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Argonne, Illinois 60439

COMPARISON OF COSTS FOR SOLIDIFICATION OF
HIGH-LEVEL RADIOACTIVE WASTE SOLUTIONS:
GLASS MONOLITHS VS. METAL MATRICES

by

L. J. Jardine, R. E. Carlton,*
and M. J. Steindler

Chemical Engineering Division

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*TERA Corporation, Berkeley, California

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ABSTRACT

A comparative economic analysis was made of four solidification processes for liquid high-level radioactive waste. Two processes produced borosilicate glass monoliths and two others produced metal matrix composites of lead and borosilicate glass beads and lead and supercalcine pellets. Within the uncertainties of the cost (1979 dollars) estimates, the cost of the four processes was about the same, with the major cost component being the cost of the primary building structure. Equipment costs and operating and maintenance costs formed only a small portion of the building structure costs for all processes.

1.0 INTRODUCTION AND BACKGROUND

1.1 Foreword

This report contains the results of estimates, made by the TERA Corporation [TERA], of costs associated with four processes for conversion of high-level radioactive waste from commercial reprocessing of irradiated reactor fuel to solids suitable for disposal in geologic formations. The purpose of the study is the comparison of costs. The goal of the study is a valid and transparent analysis of costs. The study was motivated by the results of preliminary cost comparisons that appeared in ERDA-77-43 [ERDA-1977B]. Considerable effort revealed that this preliminary study was not in reality a comparison of costs on a common basis. Those data were neither consistent nor sufficiently well identified to allow explication of the puzzling results.

The scope of the present study had to be limited, resulting in a narrow selection of processes and the exclusion of some aspects of waste disposal (e.g., transportation). Each alternative is scaled to process the same quantity of high-level waste (HLW). The annual number of canisters is held constant at 300 for each process. The size and the weight of canisters is allowed to change to accommodate the variation in waste density in the canisters for each process. Estimates of additional disposal costs attributed to factors not considered in this study (e.g., transportation) would need to be made with these differences in mind in order to be able to use the cost data that are contained in this study.

The present work suffers from some of the chronic difficulties attending any cost study. Technologies are not well defined and usually are not based on full-scale experience for such entirely remotely operated and remotely maintained facilities. Fundamental "ground rules" changed in the course of the study, and new scientific information invalidated several assumptions. Depending on the focus of interest, various readers may find their favorite topics inadequately addressed, optimistically treated, or even ignored.

We believe that this cost study provides general conclusions that remain valid even in light of criticisms of omission or inadequate analysis. Further, this cost study, unlike any other similar study available in the recent open literature, is explicit in all of the important assumptions and "rules of thumb" that are used to devise the final results. Hence, readers who perceive inadequacies in the magnitudes of our numbers can develop improved values from data contained herein.

The analysis of cost, especially of conceptual plants and processes, is acknowledged to be an art built on experience. Successful cost analysis methodology is generally not published in order to protect the effort and expense of the experience needed to ensure its success. The present study is not distinguished by an unusually small estimated margin of error, but this error margin is believed to be no larger than that found in most published studies of this kind. The reader is cautioned not to extract from these data more than is warranted by the combination of a lack of full-scale experience and the lack of all the details needed for actual construction and licensed operation.

1.2 Purpose and Scope

The purpose of this report is to provide a preliminary evaluation of the major differences in costs of four waste solidification alternatives that have been proposed for high-level liquid wastes (HLLW) generated in the reprocessing of irradiated (spent) reactor fuel. The evaluation is based upon conceptual process designs for which detailed capital and operating cost estimates were made. The cost estimates are not intended to be of budgetary quality, but rather are intended to identify major differences in costs between the four alternatives. The four principal waste solidification methods evaluated include:

- Spray calcination of HLLW, followed by melting in a continuous glass melter with glass-making additives to form a glass waste form
- Direct feed of HLLW and glass-making additives into a continuous glass melter to form a glass waste form
- Production of glass beads (by) direct feed of high-level liquid waste and glass-making additives into a continuous glass melter, followed by casting into a lead metal matrix
- Spray calcination of HLLW, followed by agglomeration with additives into pellets, which are then sintered to form supercalcine and then cast into a lead metal matrix

Conceptual processing systems have been developed for each of these methods in sufficient detail so as to allow preliminary (conceptual) engineering cost estimates to be made of the capital and operating costs associated with a solidification facility required for each process. The cost estimates do not include costs for process development, since it was assumed for this study that the technologies are already sufficiently developed. The cost evaluation was structured to allow direct comparisons of each of the waste solidification methods.

Costs are not included in this study for long-term HLLW storage, HLLW recovery and transfer from tanks, solidified waste transportation, geologic waste disposal, or potential impact of a specific plant site on the solidification facility. It has been found that long-term HLLW storage potentially affects and can distort cost differences in waste solidification options [TERA], but these differences are outside the scope of this study. Waste transportation and geologic disposal costs should not be strongly dependent on the waste solidification cost. Similarly, other external plant site factors are assumed to impact each alternative in the same way. Costs for process equipment include the installation costs, and operating costs for the solidification alternatives include all labor, consumables, and utilities services. The total solidification facility costs were based on an Allied General Nuclear Services (AGNS) design [HALL] as modified for the various solidification alternatives of this study; facility costs were subdivided into those for concrete, structural steel, building support services and stainless steel liner plate.

An additional fifth HLW solidification alternative consisting of a supercalcine monolith was only partially evaluated, and the results are presented in Appendix A. This alternative cannot be directly compared with the four primary alternatives.

1.3 Objectives

The primary objective of this study is to provide a comparison of capital and operating costs for several alternative methods of processing high-level liquid radioactive waste into canisters of solid waste. Numerous variations of processing methods are possible. However, for the purposes of this study, only the waste forms and processes identified above have been examined. It is believed that these processes adequately represent the technologies which have been postulated and/or developed.

For this study, the preliminary conceptual designs of waste-processing and solidification systems were developed, and preliminary equipment and facility layouts were prepared. The evaluation focused upon the total costs for each solidification method, with emphasis upon the differences among the processes. Additionally, an attempt was made to ensure that the process design basis would take into account the conditions that reflect the present nuclear industry situation; thus, the solidification process designs would be associated with waste from relatively aged spent fuel (e.g., $\geq$ three years, as discussed in Appendix B) rather than wastes from 160-day-old spent fuel as generally employed in previous facility design studies. Attempts have been made to minimize the impact of external factors upon the actual solidification systems while focusing on differences in process design, and, subsequently, to determine how these differences are reflected in the systems' capital and operating costs. As a result, HLLW tank storage and tank recovery, solidified-waste transportation, and geologic storage/disposal are excluded from this evaluation, as are the reprocessing facility and other site facilities. The reprocessing facility is presumed to be independent of waste solidification and reflects a design philosophy similar to that in the AGNS design where the solidification facility would be an independent but related plant facility [HALL].

1.4 High-Level Waste Sources

High-level liquid wastes are defined by the federal government to be those aqueous wastes which result from the operation of the first-cycle solvent-extraction system and the concentrated wastes from subsequent extraction cycles (or their equivalent) in a facility which reprocesses irradiated reactor fuels [CFR]. For this report, light-water reactor (LWR) commercial fuels are considered to be the feedstock to the reprocessing facility and subsequently to the solidification facility; however, the technology and evaluation methods are also generally applicable to methods required to solidify defense high-level waste. The reference sources of high-level liquid wastes contain 0.5 percent of the uranium and plutonium, 0.1 percent of the iodine, no noble gases, and more than 99 percent of the fission products and remaining transuranic elements, extracted as waste from spent fuel at a fuel reprocessing plant. As such, the HLLW includes most of the radioactivity associated with the reprocessing of spent fuel. Appendix C describes the composition of a typical reference HLLW. It is this liquid waste, containing fission products and small quantities of transuranic materials which requires handling, solidification, and disposal as high-level waste.

Reprocessing plants are now designed to reduce to a practicable minimum the quantity of liquid radioactive waste generated. The highly radioactive acidic waste from the solvent extraction system is concentrated by evaporation both to decrease the volume requiring storage and to recover the nitric acid for reuse. The degree of volume reduction by evaporation varies with the fuel reprocessing conditions used, but generally a tenfold to fiftyfold decrease in waste volume is achieved.

The concentrated liquid wastes from the evaporators contain essentially all the nonvolatile waste components from the spent fuel. This liquid waste may be stored for an interim period or processed immediately by solidification. In this study it is assumed there is no interim storage period.

Liquid wastes from commercial LWR fuel reprocessing may be stored as acidic solutions in stainless steel tanks, whereas certain neutralized defense waste (alkaline) solutions and slurries are currently stored in carbon steel tanks. Waste storage tanks are in underground stainless steel-lined concrete vaults which are provided with instrumented sumps to continuously monitor the integrity of the contained tanks. During storage, decay heat is removed through water-cooled coils submerged in the commercial waste. These tanks are equipped with appropriate instrumentation to monitor temperature, tank levels, and leakage, as well as equipment to maintain agitation of the tank contents [HALL].

High-level waste resulting from DOE-, defense-, and R&D-related programs exists in a variety of forms at a number of sites. Total volumes of high-level waste solutions and slurries stored at the Savannah River Plant, Idaho Nuclear Engineering Laboratory (INEL) and Hanford sites currently equal about 266,000 m³ (9.4 million ft³) and are projected to decline to about 257,600 m³ (9.1 million ft³) in 1985 as a result of evaporation and processing [cesium/strontium recovery and encapsulation (Hanford); calcining of HLW (INEL)]. Liquids constitute about 40 percent of the current volume, with salt cake and sludge representing nearly all of the remainder [DEUTCH]. Currently, no

commercial LWR wastes are being generated. However, some high-level wastes have accumulated through the operation of the only commercial reprocessing plant in the United States, the Nuclear Fuel Service (NFS) facility at West Valley, New York (which has been shut down). These wastes currently total about 2,320 m³ (82,000 ft³) and are stored in liquid form in underground tanks [DEUTCH]. Current HLW quantities and forms are summarized in Table 1. Table 2 describes the waste quantities projected to exist in 1985 for DOE, defense, and R&D sources [DEUTCH].

1.5 Regulations

The present regulations dealing with liquid high-level waste are limited to a formal definition of high-level liquid waste as found in the Code of Federal Regulations [CFR]. This definition identifies HLLW as aqueous waste resulting from the operation of the first-cycle solvent-extraction system and the concentrated wastes from subsequent extraction cycles (or their equivalent) in a facility for reprocessing irradiated reactor fuels. Regulations stipulate that HLLW must be solidified within five years after reprocessing and placed in sealed canisters prior to shipment off-site. These canisters must then be transferred to a federal repository no later than ten years after reprocessing. Additional criteria and regulatory rulemaking guidelines are being considered by the Nuclear Regulatory Commission. At present, the NRC's activities in these areas have been curtailed to reflect the present policy of the federal government with regard to LWR fuel reprocessing.

Prior to shipment to a federal repository, the solidified high-level waste may be stored in a solid form after its initial production. This interim storage allows radioactivity to decay, which reduces the waste's heat generation rate. Following this storage period, the solidified high-level waste would then be shipped to a federal repository. Regulations currently in effect, developed by the Department of Transportation and the NRC, govern the shipment and handling of the solidified high-level waste [NRC-1977B]. Currently, there are no regulations governing the design of the waste repository, waste-product performance requirements, and waste package requirements for solidified HLW, though such regulations are currently being developed by the NRC. In addition, various DOE contractors have addressed the questions of performance criteria of waste and repository systems.

