER STORAGE OPERATING COST ESTIMATE DETAIL

Case No.	Waste Form	Waste	Cans per Year	Est. Labor Cost* (10 ⁶ \$/yr)	Est. Material Cost (10 ⁶ \$/yr)	Est. R/R Cost (10 ⁶ \$/yr)	Total Est. Cost (10 ⁶ \$/yr)	Total Est. Cost (10 ⁶ \$/20 yr)
1	Glass	CHLW	0	0	0	0	0	0
3	Glass	CHLW	1,500	2.88	0.29	3.9	7.1	142
6	Ceramic	CHLW	406	2.08	0.21	2.7	5.0	100
8	Ceramic	CHLW	406	2.08	0.21	4.2	6.5	130
9	Ceramic	CHLW	406	2.08	0.21	5.2	7.5	150
10, 15	Ceramic	CHLW	406	2.08	0.21	5.6	7.9	158
11	Ceramic	CHLW	507	2.08	0.21	2.8	5.1	102
12	Ceramic	CHLW	541	2.08	0.21	2.8	5.1	102
13	Ceramic	CHLW	609	2.32	0.23	2.9	5.5	110
14	Ceramic	CHLW	696	2.32	0.23	3.1	5.7	114
16	Ceramic	CHLW	406	2.08	0.21	6.6	8.9	178
17, 18	Ceramic	CHLW	406	2.08	0.21	7.9	10.2	204
19	Ceramic	CHLW	406	2.08	0.21	8.6	10.9	218
20	Ceramic	CHLW	406	2.08	0.21	9.6	11.9	238
21	Ceramic	CHLW	537	2.08	0.21	2.9	5.2	104
22	Ceramic	Mixed	585	2.08	0.21	2.9	5.2	104
23	Ceramic	Mixed	608	2.32	0.23	3.0	5.6	112
24	Ceramic	Mixed	537	2.08	0.21	4.1	6.4	128
25	Ceramic	Mixed	537	2.08	0.21	5.1	7.4	148
26	Ceramic	Mixed	537	2.08	0.21	5.7	8.0	160

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TABLE G-2
CANISTER STORAGE OPERATING COST ESTIMATE DETAIL
(Continued)

Case No.	Waste Form	Waste	Cans per Year	Est. Labor Cost* (10 ⁶ \$/yr)	Est. Material Cost (10 ⁶ \$/yr)	Est. R/R Cost (10 ⁶ \$/yr)	Total Est. Cost (10 ⁶ \$/yr)	Total Est. Cost (10 ⁶ \$/20 yr)
27	Ceramic	Mixed	537	2.08	0.21	6.2	8.5	170
28	Glass	Mixed	1,983	2.88	0.29	4.8	8.0	160
29	Ceramic	Mixed	537	2.08	0.21	7.8	10.1	202
30	Ceramic	Mixed	537	2.08	0.21	8.2	10.5	210
31	Ceramic	Mixed	537	2.08	0.21	9.1	11.4	228
32	Ceramic	90%	384	2.08	0.21	2.1	4.4	88
34	Glass	CHLW	750	2.08	0.21	3.0	5.3	106

*Labor cost based on \$80,000 per man-year.

APPENDIX H

REPOSITORY COST ESTIMATE

A. CAPITAL COST ESTIMATE

McDonnell⁽⁹⁾ reports an estimated preparation cost of a vertical emplacement basalt defense high-level waste repository of 72,000 sites at \$2.25 billion, which reduces to \$31,250 per site. At present, a horizontal emplacement repository design is under consideration, with the expectation that overall repository costs can be reduced. Figure A-1 shows the arrangement of parallel canister-site boreholes used in the thermal analyses used in this study. Each 61-m (200-ft) long borehole can accommodate up to 17 canisters. When their heat loadings are high, however, the number per hole must be restricted to meet the thermal limitations.