1.6 Technologies

Solidification of high-level liquid waste has not been demonstrated in an operating commercial reprocessing plant in the U.S. However, a large amount of research, development, and demonstration has been done in the U.S. and abroad to develop technology for converting HLLW into various forms, with the major emphasis being on the generation of glass (vitrification) [IAEA, HARMON, NRC-1979, NRC-1978]. The state of high-level radioactive waste research in this country is evolving, through laboratory pilot-scale experiments, into large-scale tests. In addition, attempts are being made to develop criteria for site selection, suitable environmental standards, and licensing [NUCLEAR NEWS].

Table 1. Existing High-Level Waste (HLW)^a [DEUTCH]. (Thousands, as of 10/1/77)

	Total, ft ³	Liquid, ft ³	Salt Cake, ft ³	Sludge, ft ³	Calcine, ft ³	Cs;Sr Capsule Number
<u>Department of Energy (Defense)</u>						
Savannah River	2,900	1,700	900	300	0	0
Idaho	404	350	0	0	54	0
Hanford	6,102.5	1,600	2,800	1,700	0	2.5
Sub Total	9,406.5	3,650	3,700	2,000	54	2.5
<u>West Valley (NFS)^b</u>						
Neutralized (600,000 gal)	80.2	80.2	0	0	0	0
Acidic (12,000 gal)	1.6	1.6	0	0	0	0
Sub Total	81.8	81.8	0	0	0	0
TOTAL	9,488.3	3,731.8	3,700	2,000	54	2.5

^aThis reflects the present form of the existing waste, not necessarily the form that would be placed in permanent disposal.

^bThe neutralized waste is stored in a 750,000-gal carbon steel tank while the acidic waste is in a 15,000-gal stainless steel tank.

Table 2. Projected High-Level Waste [DEUTCH]. (Thousands as of 1/1/85)

	Total, ft ³	Liquid, ft ³	Salt Cake, ft ³	Sludge, ft ³	Calcine, ft ³	Cs;Sr Capsule, Number
<u>Department of Energy (Defense)</u>						
Savannah River	2,630	560	1,660	410	0	0
Idaho		310	150	0	0	1600
Hanford ^a	6,122.9	1,340	3,060	1,720	0	2.9
Sub Total	9,062.9	2,050	4,720	2,130	160	2.9
<u>West Valley (NFS)</u>						
Neutralized	80.2	80.2	0	0	0	0
Acidic	1.6	1.6	0	0	0	0
Sub Total	81.8	81.8	0	0	0	0
TOTAL	9,144.7	2,131.8	4,720	2,130	160	2.9

^aThis assumes that the entire backlog of fuel from the N reactor at Hanford has been processed by 1/1/85.

Field projects currently under way include:

- At INEL, high-level wastes have been stored as acid in tanks and solidified by fluidized-bed calcination for the past quarter century. The waste is presently being calcined and the solid placed in storage bins on site.
- At the Savannah River Plant, liquid wastes in tanks are scheduled to become a solidified product by the end of the century, with perhaps some interim on-site storage until shipment to a federal repository. Part of the process will include a separation step to remove the large volume of soluble salts from the waste.
- The West Valley radioactive wastes consist of several spent fuel elements, reprocessed fuel wastes (in storage tanks as liquid-sludge), and a low-level waste burial area. The major concern is for the waste in storage tanks, and several options appear available for ultimate disposal [TID].
- At Rocky Flats, the transuranic waste will probably be vitrified with ultimate disposal at a suitable site. Bench-scale testing has been done, and a pilot plant is under construction.
- At Battelle Pacific Northwest, three fuel bundles of spent fuel from the Point Beach reactor (20,900 MW·d/MT removed in 1972) have been reprocessed and the wastes solidified in a vitrification project that has been under way for about two years. The first canister of borosilicate glass was filled by spray calcination, with in-can melting in early 1979. [WHEELWRIGHT]
- At the Nevada Test Site, pressurized water reactor (PWR) fuel elements have been encapsulated in stainless steel canisters and placed in the ground, to test the various thermal and chemical interactions between fuel, cladding, canister, and environment. In the future, boiling water reactor (BWR) fuel elements will be buried in a similar fashion.
- Considerable data have been collected regarding site suitability, potential resources, and geologic formations in the vicinity of the Waste Isolation Pilot Plant (WIPP) project.
- In Sweden, the radioactive waste disposal program will consist of a six-month cooling period of fuel elements at the reactor site, followed by an away-from-reactor (AFR) storage for an additional two to ten years. Site selection for the AFR is currently in progress. Later, HLW from the reprocessing can be solidified to borosilicate glass and cooled for an additional 30 years in an intermediate, underground (about 90-m deep) repository with forced-air cooling. Finally, the material would be encapsulated in a lead titanium container with ultimate disposal at about 500 m underground in a deep geological formation, probably a granite-type rock in southeast Sweden.

- The French have been exploring calcination and vitrification of radioactive wastes for many years, and a pilot plant has been in operation since 1969. The AVM vitrification process at Marcoule is the world's first method of solidifying radioactive waste to be demonstrated on a commercial scale and began "hot" operation in July 1978.

In commercial reprocessing in the U.S., a fluidized-bed calciner for converting high-level liquid wastes to calcine in the General Electric Company's Midwest Fuel Recycle plant was licensed for construction. The calciner was installed in the plant, but the facility has not been started up; thus the technology is not presently being utilized. Two additional companies that have considered light water reactor fuel reprocessing facilities (Allied General Nuclear Services and Exxon Nuclear Company) have proposed HLLW solidification plans that include vitrification as either their main-line process or principal option. Calcination and vitrification are also being considered, by DOE [TID], for the Nuclear Fuel Services' West Valley facility.

Several other alternative solidified high-level waste forms have been or are being investigated. These include supercalcine, SYNROC, titanates, pelletized calcine and glass ceramics, metal matrix waste forms (such as glass beads or uncoated pellets in a lead matrix), multibarrier types (such as coated pellets in a metal matrix), and cermets. While none of these solidified waste forms has been developed to the extent of glass or calcine, their potential is being examined by various organizations involved in the high-level waste management program in the United States and elsewhere. Four different waste solidification processes which incorporate some or all of the technologies presently being seriously considered for the disposal of high-level liquid waste can be defined. These include:

- Borosilicate glass monolith via spray calcine feed
- Borosilicate glass monolith via direct liquid feed
- Glass bead-metal matrix composite via lead encapsulated glass beads.
- Ceramic pellet-metal matrix composite via lead encapsulated supercalcine pellets.

These four processes were selected as the reference case studies in this report.

1.7 Evaluation Methodology

The four waste forms that were chosen as representative of current technology generally encompass the characteristics of the waste solidification alternatives currently being considered. In all processes, heat is applied to drive off volatile constituents (primarily water and nitrates), resulting in either a dried or calcined solid or a melt that will cool to a monolithic solid. Each system requires the use of specially designed process schemes and equipment.

Costs estimates are based upon estimated operating and maintenance costs, and capital costs associated with the equipment for each of the alternatives. The methodology employed in developing the cost estimates is summarized as follows:

1. Develop conceptual process flowsheet designs for the solidification process systems.
2. Determine processing rates, quantities and capacities needed to meet the process requirements for each alternative.
3. Develop lists of major equipment and perform equipment-sizing calculations based upon process requirements.
4. Develop a generic solidification facility arrangement which serves as the basis for determining building costs for all alternative solidification processes.
5. Prepare capital cost estimates for the installed cost of the equipment and solidification facilities
6. Prepare cost estimates of the annual operating and maintenance costs for each alternative based upon process requirements.
7. Determine the differential capital and operating and maintenance costs for each alternative, and determine the total cost differential among the alternatives.

1.8 Evaluation Base and Assumption

A generic solidification plant was designed from the AGNS Barnwell Plant and the proposed Exxon Plant. An attempt was made to use those procedures and techniques considered to exhibit the more likely future technology and safety features. The evaluation bases and the common assumptions are discussed below.

1.8.1 High-Level Waste Characterization

- a. The LWR spent fuel from the uranium cycle is reprocessed after irradiation to 33,000 MW·d/MTU* at 30 MW/MTU. Spent fuel is reprocessed no sooner than three years after discharge from the reactor.
- b. HLLW is raffinate from the first-stage extraction in the Purex Process and does not include intermediate or low-level wastes. The HLLW generation rate from the Purex Process is 5,000 L/MTU and preconcentration and nitric acid recovery steps are performed prior to interim storage or solidification processing. The concentrated HLLW feed rate to the interim storage tanks is 756 L/MTU and 378 L/MTU to the solidification process. The nitrate concentration

*MTU = metric tonnes uranium

in the feed to the solidification process is 3.9M, which includes 2M as nitric acid and 1.9M as heavy metal nitrate salts.

- c. HLW composition is similar to the reference PW-7 composition (see Appendix C).

1.8.2 Solidification Facility Design

- a. The reprocessing plant capacity is 1,500 MTU/y and the solidification facility capacity matches the output of the reprocessing plant. The solidification plant produces 300 canisters per year.
- b. The reprocessing plant is designed in compliance with the applicable NRC Regulatory Guides in effect as of January 1979. The reprocessing facility is also designed in accordance with ANSI N101.3-1977 "Guide to Principal Design Criteria for Nuclear Fuel Reprocessing Facilities;" ANSI N305-1975 "Design Objectives for Highly Radioactive Solid Material Handling and Storage Facilities in a Reprocessing Plant;" ANSI N300-1975 "Design Criteria for Decommissioning of Nuclear Fuel Reprocessing Plants;" and other similar standards and criteria.
- c. Solidification facilities are separate from the reprocessing facilities. Solidification equipment sizing is based on an 80-percent capacity factor and availability is 300 days per year. Solidification facilities are designed for a service life of 15 years for the purpose of calculating an annual cost based on a capital recovery factor method (Section 6.0). Service life for major components is equal to that of the facility.
- d. Equipment and tank cells, and canister storage pools are lined with stainless steel liners.
- e. Facilities housing the solidification equipment, interim HLW storage tanks and canister storage pool are designed to withstand the effects of earthquakes and other natural phenomena (such as tornadoes, hurricanes and floods). Solidification process equipment for handling liquids is designed for Seismic Category 1.
- f. Canister post-filling storage is in an underwater storage pool until time of shipment. Canisters are stacked two high in the pool in racks. Solidified waste is shipped from the facility within seven years after solidification.

1.8.3 Waste Canister

- a. Maximum allowed heat content of canister is 5.0 kW at shipment to the federal repository.

- b. Canisters are fabricated of 304L stainless steel.
- c. Special facilities for off-standard waste forms are not required in the base case design.

1.8.4 Miscellaneous

- a. Operating basis will be three shifts, 7 days per week coverage.
- b. Cost estimates are developed on the basis of constant 1979 dollars.
- c. Indirect field cost, engineering cost contingency, and interest during construction (IDC) cost factors are included which are typical of nuclear facility construction costs. IDC is applied for a four-year period to the capital cost at an interest rate of 12 percent per year.
- d. Decontamination and decommissioning costs are not included.

1.8.5 Comments

Several of the bases for this study require comment. The effect of the heat-load limitation on waste canisters has become apparent only recently, and hence the 5-kW limit may appear to be high by perhaps a factor of two to five. The value for this study was selected based on high values that were formerly part of the plans for repository designs. The 80-percent-capacity factor may be slightly higher than that used elsewhere but the differences are not excessive. The assumption of the life of equipment is in some cases (e.g., glass melter) unreasonably long but, as is evident from the conclusions, not highly significant to the final costs.

Finally, it has been pointed out by several reviewers that the conceptual design is simplistic, does not address the (important) problems of remote operation and maintenance (e.g., replacement of melter electrodes), and results in generally low cost estimates. These comments are likely to be valid and require a restatement of the scope and objectives of this study. In the absence of experience or detailed process designs, estimates were developed to compare the costs of four processes for the conversion of concentrated HLLW to solids that could be used for final geologic disposal. Those areas in which future refinements of design point to necessary revisions or additions that significantly affect costs will need to be reevaluated when the quality of the new information warrants.

2.0 CONCEPTUAL HIGH-LEVEL WASTE SOLIDIFICATION FACILITIES

2.1 Introduction

The buildup of fission products and the depletion of fissile material in reactor fuel requires that the reactor operator annually replace between

one-fourth and one-third of the fuel elements with fresh fuel. The fuel elements removed from the reactor still contain (1) about one-fourth of the original ^{235}U and (2) plutonium produced from ^{238}U during irradiation. Irradiated spent fuel can be reprocessed to recover usable fissile material (both uranium and plutonium) from spent reactor fuel elements. The recovered uranium is sent to a plant for reenrichment and eventual recycle to reactors in replacement fuel elements. The recovered plutonium can be converted to plutonium dioxide and then blended with uranium dioxide (UO_2) for recycle in replacement fuel elements.

Figure 1 shows, as a simplified flow diagram, the major operations performed at the spent fuel reprocessing plant complex. Fuel elements are stored temporarily (>3 years in this study) at the reactor site and/or at the reprocessing site to permit the short half-life radionuclides to decay before the fuel elements are processed. Spent fuel assemblies are received at the reprocessing plant in heavily shielded shipping casks. The fuel assemblies are spaced arrays of sealed tubes (cladding) containing UO_2 or mixed-oxide fuel pellets. Cladding encapsulating the fuel consists of Zircaloy, although stainless steel tubing also has been used. In general, all planned commercial plants will use mechanical means to break up the fuel elements. Chemical systems for recovering special nuclear material are adaptations of the Purex process. Specific methods for mechanical disassembly of the fuel elements, dissolution of fuel material, and recovery of uranium and plutonium differ somewhat from plant to plant. Exposed fuel material is dissolved by hot nitric acid, leaving behind the chopped tubing (hulls). The solution contains the dissolved fuel material and is processed through a series of solvent extraction or ion-exchange steps. Solvent extraction separates the fission products and unwanted actinide elements from uranium and plutonium and then separates and purifies uranium and plutonium. These steps are carried out in centrifugal contactors or a series of pulse columns, or both. Ion exchange, an alternative method for purifying plutonium, is carried out in equipment containing beds of ion exchange resin. The purified uranyl nitrate is converted to uranium hexafluoride (UF_6), which is the chemical form of uranium feed for reenrichment in the uranium isotope enrichment plants. The purified plutonium nitrate product solution [$\text{Pu}(\text{NO}_3)_4$] is converted to solid plutonium dioxide (PuO_2).

The high-level radioactive waste contains most of the fission products and transuranium elements that were separated from the uranium and plutonium products. These wastes are initially confined in high integrity tanks within vaults. High-level radioactive liquid wastes must be converted to solids within five years after generation, and within 10 years after generation, these solid wastes must be transferred to a federal repository for storage. In addition to the high-level radioactive wastes, a variety of other wastes results from operations of the separation facility, the UF_6 conversion facility, the PuO_2 conversion facility, and waste handling. These wastes may be contaminated by long-lived fission products, transuranic nuclides, or both.

The conceptual design of the reprocessing plant is a modular facility. This is consistent with the design concept incorporated in the Allied-General Nuclear Services [AGNS] Barnwell Nuclear Fuel Plant at Barnwell, South Carolina [HALL], as well as the proposed Exxon facility. By using modules

Fig. 1. Simplified Flow Diagram of Reprocessing Plant Complex [NRC-1973]

as a basis, the solidification portion of the facility can be viewed as a stand-alone unit and is evaluated here as such. Shared facilities with the reprocessing plant would then be limited to auxiliary services such as electrical power, makeup water, ventilation treatment, cooling water, etc. Appendix D describes a typical reprocessing facility design.

The Waste Solidification Facility (WSF) in this study is defined as the portion of a reprocessing facility complex that converts concentrated high-level liquid wastes (HLLW) into a solid form. All process steps, commencing after HLLW recovery from storage tanks and including feed preparation, waste processing or solidification, and canister storage, are included in the Waste Solidification Facility. The generic WSF is based upon an AGNS general layout. The generic arrangement serves as the base of reference case and differences between various waste solidification processes are reflected by increasing or decreasing the building size to the extent necessary to account for the equipment, canister storage, and operational changes.

2.2 Waste Solidification Facility

The Waste Solidification Facility would be located adjacent to but separate from the Central Reprocessing Facility. It would receive liquid waste solutions aged three years or more from the waste storage tank farm complex (excluded from the scope of this study), convert the liquids to a solid, and store and facilitate the transfer of solidified high-level wastes during interim storage until eventual shipment off-site.

The WSF would contain the waste solidification equipment, canister sealing, inspection and decontamination equipment, canister interim storage pool, off-gas treatment equipment, and remote maintenance facilities in various separate process cells. The primary process functions performed in each of the major cells are presented in Table 3. All process cells in the WSF would be completely lined with stainless steel to facilitate decontamination, should a spill or equipment failure occur.

Table 3. Primary Functions of Major Process Cells
in the Waste Solidification Facility

Area	Function
High-level cell	Prepare feed for solidification system
Waste solidification cell	Solidify liquid waste; load canisters; weld canister closures.
Off-gas treatment cell	Treat off-gas from WSF process vessels
Canister decontamination cell	Decontaminate outer surfaces of canisters; transfer filled canisters to storage pool facility
Hot maintenance cell	Perform remote maintenance on contaminated equipment

The cells would be surrounded by limited access areas for operating, controlling and maintaining the processes in the cells. All operational and maintenance activities in the process cells would be performed remotely using viewing windows and/or closed-circuit television (CCTV) cameras, manipulators, and cranes. Details of the WSF for each of the waste-form alternatives are discussed in Section 3.

2.3 Waste Solidification Facility Design

The design of the Waste Solidification Facility depends on the design of the Central Reprocessing Facility, since the equipment sizing and the resultant building design are determined by the design bases of the Central Reprocessing Facility, the limitations put on the waste form by the transportation and repository acceptance criteria, and the assumed HLW characteristics.

2.3.1 Waste Solidification Design Bases

The Waste Solidification Facility is designed to solidify the HLLW resulting from the reprocessing of 1500 MTU per year. This capacity is compatible with the capacity of the Reprocessing Facility and will solidify the equivalent of 5 MTU of high-level liquid waste per day. The availability of the Waste Solidification Facility is assumed to be 300 days per year, three shifts per day, seven days per week. Equipment sizing is based upon an 80-percent capacity factor. These design bases are representative of a mature technology.

Structures, systems, and components that confine radioactive materials are designed to withstand the effects of earthquakes and other natural phenomena such as tornadoes, hurricanes, and floods. Cooling water, from wells or a surface stream, is returned to a surface stream via cooling towers and cooling ponds. All process and ventilation air which might contain radioactive contaminants is treated and filtered before discharge to the atmosphere. The plant has standby diesel equipment for emergency power, an emergency water distribution system, water treatment systems, boilers to produce steam for heating and process needs, air compressors, electrical switchgear, and sanitary waste-treatment systems.

The specific volume of the liquid waste was selected on the basis of solubility limits, to be 378 L/MTU (expected range of 378 to 567 L/MTU), which is based upon the value proposed by AGNS at the Barnwell plant [AGNS]. This value is expected to minimize accumulation of suspended solids and subsequent corrosion in the presolidification equipment, and will vary depending upon the actual separation chemistry used in the reprocessing facility. The equipment sizing is directly related to this value and would vary in size accordingly, depending on the actual reprocessing scheme. Similarly, the composition (non-volatile solids and nitrate concentration) of the wastes is also dependent upon the actual reprocessing plant flowsheet design. Different nitrate and non-volatile solids concentrations would have an impact on the equipment type and sizing. Typical HLLW characteristics were used in this evaluation and are presented in Appendix C.

The process waste to be solidified has been aged to three years after discharge from the reactor. This aging may take place either by storing the spent fuel (the current industry practice) or by reprocessing and storing

the liquid HLW. It is economically advantageous to select solidifying wastes from >3-year-aged fuel because of the reduced radiation sources and consequent reductions in facility cost. After seven years of additional on-site storage, the solid waste is shipped to a repository for disposal. At the time of shipment to the repository, a heat-load limitation of 5 kW per canister of solidified waste is imposed. These design bases determine the number and size of canisters processed per unit time and the size of the interim storage pool. Details concerning the age of the waste to be processed are provided in Appendix B.

Waste-form and thermal-loading criteria most directly impact the WSF designs. These criteria identify a potential solidification technology or technologies and establish the subsequent waste canister design. If the thermal loading is regulated to other than 5 kW/canister (which is probably high by a factor of two to five), process design changes could occur which would conceivably impact the facility design as well as the resultant cost estimates. Parametric evaluations of either increased or decreased canister heat load and their resultant impacts were not performed. Further transportation criteria might result in dispersibility characteristics for the waste form, which would require an increased quantity of inert carrier (*i.e.*, metal matrix or glass) or change the design bases for the waste canisters.

2.3.2 Solidification Facility Design Concept

The operation of the facilities would be centered in the major waste-processing solidification cells (see Table 3) in which most of the facility functions are performed. A cell is a reinforced concrete hot cell, lined with stainless steel. Operation and maintenance activities would be performed remotely using a crane. Specialty activities would be performed by appropriate equipment such as master-slave manipulators and self-propelled dollies. The major facility equipment includes feed tanks, solidification equipment, weld-inspection stations, canister storage racks, and a canister decontamination cubicle. Installation and removal of equipment would be done through shielding doors in the cell. The air lock system of the canister decontamination cubicle would permit placement and removal of the canister. Activities in the cell may be observed through four shielding glass windows and/or up to three periscopes. The operating, service, and pipe galleries, which house personnel and equipment necessary for cell operations, are located adjacent to the cell.

In addition to the major waste processing solidification cells, the Waste Solidification Facility contains the support and process facilities necessary for operation. These additional components of the facility include:

- Canister storage pool and associated cooling and purification system
- Shipping-cask loading facility
- Control room

- Staging and maintenance area
- Miscellaneous waste-processing areas
- Emergency utility area
- Office, personnel, and storage areas
- Operating galleries

Typical generic conceptual design layouts of the facility showing the spatial relationship of the components are provided in Figs. 2-5. These layout drawings are based upon the AGNS conceptual design [HALL] and have been compared with recent DOE studies [DOE-1979, LARSON-1978]. These drawings are provided to illustrate the generic layout and spatial relations between major components of the WSF and do not reflect any design effort beyond the generic conceptual design previously discussed. The layouts establish a generic WSF which may be expanded or contracted as required by the solidification process flowsheets, as discussed in Sections 3.0 and 4.0. This generic WSF is assumed to contain the equipment associated with the borosilicate glass monolith/spray calcine feed flowsheet. In general, only four areas were varied (*i.e.*, expanded and contracted); these were the High-Level Cell, Waste Solidification Cell, Off-Gas Treatment Cell, and Canister Storage Pool. The remaining areas in Figs. 2-5 were assumed to remain constant for all the solidification alternatives.

3.0 WASTE SOLIDIFICATION PROCESSES

For each of the HLLW solidification alternatives, conceptual process flowsheets and equipment designs were developed for the purpose of evaluating solidification facility costs and operating and maintenance costs. Each process is associated with five basic components which are discussed with respect to each waste-form alternative:

1. Feed Preparation (High-Level Cell)
2. Solidification process (Solidification Cell)
3. Off-gas treatment (Cell)
4. Canister handling
5. Canister storage (Pool)

Building-related factors (surface areas and building volumes) are discussed in Section 4.0.

3.1 Borosilicate Glass Monolith/Spray Calcine Feed (Reference Case)

This waste form is similar to that proposed for the AGNS facility [HALL]. The process utilizes spray-calciner technology [BONNER] coupled with the ceramic melter being developed at Pacific Northwest Laboratories [BUELT]. The conceptual process flowsheet developed for this alternative is shown in Fig. 6. This is the reference solidification alternative which is consistent with the generic WSF described in Section 2. Details of the equipment specifications described below are given in Table E-1 of Appendix E.