Westinghouse-AESD⁽²⁷⁾ gives an estimate of the total emplacement costs for both defense high-level waste (DHLW) and commercial high-level waste (CHLW). The DHLW unit cost for the 0.61-m (24-in.) canister is given as \$78,250, and the CHLW unit cost for the 0.305-m (12-in.) canister is \$52,740. This amounts to a reduction of about 30%, which is ascribed to the difference in size of the packages, which requires less overpack and allows smaller boreholes to be used. McDonnell's corresponding DHLW estimate is $(\$60,500 + \$31,250) = \$91,750$, or about 15% more than the W-AESD value.

For this study, the repository capital costs have been taken at McDonnell's value, \$31,250 per site, with an adjustment being made for scenarios in which fewer than 17 canisters per hole are allowed. That adjustment is the factor $(17/n)$, where n is the maximum number allowed.

Table H-1 summarizes the repository capital cost estimates for the scenarios used in this study.

TABLE H-1
REPOSITORY CAPITAL COST ESTIMATE DETAIL

Case No.	Waste Form	Waste	Cans/Year	Cans/Hole	Est. Repos. Cost (10 ⁶ \$/yr)	Est. Repos. Cost* (10 ⁶ \$/20 yr)
1,2,3,4	Glass	CHLW	1500	17	46.9	938
5,6,7, 15,18	Ceramic	CHLW	406	3	71.9	1438
8	Ceramic	CHLW	406	8	27.0	540
9,16,19	Ceramic	CHLW	406	13	16.6	332
10,17,20	Ceramic	CHLW	406	17	12.7	254
11	Ceramic	CHLW	507	4	67.3	1346
12	Ceramic	CHLW	541	10	28.7	574
13	Ceramic	CHLW	609	17	19.0	380
14	Ceramic	CHLW	696	17	21.8	436
21,26	Ceramic	Mixed	537	8	35.7	714
22	Ceramic	Mixed	585	14	22.2	444
23	Ceramic	Mixed	608	17	19.0	380
24,27,31	Ceramic	Mixed	537	17	16.8	336
25,29	Ceramic	Mixed	537	3	95.1	1902
28	Glass	Mixed	1983	17	62.0	1240
30	Ceramic	Mixed	537	5	57.1	1142
32	Ceramic	90%	384	17	12.0	240
34	Glass	CHLW	750	17	23.4	468

*Because the reference 72,000-site repository would handle waste for many years based on the 10-MTU/day processing rate used in this study, a 20-year total of the unit capital costs is used in the estimated total cost for waste handling for each scenario.

B. OPERATING COST ESTIMATE

McDonell⁽⁹⁾ reports the estimated operating cost for a repository handling 0.61-m (24-in.) DHLW canisters to be \$60,500/unit. This includes the costs of package assembly (overpack), handling, and emplacement. He also reports a similar estimate for an 0.46-m (18-in.) DHLW canister at \$50,000/unit. The difference is primarily in the cost of the package assembly and is related to the reduced amount of overpack needed for the smaller canister.

Westinghouse-AESD⁽²⁷⁾ gives an estimate of the package manufacturing and assembly and of the repository handling and treatment costs for 0.61-m (24-in.) DHLW canisters at \$66,050/unit, total. An analogous estimate for 0.305-m (12-in.) CHLW canisters is also given by W-AESD at \$39,840/unit, total.

For this study, the McDonell approach has been extended to obtain an estimated cost for a 0.305-m (12-in.) CHLW canister. A \$10,500/unit difference is based on the canister size reduction from 0.61 to 0.46 m (24 to 18 in.), for which the reduction in material is about 20%. The reduction in the amount of material between a 0.61-m (24-in.) and a 0.305-m (12-in.) canister is about 40%, so the reduction in package assembly cost is taken \$10,000 below McDonell's 0.46-m (18-in.) canister estimate, or at \$40,000/unit. This is consistent with the \$39,840 Westinghouse-AESD figure. For Case 34, which involves a 0.43-m (17-in.) canister, the unit cost was scaled to \$48,300.