Fig. 2. Generic Conceptual Design, Lowest Elevation Plan. Vi

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sign, Lowest Elevation Plan. View at 0 ft 0 in. elevation.

Fig. 3. Generic Conceptual Design, Middle Elevation Plan. View at 30

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Fig. 4. Generic Conceptual Design, Upper Elevation

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ai Design, Upper Elevation Plan. View at 60 ft 0 in. elevation.

Fig. 5. Generic Conceptual Design, Sectional

SECTION A-A

SECTION B-B

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ITEM	STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION		HLW	Calciner Feed	Calciner Feed	Atomizing Air	Calciner Effluent	RU Absorber Effluent	Off Gas	Calciner Condensate	Calcine Product
RATE		98.4 L/hr	98.4 L/hr	98.4 L/hr	16.7 m ³ /min	47.6 m ³ /min	--	21.8 m ³ /min	90.7 L/hr	--
TEMP °C		60	60	60	40	350	--	40	--	--
PRESSURE		atm	40 psig	40 psig	760 torr	684 torr	--	740 torr	--	684 to
DENSITY g/cm ³		1.30	1.30	1.30	1.13 k /m ³	0.49 kg/m	--	1.00 kg/m	1.00	--
H ⁺ IO ₃ (M)		2.0	2.0	2.0	--	--	--	--	--	--
CATION NITRATES kg/hr		23.9	23.9	23.9	--	--	--	--	--	--
WATER kg/hr		90.8	90.8	90.8	--	90.8	90.8	0.09	90.7	--
NO _x kg/hr		--	--	--	--	14.6	14.6	14.6	2.70 x 10 ⁻	--
NH ₃ kg/hr		--	--	--	--	--	--	--	--	--
H ₂ kg/hr		--	--	--	1002	1002	1002	1002	--	--
O ₂ kg/hr		--	--	--	286	289	289	289	--	--
SOLIDS kg/hr		12.8	12.8	12.8	--	0.0128	0.0128	--	0.0128	12.8

Fig. 6. Flow Diagram for Borosilicate

SOLID

MEL

9
alcine
Produc

94 to

12.8

	3	4	5	6	7	8	9	10	11
r	Calciner Feed	Atomizing Air	Calciner Effluent	RU Absorber Effluent	Orf Gas	Calciner Condensate	Calciner Product	Frit	Canister
r	98.4 L/hr	16.7 m ³ /min	47.6 m ³ /min	--	21.8 m ³ /min	90.7 L/hr	--	--	--
	60	40	350	--	40	--	--	ambient	1100
	40 psig	760 torr	684 torr	--	740 torr	--	684 torr	atm	atm
	1.30	1.13 k /m ³	0.49 kg/m	--	1.00 kg/m	1.00	--	--	--
	2.0	--	--	--	--	--	--	--	--
	23.9	--	--	--	--	--	--	--	--
	90.8	--	90.8	90.8	0.09	90.7	--	--	--
	--	--	14.6	14.6	14.6	2.70 x 10 ⁻	--	--	--
	--	1002	1002	1002	1002	--	--	--	--
	--	286	289	289	289	--	--	--	--
	12.8		0.0128	0.0128		0.0128	12.8	33.4	46.2

Fig. 6. Flow Diagram for Borosilicate Glass/Spray Calcine Feed

at

IR

SOLIDIFICATION
CELL

(5)

(6)

RUTHENIUM
ADSORBER

(7)

VOG
CELL VOG SYSTEM
FIGURE 10QUENCH
TOWER

9

QUENCH TOWER
SURGE TANKCOOLING
WATER

CERAMIC MELTER

FLOW
DIRECTION

(8)

8	9	10	11
Insate	Calciner Product	Unit	Canister
L/hr	--	--	--
--	--	ambient	1100
--	684 torr	atm	atm
00	--	--	--
--	--	--	--
--	--	--	--
.7	--	--	--
x 10 ⁻	--	--	--
--	--	--	--
--	--	--	--
128	12.8	33.4	46.2

Rosilicate Glass/Spray Calcine Feed

3-2

TERA CORPORATION

3.1.1 Feed Preparation (High-Level Cell)

Concentrated HLLW is transferred to a stainless steel feed preparation tank (2960 L) in the high-level cell where the HLLW is sampled and chemically adjusted as necessary. The actual transfer of the waste from the preprocessing plant complex of the waste is excluded from this study. Since the HLLW will generate substantial decay heat, cooling to the tank is provided to maintain the waste temperature below 60°C. The tank is also equipped with an agitator to maintain particle suspension and mix any chemicals added to the HLLW.

The HLLW is then transferred to the calciner feed tank (2960 L), a stainless steel tank provided with cooling coils to maintain the waste at 60°C. An agitator is provided to maintain particle suspension. Both the feed preparation and calciner feed tanks are sized for one batch (1890 L) of HLLW to provide one canister of final waste product. Two tanks are required--one being readied for solidification processing while the calciner is being fed at a controlled rate from the other tank.

3.1.2 Solidification (Solidification Cell)

Waste is pumped from the calciner feed tank into the solidification cell and to the spray calciner at 98.4 L/h. Air is supplied to the calciner unit through a spray nozzle to atomize the HLLW [BONNER]. The nozzle is constructed of an abrasion-resistant material to prolong the service life in the presence of small particulate matter such as shearing fines from the cladding shearing process, and is designed to minimize the potential for plugging. Before the waste solution contacts the calciner wall, which is maintained at about 700°C (600-800°C) by a multizone furnace, the solution is heated and the resultant chemical salts then converted to oxides. Water, oxygen, nitrogen oxides, and atomizing and dissolved air from processed water are exhausted through a sintered stainless steel filter in the calciner unit to an off-gas preprocessing system. Air is intermittently (pulsed) blown back through the sintered metal filters to remove loosely adherent calcine particles carried into the off-gas stream. Only about 0.1 wt % of the calcine product passes through the filters and is then retained in the off-gas system [BONNER, BJORKLUND]. Less than two percent of the ruthenium is volatilized and escapes the calciner, but this ruthenium is retained in the off-gas system (Section 3.1.3). All iodine and tritium remaining in the HLLW volatilize and are included in the calciner off-gas. The balance of HLLW radionuclides remains in the calcine. The powdered calcine product falls from the vessel surfaces along the conical bottom surface and into a bottom outlet pipe.

Borosilicate glass-forming additives (SiO_2 , B_2O_3 , Na_2O , ZnO , CaO , and TiO_2) are gravity-fed into the bottom of the calciner from a carbon steel frit hopper (562 L). The frit hopper is located outside the solidification cell in the service area to allow direct access for operations and maintenance. Glass-forming additives are added to the melter in the approximate ratio of 2:1 per unit weight of HLW oxides [LARSON-1976].

The frit-calcine mixture drops from the calciner into a ceramic melter. The calciner-melter coupling is shown in Figure 7. The ceramic melter is a combination joule-heated/electrical resistance 200-kW unit with remotely

Fig. 7. Schematic of Spray Calciner/Ceramic Melter System [BUELT]

replaceable electrodes and a glass production capacity of 100 kg/h [BUELT]. The feed mixture is continuously fed into the melter crucible and molten borosilicate glass is formed at the high temperature. Off-gases from the glass-forming process and further nitrate decomposition are collected in a vent line and diverted to off-gas processing equipment. The melter itself is designed with remotely replaceable electrodes. No spare melter is provided

for this solidification alternative. The lifetime of the melter is assumed to be the life of the WSF, and extra costs associated with shorter lifetimes are assumed to be accounted for by the maintenance costs. The advances likely to be made in electrode replacement and melter design are expected to improve the likelihood of meeting the assumed process criteria but will have little influence on the present cost estimates.

A melter design is shown in Figure 8 [BUELT]. Product sampling can be performed in the melter. The tilt-drain method is used to drain the melter. In this melt-drain approach, the entire melter is simply rotated a few degrees (typically less than $+5^\circ$) to start or stop the drainage of glass. The slight rotation allows about six hours of continuous operation while a filled canister is being replaced. This approach requires flexible connections, but if the location and angle of the connections and the pivot point are selected properly, this design problem can be minimized.

Fig. 8. Joule-Heated Ceramic Melter Schematic [BUELT]

The average annual throughput is a function of the assumed canister heat content at the time of shipment, the processing capacity of the facility, the annual operating time, and the decay heat content of the reprocessed spent fuel. Using an assumed canister heat content of 5 kW at ten years decay, 1,500 MTU/y processing rate, 1 kW/MTU decay-heat rate of the spent fuel (see Appendix C) at ten years, and a 300-day-per-year operating time, the number of canisters per year processed is 300.

Figure 9 shows glass cast into a prototype test canister having internal fins. This waste form for the present study does not employ an internally-finned canister.

Fig. 9. Cross Section of a 20-cm-dia Canister Filled with Waste Glass at PNL (Courtesy Battelle Pacific Northwest Laboratory)

3.1.3 Off-Gas Treatment (Solidification Cell and VOG Cell)

Major components are required in the solidification facility for off-gas treatment; this treatment is done both in the solidification cell and a specific vessel off-gas (VOG) cell. Off-gases from the spray calciner and ceramic melter include water, nitrogen oxides, atomizing air, and volatile wastes. The off-gases flow at $47.6 \text{ m}^3/\text{min}$ at 350°C and 684 torr to four ruthenium adsorbers. The ruthenium adsorbers are ferric oxide within a rectangular finned stainless steel vessel in the solidification cell [EXXON]. Off-gases are then processed through a stainless steel countercurrent spray quench tower 3.1-m high and 1.4-m in diameter in order to condense steam and reduce the off-gas temperature to less than 100°C .

Condensate from the quench tower gravity drains to a quench tower surge tank which is cooled with internal cooling coils. The quench tower surge tank is stainless steel with a height of 4.3 m and a diameter of 2.7 m. The condensate is then recirculated at 60,400 L/h from the surge tank to a spray nozzle in the quench tower to condense incoming steam from the off-gas effluent. Condensate which is not recirculated to the quench tower spray header is drained to the HLW concentrator in the reprocessing plant. The final off-gas flow rate to the VOG cell, after quenching, is about $22 \text{ m}^3/\text{min}$ at 40°C and 740 torr.

An identical vessel off-gas system concept was selected for all the alternative solidification systems. In conjunction with the quench tower and the ruthenium adsorber, the VOG provides a decontamination factor

greater than 10^4 for radioiodine and radioactive particulates [EXXON]. Since the VOG system exhausts to the facility's HVAC system, additional removal of radioiodine and radioactive particulates from the process stream would be required before release to the environs.

The proposed VOG cell system (shown in Fig. 10) is functionally similar to the VOG system proposed by EXXON [EXXON]. In contrast to the EXXON system, which has other off-gas sources, the VOG systems developed for this study are designed only to process off-gas from the solidification processes. The component sizing is based on the off-gas flow rates of each alternative process. The off-gas processed by the VOG system (located in the VOG cell) originates from the quench tower (located in the solidification cell).

Entering the VOG system, the off-gas ($22 \text{ m}^3/\text{min}$) is processed by the VOG adsorber. The VOG adsorber is a bubble cap tray adsorber ($0.3 \text{ m OD} \times 4.6\text{-m-high}$) with 8 trays (EXXON). The purpose of the adsorber is to remove radioactive particulates, radioiodine, and nitrogen oxides. The nitrogen oxide composition was assumed to be 50% NO and 50% NO_2 [AGNS]. Water vapor is then condensed from the process stream by the glycol-cooled VOG cooler. By removing the water vapor, the flow rate is reduced and the downstream iodine removal is enhanced. Some radioiodine is also removed with the condensed water from the process stream. Moisture in the gas stream is removed by the de-entrainer.

The gas is then heated by the electric resistance VOG heaters. Two 100%-capacity resistance heaters are provided to heat the off-gas to approximately 15°C to enhance the iodine adsorption downstream. To protect the VOG iodine adsorbers, two 100%-capacity $27\text{-m}^3/\text{min}$ particulate filters are provided. The filters are deep-bed fiberglass filters [EXXON]. At this point in the VOG system, only small quantities of radioactive particulates are expected to be present.

The off-gas then enters the VOG iodine adsorbers (two adsorbers are provided). A deep bed of silver zeolite is the adsorbing medium for any residual radioiodine in the process stream. The adsorber unit(s) is sized to provide a face velocity of 10 m/min to enhance adsorption. The bed has a capacity of 40 milligrams iodine per gram of silver zeolite [EXXON].

The $27\text{-m}^3/\text{min}$ VOG blowers provide the motive force in the system. The blowers discharge to the shell-and-tube NO_x feed-effluent heat exchanger which heats the feed gas before it passes to the NO_x reactor heater where the temperature is raised to 450°C . The heat exchanger also cools the effluent gas to 150°C . The NO_x reactor is a catalyst bed that combines the NO_x with ammonia (NH_3) to form N_2 and H_2O . Effluent from the reactor is passed through the NO_x feed-effluent heat exchanger, then discharged through the facility's HVAC system.

3.1.4 Canister Sizing and Handling

The waste canister is constructed of Type-304L stainless steel. Maximum canister temperatures are limited to 460°C to prevent sensitization of the stainless steel [LARSON-1976]. The size of the canister is based on minimizing the ratio of canister length to canister diameter and maintaining the canister heat load at 5 kW per canister at the time of shipment to a repository (*i.e.*, at ten years decay after the spent fuel is discharged from the

ITEM	STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION		Condensation Off Gas	Absorber Off Gas	Condensate	Non-Cond. Off Gas	Filter Off Gas	Indine Absorber Effluent	NOx Reactor Effluent	NOx Reactor Feed	NOx Heater Feed
RATE m ³ /min		21.8	21.8	1.50 x 10 ⁻⁹	12.7	27.0	27.0	27.4	34.2	20.0
TEMP °C		40	40	4.4	4.4	150	150	150	450	150
PRESSURE		740	740	740	740	740	740	900	1000	1000
DENSITY kg/m		1.00	1.00	1000	1.23	0.81	0.81	0.98	0.64	1.09
H ₂ O (g/hr)		--	--	--	--	--	--	--	--	--
CATION		--	--	--	--	--	--	--	--	--
NITRATES kg/hr		--	--	--	--	--	--	--	--	--
WATER kg/hr		0.09	0.09	0.09	--	--	--	10.4	--	--
NO _x kg/hr		14.6	14.6	--	14.6	14.6	14.6	--	14.6	14.6
NO ₂ kg/hr		--	--	--	--	--	--	--	--	--
N ₂ kg/hr		1002	1002	--	1002	1002	1002	1013	1002	1002
O ₂ kg/hr		289	289	--	289	289	289	289	289	289

Fig. 10. Borosilicate Glass/Spray C

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VOG COOLER

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NO_x FEED TO
EFFLUENT H₂

3	4	5	6	7	8	9
Condensate	Non-Cond Eff Gas	Effluent Eff Gas	Iodine Absorber Effluent	NO _x Reactor Effluent	NO _x Reactor Feed	NO _x Heater Feed
11.2	11.2	11.2	11.2	22.4	34.2	20.0
14	14	14	14	150	450	150
40	40	40	40	900	1000	1000
00	1.23	1.41	1.11	0.98	0.64	1.09
--	--	--	--	--	--	--
--	--	--	--	--	--	--
09	--	--	--	10.4	--	--
--	14.6	14.6	14.6	--	14.6	14.6
--	--	--	--	--	--	--
--	1002	1002	1002	1013	1002	1002
--	289	289	289	289	289	289

Fig. 10. Borosilicate Glass/Spray Calcine Feed VOG System

9
 x Heater
 Feed
 20.0
 150
 1000
 1.09
 --
 --
 --
 14.6
 --
 1002
 289

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Spray Calcine Feed VOG System

reactor). Product and canister temperatures are determined from effective canister product conductivity, canister heat content and canister geometry. Hollow cylindrical (annular) canisters were not considered. Based on a waste source of HLLW associated with the reprocessing of 5 MTU, and assuming a final waste-glass volume of 60 L/MTU and borosilicate glass conductivity of $1.1 \text{ W/m}\cdot\text{K}$ [NRC-1977A], the waste canister dimensions for this waste form are 0.46-m diameter and 1.81 m in length. No fins are considered in this analysis. Canister centerline temperatures do not exceed 700°C . It is likely that actual canisters will not have centerline temperatures nearly this high since other technical alternatives such as dilution and internal fins exist. Details of the canister size determination are given in Appendix F.

Variations in radiolytic decay heat of the calcined waste should be minimal for liquid waste transfers from a specific interim storage tank. The specific power of the glass would be regulated by changes in the rate of frit addition during vitrification. Significant variation in radiolytic decay heat of the calcine, however, may be anticipated when HLLW transfers are made from one interim storage tank to another. Such changes may probably require a change in canister diameter. Canister handling comprises those steps taken to introduce the empty prefabricated waste canisters into the solidification cell, to hold the canister during filling, to seal weld and test the canister lid, to decontaminate the filled canister and to transfer the canister to the storage pool. Once the canisters have been transferred to the solidification cell, all canister operations are performed remotely due to the high radiation levels.

The empty canisters are inspected in the staging area outside of the solidification cell. They are placed on a dolly and transferred through a double-doored shield tunnel to the solidification cell. Once inside the cell, the remotely operated bridge crane within the cell moves the canisters to the canister storage rack and then to the fill station where the flexible canister-melter connection is attached by electro-pneumatic devices. Only one storage rack is assumed and detailed engineering studies are required to provide more design definition. Air is then purged from the storage rack by an inert cover gas, such as argon, to prevent canister spalling during the fill operation. The screw jack which tilts the melter to raise one end of the melter, thus beginning the canister fill process, is activated. Once the canister is filled, the melter is returned to the horizontal position, and cooling of the canister through cooling coils in the canister storage rack is begun. The melter-canister connection is then broken and the canister moved to the weld station.

At the weld station a helium source for leak detection is placed in the canister by a manipulator. The manipulator then places the canister lid on the canister and positions the welding device (gas tungsten arc welder) on the canister. The electrical and inert shielding gas connections are attached to the welding device. The weld is then made, sealing the canister. An example of the canister welding unit is shown in Figure 11.

The canister is then moved to the remote helium leak test head and the canister seal weld checked for leaks. If the seal weld is unacceptable for interim canister storage, rework of the canister by rewelding or the addition of an overpack would occur. This occurrence, as well as the handling

Fig. 11. The PNL-Developed Remotely Operable Welder Sealing a Prototype Canister (Courtesy Battelle Pacific Northwest Laboratory)

of unacceptable waste form, is excluded from the present study. If the seal weld is leak tight, the canister is then moved to the gross decontamination area of the solidification cell and decontaminated. Post-weld canister annealing is not required, based upon design developed by others [DOE-1979, HALL]. Then the canister is transferred to the decontamination cell where it is further decontaminated by a combination of chemicals, steam, or high-pressure water sprays, and/or ultrasonic baths [HALL]. After decontamination and final rinsing, the filled canister is smeared to detect residual surface activity, a calorimetry measurement is performed, and the canister is transferred to the storage pool.

3.1.5 Canister Storage Design

The storage pool is designed to store the filled canisters until the canisters are ready to be shipped to a waste repository for ultimate disposal; the reference case requires a period of several years after solidification (i.e., 10-year-old waste). The canisters are stored on double-tiered storage racks with 0.3 m between canisters. Dimensions of the stainless steel-lined pool are: 25 m wide by 25 m long by 9.5 m deep. The pool liner (1,575 m²) has leak detection and sampling capability between the liner and the concrete basin. The pool has a capacity of 2,100 canisters. The depth of water above the upper canister is approximately 6 m.

Cooling of the pool is accomplished by circulating the pool water through heat exchangers that are cooled by the WSF cooling-water system. Approximately 4.7×10^7 W of decay heat (peak) are removed from the canister storage pool by the cooling-water system. Approximately 1.6×10^4 gal/min of cooling water are circulated through the pool, requiring 180 kW of pumping energy to be expended for canister storage pool cooling.

Canisters are handled within the pool by the pool bridge crane that traverses the pool. Surveillance of the canisters is performed visually from the pool surface and by underwater TV cameras. Water purity is maintained by filtration and demineralization of the pool water, thus providing a benign environment for canister storage as well as maintaining water clarity for visual surveillance of the canisters.

After a suitable storage period (seven years, in accord with the assumptions of the study) the canisters are removed from the pool for shipment. Once removed from the pool, the canisters are decontaminated, surveyed, and a calorimetry measurement performed to determine the canister heat evolution rate. If required, the canister could be provided with an overpack which is seal-welded and leak-tested in a manner similar to that performed initially for the canister; however, this possibility was excluded from the study because it was related to canister shipment and also is not currently required by transportation regulations. The package, either the original canister or canister in overpack, is placed into a multiple-hole cask insert. When filled, the cask insert is then transferred into a shielded dry shipping cask and loaded onto a railcar or truck for shipment to the repository [HALL].

3.1.6 Solidification, High-Level, and Vessel Off-Gas (VOG) Treatment Cell Designs

General. The design and layout of the solidification facility is based upon the design proposed for the AGNS facility which locates the process equipment in three distinct subcells: the solidification cell, the high-level cell, and the vessel off-gas (VOG) treatment cell [AGNS, HALL]. Figures 2-5 provide a generic design layout of the major areas expected to be provided in a WSF. This layout is provided to illustrate the general relations between various building areas and particular specialized cells.

Based upon an examination of several proposed waste solidification facility layouts [HALL, EXXON, DOE-1979, BUELT, LARSON-1978], it was evident that the generic facility illustrated in Figs. 2-5 could serve as a

reference facility for this study in the absence of detailed engineering studies for each waste-process alternative. Based on this reference facility, variations in the facility costs due to process flowsheet differences were handled by determining differential surface areas and building volumes for these three cells. These bulk quantity differentials (discussed in Section 4.0) then were reflected in capital costs by determining unit costs for the building (concrete, structural steel, stainless steel liner, etc.) and multiplying these costs by the appropriate differential surface areas and building volumes required for each solidification process. Differential surface areas and volumes were also utilized for the interim canister storage.

The building areas enclose the process equipment that contains essentially 100 percent of the radionuclides. The hot cells are areas designed only for remote operation and remote maintenance and no entry by personnel. Viewing windows are provided in each cell at strategic locations. Closed-circuit television cameras are installed in the solidification cell to provide high-resolution viewing for maintenance of the calciner and ceramic melter. Each cell is serviced by an in-cell hoist, manipulators, and/or transfer carts for materials handling and maintenance where applicable. All cells are lighted. All of the cell floors and sumps are lined with stainless steel. In-cell sprays are provided for cell decontamination. Manual operating and maintenance functions are performed in and/or from galleries. Remote manual operating functions include such activities as canister handling, welding, leak testing, and decontamination and calorimetry measurements. Cell penetrations are from the service galleries at the back side of the cells. Transmitters, valves for nonradioactive service, and utility piping are distributed in these areas. Routine surveillance activities and solid waste handling are also remote functions.

The HLLW transfer lines from interim liquid storage to the solidification facility are encased (pipe-in-pipe) and contained in a shielded concrete trench. The trench parallels the utility tunnel and penetrates the building. The transfer lines and trench are sloped for drainage in two directions from the midpoint. Leak detection capability is provided between confinement barriers [HALL].