This study has included the costs associated with the overpack in the canister packaging costs at the repository, following the lead of McDonell and Westinghouse-AESD. However, there is a question that is yet to be resolved regarding the need for an extensive overpack.

Table H-2 summarizes the repository operating cost estimates for the scenarios used in this study.

TABLE H-2
REPOSITORY OPERATING COST ESTIMATE DETAIL

Case No.	Waste Form	Waste	Cans/Year	Est. Operating Cost (10 ⁶ \$/yr)	Est. Operating Cost (10 ⁶ \$/20 yr)
1,2,3,4	Glass	CHLW	1500	60	1200
5,6,7,8, 9,10,15, 16,17,18, 19,20	Ceramic	CHLW	406	16.2	324
11	Ceramic	CHLW	507	20.3	406
12	Ceramic	CHLW	541	21.6	432
13	Ceramic	CHLW	609	24.4	488
14	Ceramic	CHLW	696	27.8	556
21,24,25, 26,27,29, 30,31	Ceramic	Mixed	537	21.5	430
22	Ceramic	Mixed	585	23.4	468
23	Ceramic	Mixed	608	24.3	486
28	Glass	Mixed	1983	79.3	1586
32	Ceramic	90%	384	15.4	308
34	Glass	CHLW	750	36.2	724

APPENDIX J
SELF-SHIELDED CANISTER COST ESTIMATE

The cost estimate for Case 33, the use of a heavy-walled self-shielded canister, is based on the following sequence of steps. The commercial PWR fuel elements are held at the reactor site for 5 years and are processed to recover uranium and plutonium values. The CHLW is then immediately fed to the immobilization plant and processed through the hot isostatic press (HIP) operation. The HIP cans are then loaded directly into the heavy-walled self-shielded canisters and seal-welded. (The standard 0.305-m (12-in.) canister is eliminated.) The self-shielded canisters are then shipped to a storage site with no additional shield requirements, which could reduce shipping costs in that cask costs would be reduced. Case 33 parallels Case 10, in that the canisters are stored until the waste is 30 years old, thus requiring 25 years' storage in the canister. The canister can be cooled by natural convection, and therefore the storage facility cost can be minimal. At a waste age of 30 years, the self-shielded canisters can be transported to the repository and emplaced. The heavy wall of the canister is assumed to provide adequate long-term protection of the waste from any leaching process, so that preparation and handling costs are minimal. The capital cost of the repository is assumed to be \$31,250 per site, as estimated in Appendix H.

The estimated costs of the individual steps are developed below:

Costs through reprocessing are not applicable to waste handling.

Immobilization Plant Costs. The processing rate and schedule is identical to that of Case 10, for which a capital cost of \$457E6 and a 20-year operating cost of \$530E6 were developed in Appendix B.

Self-Shielded Canister Cost. Westinghouse-AESD⁽²⁷⁾ evaluates three materials for self-shielded canisters. Required are 22,000 kg (22 metric tons) of steel; component manufacture and package assembly costs are estimated at \$50,340/unit for cast steel, \$39,640/unit for ductile cast iron, and \$29,140/unit for gray iron. Using the mid-range material, ductile cast iron, and three HIP cans, the estimated cost becomes:

$$(3)(\$3,000) + \$39,640 = \$50,000/\text{unit}.$$

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The costs associated with loading these canisters are considered to be included in the immobilization facility operating costs. Canister costs are therefore

$$(\$50,000)(406) = \$20\text{E}6/\text{year}$$

or

$$\$400\text{E}6/20 \text{ year}.$$

Shipping. The shipping cost is taken as that established in Appendix D, neglecting any reduction that might be possible in reduced cask amortization costs. The 20-year shipping cost at 406 canisters/year is therefore \$81E6.