The spray calcination/vitrification process is designed for continuous operation. All process-related operations including such semi-continuous or routine functions as liquid transfers, operation of the condensable effluent treatment system (concentrators), and valving changes for alternate routing selections are automatically controlled and monitored from the control room.

Process equipment installed in the hot cells is designed for rapid replacement, or, if warranted, an installed spare (redundance) is provided. The concept of modular component installation and replacement is utilized to the maximum extent possible. Remote connectors are used exclusively.

Master-slave manipulators are used in conjunction with in-cell hoists for equipment replacement and/or repair. Manipulators are available fulltime in the cells requiring routine manipulator operation and maintenance.

High-Level Cell. The high-level cell contains those components necessary for sampling and preconditioning of the feed to solidification, and includes the feed preparation tank and the calciner feed tank. This cell is located below the solidification cell. Surge tanks are also provided to allow for additional storage capacity in the event of process malfunction and for storage of HLLW material that was determined to be inappropriate for processing after feed preparation and sampling of the HLLW. Off-grade HLLW can be transferred back to the HLLW interim storage facility (not included in this study) for further treatment or dilution prior to returning to the high-level cell.

Solidification Cell. The solidification cell contains the equipment necessary to convert the HLLW into a solid, and to seal-weld, leak-detect, and decontaminate the waste canister. Other equipment within the cell includes a bridge crane to facilitate canister movement and equipment maintenance, a self-propelled dolly to move the empty waste canisters, a canister storage rack to provide for canister alignment during filling and for post-fill canister cooling, manipulators to facilitate process operation and equipment maintenance, and the vessel off-gas pretreatment equipment (ruthenium adsorbers, the quench tower, and quench tower tank).

Vessel Off-Gas Cell. The vessel off-gas (VOG) treatment cell contains the equipment necessary to process the off-gases from the calciner and the ceramic melter. This cell has the necessary provisions for remote operation. The VOG system components that are highly radioactive are:

- VOG adsorber
- VOG cooler
- VOG moisture de-entrainer
- VOG heaters
- VOG particulate filters
- VOG radioiodine adsorbers

After discharge from the radioiodine adsorber in the VOG system, the off-gas goes to the VOG blowers. The radiation levels at the process piping and equipment are low at this point in the process due to the effectiveness of the upstream fission-product removal equipment. The remainder of the VOG equipment, the VOG blower, the NO_x feed-effluent heat exchanger, the VOG heaters, and the NO_x reactor are separated from the preceding equipment by a shield wall to allow hands-on maintenance of the equipment.

All three solidification process cells are provided with all the necessary auxiliary services to allow successful process operation and to facilitate equipment maintenance, repair, and removal. Process services such as cooling water, service air, instrument air, breathing air (for periods of limited occupancy), demineralized water, electrical connections, and ventilation are all provided as needed by the process cells.

Equipment sizes for all major process equipment are presented in the equipment lists given in Appendix E. Details such as number and location of all equipment connections are not provided; however, it is believed, based upon other conceptual and preliminary designs [HALL, EXXON, DOE-1979,

BUELT, LARSON-1978], that sufficient space within the facility has been allocated to allow the installation, operation, and maintenance of the solidification process equipment.

3.2 Borosilicate Glass Monolith/Direct Liquid Feed

This waste form is similar to the preceding form except that the ceramic melter is continuously fed HLLW in liquid form as opposed to a calcined solid waste product form. The flow diagram for this waste-form process is given in Fig. 12.

3.2.1 Feed Preparation (High-Level Cell)

Preparation of the feed for the melter requires the addition of the glassforming additives to the HLLW in the feed preparation tank (3150 L) located in the high-level cell. An alternative method of adding solids to the melter exists but the only effect is to reduce the size of the feed tanks. The glass frit is metered to the feed preparation tank from a hopper outside of the cell (service area) after the HLLW is transferred to the tank. If required, chemical adjustment of the HLLW can be accomplished at this time. After mixing, the waste is transferred to the 3150-L melter feed tank for processing by the melter. The design of these tanks is identical to those discussed in the previous waste-form alternative. Further engineering analyses may show that the frit and HLLW can be added to the melter in separate streams but this alternative was not evaluated.

3.2.2 Solidification (Solidification Cell)

The solidification of the HLLW is accomplished by the introduction of the slurry of HLLW and glass-forming frit directly to the glass melter [BUELT, CHAPMAN]. The liquid waste slurry is evaporated, denitrated, and melted under a boiling layer of the solution. All steam, NO_x , and other volatile components are confined within the melter and routed to the off-gas preprocessing system and the VOG system. It is noted that this off-gas stream is much smaller than that for the spray calciner system used in the previous (reference) alternative since no atomizing air is required. The residual oxides are melted into a glass form in the melter. Only a single melter is provided in this solidification alternative. The melter is identical in design to the calcine-fed melter discussed previously, with the exceptions of the melter feed introduction (being fed directly from the melter feed tank), the depth and size of the melting cavity, and the distribution of power to the melter electrodes. For the purpose of the study, the two melter designs are assumed to be indistinguishable because the design differences at this time are not judged to be significant [CHAPMAN].

3.2.3 Off-Gas Treatment (Solidification Cell and VOG Cell)

The off-gas treatment system is identical in concept to that for the calcine-fed borosilicate glass waste form except that the VOG system processes a significantly reduced quantity of air due to the absence of the atomizing air required by the spray calcination process. The source of off-gas for this VOG system is assumed to be process off-gas only. Further engineering studies will be required to determine the technical adequacy of

ITEM	STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION	FRIT	HLW	Melter Feed	Melter Feed	Melter Effluent	RU Absorber Effluent	Off Gas	Melter Condensate	Melter Product	
RATE	--	98.4 L/hr	98.4 L/hr	98.4 L/hr	5.13 m /min	--	0.18 m /min	90.8 L/hr	--	
TEMP °C	ambient	60	60	60	350	--	60	60	1100	
PRESSURE	atm	atm	40 psig	40 psig	684 torr	--	740 torr	740 torr	684 t	
DENSITY g/cm ³	--	1.30	1.64	1.64	0.34 kg/m	--	1.35 kg/m	1.00	--	
HNO ₃ (M)	--	2.0	2.0	2.0	--	--	--	--	--	
A N kg/hr	--	23.9	23.9	23.9	--	--	--	--	--	
NITRATES	--	90.8	90.8	90.8	90.8	90.8	0.09	90.8	--	
WATER kg/hr	--	--	--	--	14.6	14.6	14.6	--	--	
NO kg/hr	--	--	--	--	--	--	--	--	--	
NH kg/hr	--	--	--	--	--	--	--	--	--	
N kg/hr	--	--	--	--	--	--	--	--	--	
O ₂ kg/hr	--	--	--	--	--	--	--	--	--	
SOLIDS kg/hr	33.4	12.8	46.2	46.2	0.046	0.046	--	--	46.2	

Fig. 12. Flow Diagram for Borosilic

9	8	9	10
Melter Product	lter densate	Melter Product	Canister
--	L/hr	--	--
1100	60	1100	--
684	740 torr	684 torr	atm
--	1.00	--	--
--	--	--	--
--	--	--	--
--	90.8	--	--
--	--	--	--
--	--	--	--
--	--	--	--
46.2	--	46.2	46.2

rosilic
 r Borosilicate Glass/Direct Liquid Feed

this assumption since the equipment sizing may be controlled by non-process off-gas sources. Further, since process off-gas is the major source processed by the VOG, this source, because of its small volumetric flow, could be processed by other systems available in the nearby reprocessing facility (i.e., dissolver off-gas system). Figure 13 shows the VOG system for this waste solidification process. The VOG system design is discussed in Section 3.1.3, while the VOG equipment sizing is given in Appendix E. The flow rate to the VOG preprocessing is about 0.2 m³.min at 350°C and 684 torr.

3.2.4 Canister Sizing and Handling

The canister, canister product and form, and canister-handling operations are identical to those for the calcine-fed ceramic melter discussed in Section 3.1.4.

3.2.5 Canister Storage Design

Storage of the canister containing this waste form product is identical to that for the calcine-fed borosilicate glass waste form discussed previously in Section 3.1.5.

3.2.6 Solidification, High-Level, and Vessel Off-Gas (VOG) Treatment Cell Designs

The design of the solidification cells is similar to that of the spray calcine-fed borosilicate glass alternative discussed previously. The resultant differences in cell design (building volume, quantity of concrete, stainless steel liner, etc.) are as follows:

- The high-level cell is slightly larger due to larger feed preparation and melter feed tanks requiring glass-forming frit addition (to these tanks) prior to solidification.
- The solidification cell is smaller due to the absence of the spray calciner and the use of smaller equipment to process the smaller volume of melter effluent.
- The off-gas treatment cell is smaller due to the reduction in equipment size attributable to the absence of the atomizing air of the spray calciner. The only air processed by the VOG for this waste form is that which is contained in the air-saturated waste (see Appendix C) and any process in-leakage (which is assumed to be negligible).

3.3 Glass Bead-Metal Matrix Composite/Lead-Encapsulated Glass Beads

This waste form has been under development in Europe and in the U.S. [ERDA-1976, VAN GEEL-1975, VAN GEEL-1980, JARDINE-1978]. Pacific Northwest Laboratory (PNL) has been active in developing borosilicate glass beads suitable for encapsulation in metal matrix contained in a canister [RUSIN].

ITEM \ STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION	Solidification Off-Gas	Absorber Off-Gas	Condensate	Non-Cond Off-Gas	Filter Off-Gas	Iodine Absorber Effluent	NO _x Reactor Effluent	NO _x Reactor Effluent	NO _x Heater Feed
RATE m ³ /min	0.14	0.18	0.09	0.15	0.23	0.23	0.47	0.29	0.17
TEMP °C	60	60	4.4	4.4	150	150	150	450	150
PRESSURE	740	740	740	740	740	740	900	1000	1000
DENSITY kg/m ³	1.35	1.35	--	1.62	1.06	1.06	0.75	0.84	1.43
PH (0.3 M)	--	--	--	--	--	--	--	--	--
CATION	--	--	--	--	--	--	--	--	--
FILTRATES kg/hr	--	--	--	--	--	--	--	--	--
WATER kg/hr	.09	.09	.09	--	--	--	10.4	--	--
NO _x kg/hr	14.6	14.6	--	14.6	14.6	14.6	--	14.6	14.6
NH ₃ kg/hr	--	--	--	--	--	--	--	--	--
H ₂ kg/hr	--	--	--	--	--	--	10.8	--	--
O ₂ kg/hr	--	--	--	--	--	--	--	--	--

Fig. 13. Borosilicate Glass/Direct Liquid Fe

7	8	9
Reactor In	NO _x Reactor Feed	NO _x Heater Feed
0.47	0.29	0.17
150	450	150
900	1000	1000
0.75	0.84	1.43
--	--	--
--	--	--
0.4	--	--
--	14.6	14.6
--	--	--
0.8	--	--
--	--	--

Argonne National Laboratory has been active in developing encapsulation technology [ANL-79-29, JARDINE-1979A]. Advantages of this waste form are (1) lower waste temperatures due to the increased thermal conductivity of the product, (2) a package geometry that may be more easily handled due to a lower canister length-to-diameter ratio, (3) greater impact resistance in case of transportation or handling accidents, and (4) an additional barrier between the waste and the environment (the stable matrix).

Possible disadvantages of this waste form are the increased number of active process components required by the metal matrix composite process, increased raw resource requirements to form the metal matrix, and significantly increased waste-package weight due to the addition of metal. The flowsheet for this waste-form alternative is given in Fig. 14.

3.3.1 Feed Preparation (High-Level Cell)

Since this waste form employs a direct liquid feed ceramic glass melter, feed preparation is identical to that of the borosilicate glass monolith/direct liquid feed described in Section 3.2.1.

3.3.2 Solidification (Solidification Cell)

The solidification process for this waste-form alternative consists of the generation of borosilicate glass from the waste, the formation of approximately spherical glass beads from the glass, and the encapsulation of these beads in a lead alloy matrix in a sealed waste canister. This process is currently in the developmental stages at PNL and ANL.

A single joule-heated ceramic melter, identical to that described in Section 3.2.2, is used to produce the borosilicate glass. On leaving the tilted melter through the overflow weir, the glass is dripped at a controlled rate onto a series of cast aluminum molds mounted on a chain conveyor [SLATE]. A picture of the prototype machine is shown in Fig. 15. This chain is continuously vibrated, causing a rotation of the formative glass bead within the mold. This rotation causes an approximately spherical glass bead to form. Preliminary tests at PNL have demonstrated that glass beads are of excellent mechanical strength. This chain conveyor drops the glass beads into a 600-L water-cooled hopper sized to adequately hold the volume equivalent of one waste canister of glass-bead product. The molds are cooled and returned for repeated filling. When the hopper is filled or the melt has been exhausted, the melter is returned to the horizontal position, terminating glass flow to the bead-formation device until the next batch of beads is required.

After a sampling to verify product acceptability, the beads are transferred from the storage hopper to the waste canister which is equipped with a device such as a retaining screen to hold the glass beads in place during the formation of the metal-matrix composite. Treatment of glass beads not meeting specifications is not considered in this study. Such a canister conceptual design is shown in Fig. 16 [ANL-79-29, JARDINE-1979, VAN GEEL-1980]. The waste canister is a double-walled container constructed of two concentric cylinders. The wall of the inner canister or retainer is penetrated in three places. A penetration at the bottom is closed by a wire mesh screen that retains the waste glass beads within the inner canister prior to introduction

STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION	FRIT	HLW	Melter Feed	Melter Feed	Melter Effluent	RU Absorber Effluent	Off Gas	Melter Condensate	Melter Product
RATE	--	98.4 L/hr	98.4 L/hr	98.4 L/hr	5.2 m/min	--	0.18 m/min	90.8 L/hr	--
TEMPERATURE	ambient	60	60	60	350	--	60	60	1100
PRESSURE	atm	atm	760 psig	40 psig	684 torr	--	740 torr	740 torr	684 torr
DENSITY kg/m ³	--	1.30	1.64	1.64	0.34 kg/m	--	1.35 kg/m	1.00	--
PH ₂ O ₂ (M)	--	2.3	--	2.0	--	--	--	--	--
ALUMINUM NITRATES	--	23.9	23.9	23.9	--	--	--	--	--
WATER kg/hr	--	90.4	90.8	90.8	90.8	90.9	.09	90.8	--
NO _x kg/hr	--	--	--	--	14.6	14.6	14.6	--	--
NH ₃ kg/hr	--	--	--	--	--	--	--	--	--
N ₂ kg/hr	--	--	--	--	--	--	--	--	--
O ₂ kg/hr	--	--	--	--	--	--	--	--	--
SOLIDS kg/hr	33.4	12.8	46.2	46.2	0.046	0.046	--	--	46.2
LEAD kg/annister	--	--	--	--	--	--	--	--	--

Fig. 14. Flow Diagram for Glass Bead-Metal Ma

8	9	10	11	12
Melter Condensate	Melter Product	Lead	Lead	Canister
0.8 L/hr	--	--	--	--
60	1100	--	ambient	--
740 torr	694 torr	atm	atm	atm
1.00	--	--	--	--
--	--	--	--	--
--	--	--	--	--
90.8	--	--	--	--
--	--	--	--	--
--	--	--	--	--
--	--	--	--	--
--	46.2	46.2	--	46.2
		2270	--	--

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Glass Bead-Metal Matrix Composite Process

Fig. 15. Glass Bead-Making Machine (Courtesy Battelle Pacific Northwest Laboratory)

of molten lead into the canister. One top penetration of the inner canister is coupled to a tube for filling of the canister with solid waste granules and purging of the canister with an inert gas. The purge gas escapes through the lower opening. The other upper penetration of the inner canister has a lead metal plug which seals sufficiently well so that the purge gas escapes through the annulus between the outer canister and the inner canister. The fusible seal is destroyed during the canister lead-filling operation and thus becomes another access point for lead to the inner canister.

The encapsulation process consists of first filling the inner retainer with solid waste granules. Next, a wire mesh is placed in the fill tube so that the waste granules do not escape during the lead-filling operations. If cooling is required prior to metal encapsulation, the canister can be purged with an inert gas through the lead-fill and waste-fill tubes.

Fig. 16. Metal-Matrix Canister Conceptual Design [JARDINE-1979A]

Lead shot, stored outside of the solidification cell in the service area, is then metered into the waste canister. The waste canister, which has been positioned in the matrix formation furnace, is heated to form the metal matrix. The option also exists of pouring molten lead directly into the canister; in this case the main furnace would be located outside of the radioactive solidification cell. Molten lead then flows downward, enters the inner canister through the lower penetration of the inner canister, and rises in the inner retainer to fill the spaces between the waste granules. Gases are vented through one of the openings in the outer canister. Zone cooling of the canister is required to control lead shrinkage and to produce a suitable casting.

3.3.3 Off-Gas Treatment (Solidification Cell and VOG Cell)

Process off-gas from this waste-form concept originates from two sources: the ceramic melter and the matrix formation furnace. The most significant quantity of off-gas to be processed is associated with the dehydration and denitrification of the HLLW which occurs in the ceramic melter. The flow rate to the VOG preprocessing equipment is estimated to be about 0.2 m³/min at 350°C and 684 torr, and the flow is composed of air, water, nitrous oxide, and volatile fission products. The source of off-gas for this VOG system is assumed to be process off-gas only. Further engineering studies will be required to determine the technical adequacy of this assumption since the equipment sizing may be controlled by non-process off-gas sources. Furthermore, if process off-gas is the only major source processed by the VOG, this source, because of its low volumetric flow rate, could be processed by other systems available in the reprocessing facility (i.e., dissolver off-gas system). Figure 17 is the flowsheet for the VOG system for this waste solidification process.

ITEM	STREAM	1	2	3	4	5	6	7	8	9	
DESCRIPTION	Solidification Off-Gas	Absorber Off-Gas	Condensate	Non-Cond. Off-Gas	Filter Off-Gas	Iodine Absorber Efflu n	NO _x Reactor ff n	NO _x Reactor ff n	NO _x Heater F d		cto
RATE m ³ /min	0.18	0.18	--	0.15	0.23	0.23	0.47	0.29	0.17		9
TEMP °C	60	60	4.4	4.4	150	150	150	450	150		0
PRESSURE	740	740	740	740	740	740	900	1000	1000		0
DENSITY cm	1.35	1.35	--	1.62	1.06	1.06	0.75	0.84	1.43		4
HNO ₃ (%)	--	--	--	--	--	--	--	--	--		
HAZARDOUS	--	--	--	--	--	--	--	--	--		
NITRATES kg/hr	--	--	--	--	--	--	--	--	--		
WATER kg/hr	.09	.09	<u>.09</u>	--	--	--	10.4	--	--		
NO kg/hr	14.6	14.6	--	14.6	14.6	14.6	--	14.6	14.6		6
NH kg/hr	--	--	--	--	--	--	--	--	--		
N kg/hr	--	--	--	--	--	--	10.8	--	--		
O ₂ kg/hr	--	--	--	--	--	--	--	--	--		

Fig. 17. Glass Bead-Metal Matrix

Heater	9	Heater	9
Feed	ctor	NO _x	Feed
0.17	9	0.17	
150	0	150	
1000	0	1000	
1.43	4	1.43	
--		--	
--		--	
--		--	
14.6	6	14.6	
--		--	
--		--	
--		--	

3.3.4 Canister Sizing and Handling

The canister product is a composite of borosilicate glass beads confined in a canister with metallic lead surrounding the glass beads. The presence of the metal in the waste product increases the effective thermal conductivity of the waste product and provides an additional barrier between the radioactive products in the waste and the environment, as well as forming a waste product that is more durable and less susceptible than other waste forms to damage in the event of a handling or transportation mishap. The increased thermal conductivity of the final waste composite allows for a more compact waste package configuration. A picture of the lead-encapsulated glass beads cast into a prototype canister fabricated at ANL is given in Fig. 18 [JARDINE-1979B]. In the annulus is a protective envelope of metallic lead, free of waste beads, that isolates the waste from exterior events and the environment.

Limitations exist on the maximum centerline temperature (300°C) of the waste in air at the time of removal from the storage basin (10 years after reactor discharge) due to the relatively low melting point of the lead alloy forming the matrix. Details of the thermal analyses of the loaded waste canister are given in Appendix F. The resultant canister has a diameter of 0.86 m and a length of 0.86 m. It should be pointed out, however, that process development of the glass bead-metal matrix composite is not as advanced as that of the other waste forms. It is less certain than the two processes previously evaluated.

Canister handling is similar to that for the previous waste forms up to canister filling. Differences include deletion of the coupling of the canister to the ceramic melter, the addition of two movable filling tubes illustrated in Fig. 16, and the use of a canister storage rack design which utilizes multi-zone, forced-air cooling in lieu of the water cooling utilized in glass monoliths. Due to lower waste processing temperatures, no inert cover gas is required to prevent spalling and sensitization of the stainless steel canister during filling. The remainder of the canister handling operations are similar to those previously discussed.

3.3.5 Canister Storage Design

Glass bead-metal matrix composite canisters are stored in a stainless steel-lined pool (approximately 2,590 m² surface area) similar in design to those discussed previously. Pool dimensions are 38 m wide by 38 m long with a depth of 7.5 m. This is significantly larger than for either of the two previous alternatives. This allows double stacking of the 2,100 waste canisters with adequate shielding by the pool water (about 6 m) to reduce radiation levels at the pool surface to acceptable levels. The pool heat load is the same as for the two previous waste-form concepts discussed. Structural requirements for the pool are increased due to the additional mass of the lead in the waste canister; however, the detailed structural engineering studies necessary to quantify the increased requirements were beyond the scope of this study and the increased structural costs not determined.

Fig. 18. Encapsulated Glass Beads in a Lead Matrix (Pilot Specimen).
ANL Neg. No. 308-79-635

3.3.6 Solidification, High-Level, and Vessel Off-Gas (VOG)
Treatment Cell Designs

The design of the solidification, high-level, and off-gas treatment cells is similar to that proposed for the direct liquid feed/borosilicate glass waste form with the following exceptions:

- The size of the solidification cell is larger than that for the direct liquid feed glass waste form to allow for the installation of the glass bead-forming machine, the glass bead hopper, and the matrix formation furnace.
- Water cooling for the canister storage rack is not required, a zone-cooled furnace is required.
- Additional storage space must be provided outside the solidification cell in the service area for lead shot storage and metering.
- Provisions for one additional power manipulator and two additional master-slave manipulators are required in the solidification cell.

3.4 Ceramic Pellet-Metal Matrix Composite Lead-Encapsulated Supercalcine Pellets

This waste-form alternative involves the encapsulation of supercalcine pellets in a lead matrix within the stainless steel waste canister. The supercalcine product is a crystalline ceramic waste form prepared by modifying the HLLW with selected additives so that when it is calcined and given additional heat treatment, an assemblage of thermodynamically stable crystalline phases will be formed which are more refractory and leach-resistant than ordinary oxide calcine formed without additives and heat treatment [RUSIN]. The product is shaped into pellets prior to the heat treatment that forms the supercalcine product. The pellets can then be incorporated into a lead matrix for storage and disposal. The flow diagram for this alternative is given in Fig. 19. The status of the flowsheet has been discussed in detail in a recent paper [JARDINE-1979A].