Storage. The capital cost of the canister storage facility is taken at the fixed cost of the facility described in Appendix G, \$10E6 per 7500 units. The estimated cost of the facility to house $(406)(25) = 10,150$ units is thus \$20E6, for the two storage units needed.

The operating cost of the self-shielded canister storage facility is based on the operating staff developed in Appendix G, but with a smaller staff because there should be less maintenance, repair, and general upkeep expense in a simpler facility. A 20-man staff is assumed, with a maintenance and supplies budget at 10% of the labor budget per year and a replacement/repair allowance of 3% of the capital per year. The annual operating costs thus become

Labor (20)(\$80,000)	=	\$1.60E6
Maintenance and Supplies	=	0.16E6
Replacement/Repair (0.05)(\$20E6)	=	<u>1.00E6</u>
Total		\$2.76E6/year

The 20-year canister storage operating cost estimate is then \$55E6.

Repository. The capital cost estimate for the repository expense is taken at $(\$31,250/\text{unit})(406 \text{ canisters}) = \$12.7\text{E}6/\text{year}$ so that for 20 years, the cost becomes \$254E6.

The operating cost of the repository when handling self-shielded canisters involves about the same amount of handling and emplacement costs as standard canisters. Based on the repository handling presentation of McDonnell,⁽⁹⁾ an estimated cost of \$15,000/unit is identified. Using this value, the annual repository operating cost for emplacing the self-shielded canisters is

$$(406)(\$15,000) = \$6.1\text{E}6/\text{year}.$$

For a 20-year period, the total estimated cost becomes \$122E6.

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APPENDIX K WASTE HANDLING COST ESTIMATE FOR FRENCH WASTE

It is of interest to prepare a cost estimate for the management of French waste. Their reported production rate is one canister per day of a glass waste form containing 15 wt. % waste. Their plan is to store these canisters for 50 years to allow time to design and build a repository.

At 15% waste loading, one canister will contain waste equivalent to 1.2 MTU, so that their immobilization plant capacity is one-eighth that used as reference elsewhere in this report. At the same waste handling rate, immobilization in a ceramic form at 60 wt. % and 5.2-g/cm³ density will require the production of one canister (three HIP cans) every 6 days. This is a very slow rate, and the continuous operation of such a small facility will be relatively expensive.

The immobilization facility hot cell area for a 1.2-MTU/day glass plant is estimated to require 557 m² (6000 ft²). These are nominally half the size of a 10-MTU/day plant. The unit cost for these areas is based on Appendix B.

The estimated capital costs for the glass plant become:

Hot cell (6000/11,764) ^{0.6} (\$455E6)	= \$304E6
Equipment	30E6
Can shipment facility	25E6
Surge storage ($\frac{300}{1000}$) ^{0.6} (\$25E6)	= <u>13E6</u>
Total	\$372E6

The estimated capital costs for the ceramic plant are based on a 465-m² (5000-ft²) hot cell area:

Hot cell (5000/11,764) ^{0.6} (\$455E6)	=	\$272E6
Equipment		30E6
Can shipment facility		25E6
Surge storage ($\frac{50}{1000}$) ^{0.6} (\$26E6)	=	<u>4E6</u>
Total		\$331E6

The estimated operating costs for the glass immobilization plant are based on a work crew of 120 direct men, a 50% allowance for materials and supplies, and an equipment replacement/repair allowance of 30% of capital cost. The estimate becomes:

Labor (120)(\$80,000)	=	\$ 9.6E6/year
Materials	=	4.8E6/year
Replacement/repair	=	<u>9.0E6/year</u>
Total		\$23.4E6/year
or		\$468E6/20 years

The estimated operating costs for the ceramic immobilization plant are based on a work crew of 100 direct men, a 50% allowance for materials and supplies, and an equipment replacement/repair allowance of 20% of capital cost. The estimate becomes:

Labor (100)(\$80,000)	=	\$ 8.0E6/year
Materials, supplies		4.0E6/year
Replacement/repair		<u>6.0E6/year</u>
Total		\$18E6/year
or		\$360E6/20 years

The canister costs are based on Appendix C and are:

$$\text{Glass form (300/year)(20 years)(\$5,500) = \$33E6}$$

$$\text{Ceramic form (50/year)(20 years)(\$14,500) = \$15E6}$$

The transportation costs are taken at one-half those used in Appendix D because travel distances in Europe are almost certainly to be less than those in the United States. These costs are:

$$\text{Glass form (300)(20)(\$5,000) = \$30E6}$$

$$\text{Ceramic form (50)(20)(\$5,000) = \$5E6}$$

The dry storage capital costs are based on Appendix G. For the glass waste form, a $300 \times 50 = 15,000$ capacity is needed. The average heat load for a continuously operating facility is 625 W/MTU or 750 W/canister. The capital costs then become:

$$\text{Fixed cost (2)(\$10E6) = \$ 20E6}$$

$$\text{Component cost } \left[\frac{15,000 \times 750}{1,030 \times 420} \right]^{0.6} (\$2E6) = 14E6$$

$$\text{Space cost } \left[\frac{15,000}{1,030} \right]^{0.6} (\$14E6) = \underline{70E6}$$

$$\text{Total } \$104E6$$

The capital cost estimate of dry storage of the ceramic waste form is also based on Appendix G. For the ceramic, a $50 \times 50 = 2500$ canister capacity is needed. The canister heat load is $(7.39 \text{ MTU/can})(625 \text{ W/MTU}) = 4620 \text{ W/can}$. The capital costs then become:

$$\text{Fixed cost = \$10E6}$$

$$\text{Component cost } \left[\frac{2500 \times 4620}{1030 \times 420} \right]^{0.6} (\$2E6) = 14E6$$

$$\text{Space cost } \left[\frac{2500}{1030} \right]^{0.6} (\$14E6) = \underline{24E6}$$

$$\text{Total } \$48E6$$

The operating costs for the glass storage facility are based on Appendix G. A 26-man crew is assigned, the materials and supplies allowance is 10%, and the replacement/repair allowance is 5% of capital. The operating cost estimate becomes:

$$\begin{array}{rcl}
 \text{Labor (26)($80,000)} & = & \$2.08\text{E6/year} \\
 \text{Materials and supplies} & = & 0.21\text{E6/year} \\
 \text{Replacement/repair} & = & \underline{5.0\text{E6/year}} \\
 \text{Total} & & \$7.3\text{E6/year} \\
 \text{or} & & \$146\text{E6/20 years}
 \end{array}$$

The operating cost for the ceramic storage facility is based on a 20-man crew, with a 10% allowance for materials and supplies and a 5% of capital allowance for replacement/repair. The estimate is:

$$\begin{array}{rcl}
 \text{Labor (20)($80,000)} & = & \$1.6\text{E6/year} \\
 \text{Supplies} & & 0.16\text{E6/year} \\
 \text{Replacement/repair} & = & \underline{2.5\text{E6/year}} \\
 \text{Total} & = & \$4.3\text{E6/year} \\
 \text{or} & & \$86\text{E6/20 years}
 \end{array}$$

The repository costs are based on Appendix H, in which the \$31,250/canister cost for capital and the \$40,000/canister cost for operating are developed. The costs are:

$$\begin{array}{rcl}
 \text{Glass — Capital (20)(300)($31,250)} & = & \$188\text{E6} \\
 \text{Ceramic — Capital (20)(50)($31,250)} & = & \$ 31\text{E6} \\
 \text{Glass — Operating (20)(300)($40,000)} & = & \$240\text{E6} \\
 \text{Ceramic — Operating (20)(50)($40,000)} & = & \$ 40\text{E6}
 \end{array}$$

Table K-1 shows a summary of these estimated costs for the immobilization of French waste. The difference in these estimates is \$665E6, which amounts to a potential savings by the use of the ceramic waste form of about \$33E6/year.

TABLE K-1
WASTE MANAGEMENT OF FRENCH WASTE

Cost Element	Glass Plant	Ceramic Plant
Canister/year	300	50
Immobilization Plant		
Capital	\$ 372E6	\$331E6
20-year operating	468	360
Canisters	33	15
Transportation	30	5
Dry storage		
Capital	104	48
Operating	146	86
Repository		
Capital	188	31
Operating	240	40
Total	\$1581E6	\$916E6

Difference = \$665E6, or \$33.3E6/year

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APPENDIX L

SUMMARY OF ESTIMATED CAPITAL AND 20-YEAR OPERATING COSTS OF THE WASTE HANDLING FOR A 3000-MTU/YEAR REPROCESSING PLANT

The estimated 20-year capital and operating costs in the foregoing appendices are collected and totaled in Table L-1 for each of the 34 waste disposal scenarios addressed in this study.

TABLE L-1
CAPITAL AND 20-YEAR OPERATION WASTE HANDLING COST SUMMARY
(Millions of 1981 Dollars)

Case	Immobilization Plant		Canisters	Storage		Ship	Repository		Total Est. Cost
	Capital	Operating		Capital	Operating		Capital	Operating	
1	499	648	165	0	0	300	938	1200	3750
2	499	648	165	544 ^a	176 ^a	300	938	1200	4470
3	499	648	165	78	142	300	938	1200	3970
4	499	648	165	230 ^b	51 ^b	300	938	1200	4031
5	470	530	118	544 ^a	176 ^a	81	1438	324	3681
6	470	530	118	53	100	81	1438	324	3114
7	470	530	118	230 ^b	51 ^b	81	1438	324	3242
8	470	530	118	83	130	81	540	324	2276
9	470	530	118	104	150	81	332	324	2109
10	470	530	118	114	158	81	254	324	2049
11	470	534	147	56	102	101	1346	406	2164
12	473	534	157	57	102	108	574	432	2139
13	474	538	177	59	110	112	380	488	2338
14	476	538	202	61	114	139	436	556	2522
15	470	530	118	114	158	81	1438	324	3233
16	470	530	118	132	178	81	332	324	2165
17	470	530	118	158	204	81	254	324	2139
18	470	530	118	158	218	81	1438	324	3337
19	470	530	118	171	218	81	332	324	2244
20	470	530	118	192	238	81	254	324	2207

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TABLE L-1
CAPITAL AND 20-YEAR OPERATION WASTE HANDLING COST SUMMARY
(Millions of 1981 Dollars)
(Continued)

Case	Immobilization Plant		Canisters	Storage		Ship	Repository		Total Est. Cost
	Capital	Operating		Capital	Operating		Capital	Operating	
21	473	534	156	57	104	107	714	430	2575
22	474	538	170	58	104	117	444	468	2373
23	474	538	176	59	112	122	380	486	2347
24	473	534	156	82	128	107	336	430	2246
25	473	534	156	101	148	107	1902	430	3851
26	473	534	156	114	160	107	714	430	2688
27	473	534	156	124	170	107	336	430	2330
28	499	648	218	96	160	397	1240	1586	4844
29	473	534	156	155	202	107	1902	430	3959
30	473	534	156	164	210	107	1142	430	3216
31	473	534	156	182	228	107	336	430	2446
32	470	730 ^c	111	42	88	77	240	308	2466
33	470	530	400	20	55	81	254	122	1932
34 ^d	495	636	117	62	106	150	468	724	2758

^aSpent-fuel element storage (SFE)

^bHigh-level liquid waste storage (HLLW)

^cCosts of the HLLW fractionation have been added to the basic immobilization plant figure;

^d400 for capital and 200 for operation

^dOptimized canister size for glass waste form

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