3.4.1 Feed Preparation (High-Level Cell)

Feed to the solidification process is prepared in the high-level cell where the supercalcine formation additives (Sr, Ca, Al nitrates, and SiO_2) are added to the HLLW in the feed preparation tank (4750 L). The additives are in a slurry that has been prepared in the chemical addition tank (1800 L) located outside of the high-radiation areas of the facility and transferred to the feed preparation tank. Once mixing of the tank contents is completed, the solution is sampled and further chemical adjustments made if necessary, or the waste can be transferred back to the HLLW storage for additional treatment or dilution.

Once the acceptability of the waste for processing has been determined, the waste is transferred to the calciner feed tank. Both the feed preparation tank and the calciner feed tank are equipped with cooling coils to remove decay heat and agitators to mix the contents of the tanks and maintain particulate material in suspension.

3.4.2 Solidification (Solidification Cell)

Solidification of the HLLW is accomplished by spray calcination of the HLLW supercalcine additive mixture and is similar to the spray calcination

ITEM	STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION		Supercalcine Additives	HLW	Calciner Feed	Calciner Feed	Atomizing Air	Calciner Product	Calciner Effluent	Ruthenium Absorber Effluent	Off Gas
RATE		59.8 L/hr	98.4 L/hr	158.2 L/hr	158.2 L/hr	25.0 m ³ /min	--	71.4 m ³ /min	--	31.5 m ³ /min
TEMP °C		ambient	60	60	60	40	60	350	--	60
PRESSURE		atm	atm	40 psig	40 psig	769 torr	atm	684 torr	--	740 torr
DENSITY g/cm ³		1.16	1.30	1.24	1.24	1.29 kg/m ³	--	0.49 kg/m ³	--	1.03 kg/m ³
HNO ₃ (M)		--	2.0	--	--	--	--	--	--	--
HAZ NITRATES kg/hr		6.3	23.9	30.2	30.2	--	--	--	--	--
WATER kg/hr		55.2	90.8	146	146	--	--	146	152	0.15
NO kg/hr		--	--	--	--	--	--	18.5	18.5	18.5
NH ₃ kg/hr		--	--	--	--	--	--	--	--	--
N kg/hr		--	--	--	--	1500	--	1500	1500	1500
O ₂ kg/hr		--	--	--	--	428	--	424	424	424
LEAD kg/canister		--	--	--	--	--	--	--	--	--
SOLIDS kg/hr		7.8	12.8	20.6	20.6	--	33.9	0.034	0.034	--

Fig. 19. Flow Diagram for Ceramic P

	2	3	4	5	6	7	8	9	10	11	12	13
	HLW	Calciner Feed	Calciner Feed	Atomizing Air	Calciner Product	Calciner Effluent	Ruthenium Absorber Effluent	Off Gas	Calciner Condensate	Turbulator Product	Binder	Pellet
Flow	1.4 L/hr	158.2 L/hr	158.2 L/hr	25.0 m ³ /min	--	71.4 m ³ /min	--	11.5 m ³ /min	146 L/hr	39.6 kg/hr	6.0 L/hr	--
Pressure	60	60	60	40	60	350	--	60	60	ambient	ambient	--
Temperature	atm	40 psig	40 psig	769 torr	atm	684 torr	--	740 torr	740 torr	atm	atm	atm
Density	1.30	1.24	1.24	1.29 kg/m ³	--	0.49 kg/m ³	--	1.03 kg/m ³	1.00	--	1000	--
Viscosity	2.0	--	--	--	--	--	--	--	--	--	--	--
Concentration	23.9	30.2	30.2	--	--	--	--	--	--	--	--	--
Mass Flow	90.8	146	146	--	--	146	152	0.15	152	6	6	--
Heat Flow	--	--	--	--	--	18.5	18.5	18.5	9.49 x 10 ⁻³	--	--	--
Power	--	--	--	1500	--	1500	1500	1500	--	--	--	--
Cost	--	--	--	428	--	424	424	424	--	--	--	--
Efficiency	12.8	20.6	20.6	--	33.9	0.034	0.034	--	.034	33.9	--	33.9

Fig. 19. Flow Diagram for Ceramic Pellet-Metal Matrix Process

	9	10	11	12	13	14	15
Pellet	Off Gas	Calciner Condensate	Turbolator Product	Binder	Pellet	Lead	Canister
--	31.5 m ³ /min	146 L/hr	39.6 kg/hr	6.0 L/hr	--	--	--
--	60	60	ambient	ambient	--	ambient	--
atm	740 torr	740 torr	atm	atm	atm	atm	atm
--	1.03 kg/m	1.00	--	1000	--	--	--
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
--	0.15	152	6	5	--	--	--
--	18.5	9.49 x 10 ⁻³	--	--	--	--	--
--	--	--	--	--	--	--	--
--	1500	--	--	--	--	--	--
--	424	--	--	--	--	--	--
33.9		.034	33.9		33.9	1360	33.9

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performed for the borosilicate glass monolith/spray calcine feed waste form. The calcined waste then enters the calciner surge tank (500 L) by gravity feed. The calciner surge tank is sized to hold the volume equivalent of two canisters of final waste product. Cooling coils are provided to this tank. The powder-like calcined waste is then fed to the pelletizer. A binder material is added to the agglomeration device to aid in pellet formation.

Two options exist for the pelletization of the calcined product: a disc pelletizer or a turbulator. Both devices require the addition of a binder material (water) to the calcined product as an aid in pellet formation. Disc pelletizers may have a severe problem with dust formation during the pellet-forming operation [HOLLEY]. This dusting of the highly radioactive calcined product requires additional containment devices to prevent the spread of contamination outside of the pelletizer. Pelletizers have been studied at PNL [MC ELROY] and INEL [LAMB]. Pelletizer development is continuing at INEL and also at PNL.

A turbulator is a fully enclosed device which utilizes a pin mixer to blend the calcined waste with the binder material (water). The feed material is metered into the device and water sprayed onto the feed material. A pinned shaft rotates about the axis of the machine mixing, pelletizing, and densifying the calcine product into spherical pellets which then undergo further treatment prior to encapsulation. A simplified drawing of the device is given in Fig. 20. This alternative to the disc pelletizer is considered the preferred device by the disc pelletizer and turbulator supplier [HOLLEY]. For the purposes of this study, the selection of either device does not affect the total cost estimates.

The "green" calcine pellets are then fed to the drying and sintering furnace to remove any residual binders from the waste product and to form the supercalcine product. The drying and sintering furnace is a four-zone design with an internal hopper to retain the pellets, sealed to prevent the release of off-gases from the sintering process. After the sintering process, the furnace is purged with an inert gas such as argon and the pellets transferred by an air eduction system to the pellet storage tank. During the drying and sintering process, the pellets undergo significant shrinkage, reducing the specific volume by almost forty percent. The heat cycle may require two hours at 1,200°C with preheat and postheat cycles requiring additional time of unknown length but probably of several hours duration.

The pellet storage tank (700 L) retains the sintered pellets prior to their transfer to the waste container for final product formation. The pellet storage tank is sized to hold the equivalent of one canister volume of supercalcine pellets. The tank is provided with cooling to reduce the temperature of the supercalcine pellets. This allows for the temporary storage of the supercalcine in the event of an equipment failure. During this brief storage period, another sample of the supercalcine pellets is taken to verify the acceptability of the final product form prior to the encapsulation step. The treatment of offgrade supercalcine product has not been a consideration in the process development to date and is not addressed in this study.

Matrix encapsulation is accomplished by blending the supercalcine pellets with a metered quantity of lead shot in the waste canister

Fig. 20. Turbulator or Pin Mixer [HOLLEY]

(i.e., design similar to Fig. 16) and subsequent heating of the canister in the matrix formation furnace. The canister will require an internal "basket" or retainer to contain the buoyant supercalcine pellets in the molten matrix during fabrication. Molten lead may be used rather than solid lead. Zone cooling is used to control shrinkage during solidification.

3.4.3 Off-Gas Treatment (Solidification Cell and VOG Cell)

Process off-gases from this process originate from the spray calciner, the turbulator (or disc pelletizer), the drying and sintering furnace and the matrix formation furnace. The dominating source of off-gas is the spray calciner. Off-gas treatment is identical to that discussed for previous waste-form processes. VOG system design will require additional considerations of dusting and particulate control. The VOG system for this process is shown in Fig. 21.

3.4.4 Canister Sizing and Handling

The canister product is a composite of supercalcine ceramic pellets surrounded by metallic lead, confined in a canister. The presence of the metal in the waste product increases the effective thermal conductivity of the waste product and provides an additional barrier between the radioactive products in the waste and the environment, as well as forming a waste product that is more durable and less susceptible to damage in the event of a handling mishap than other nonmetal matrix waste forms. The increased thermal conductivity of the final waste composite allows for a more compact waste package configuration.

Limitations are present on the maximum centerline temperature (300°C) of the waste in air at the time of removal from the interim storage basin (10 years after reactor discharge) due to the relatively low melting point of the lead alloy forming the matrix. Details of the thermal analyses of the waste canister and product are given in Appendix F. The resultant canister has a diameter of 0.73 m and a length of 0.73 m.

Canister handling operations are similar to those performed for the glass bead-metal matrix waste form.

3.4.5 Canister Storage Design

Canister storage is in a stainless steel-lined (approximately 2180 m² surface area) pool similar in design to those previously discussed in Section 3.3.5. Pool dimensions are 34-m wide by 34-m long with a depth of 7.5 m. This is larger than required for the two glass monolith alternatives but not as large as for the lead-glass bead alternative. This allows for the double stacking of the 2,100 waste canisters with adequate shielding being provided by approximately 6 m of water. The pool heat load is the same as for the previous waste-form concepts. Structural requirements for the pool are increased due to the increased mass of the metal matrix composite canister relative to the monolithic waste forms as discussed in Section 3.3.5.

ITEM \ STREAM	1	2	3	4	5	6	7	8	9
DESCRIPTION	Scrubbing Off Gas	Absorber Off Gas	Condensate	Non-Cond Off Gas	Filter Off Gas	Iodine Absorber Effluent	NO _x Reactor Effluent	NO _x Reactor Feed	NO _x Heater Feed
RATE m ³ /min	21.3	31.5	2.17 x 10 ⁻³	26.2	30.3	4.1	33.2	57.9	29.7
TEMP °C	40	60	4.4	4.4	150	140	150	450	150
PRESSURE	740	740	740	740	740	740	900	1000	1000
DENSITY g/cm ³	1.29	1.03	1000	1.22	0.80	0.80	1.38	0.63	1.08
HNO ₃ (M)	--	--	--	--	--	--	--	--	--
CATION NITRATES ug/hr	--	--	--	--	--	--	--	--	--
WATER kg/hr	0.15	0.15	0.15	--	--	--	13.1	--	--
NO _x kg/hr	18.5	18.5	--	18.5	18.5	18.5	--	18.5	18.5
NH ₃ kg/hr	--	--	--	--	--	--	--	--	--
N ₂ kg/hr	1500	1500	--	1500	1500	1500	1514	1500	1500
O ₂ kg/hr	424	424	--	424	424	424	424	424	424

Fig. 21. Ceramic Pellet-Metal

NO_x FEED TO
EFFLUENT H_x

TO PLANT VENT

VOG BLOWE
(2)

NO _x Reactor Feed	NO _x Reactor Effluent	NO _x Reactor Conversion
1500	450	70%
1000	300	70%
630	190	70%
150	45	70%
15	4.5	70%
1.5	0.45	70%
0.15	0.045	70%
0.015	0.0045	70%
0.0015	0.00045	70%
0.00015	0.000045	70%
0.000015	0.0000045	70%

Fig. 21. Ceramic Pellet-Metal Matrix VOG System

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1500

424

let-Metal Matrix VOG System

3.4.6 Solidification, High-Level, and Off-Gas Treatment Cell Designs

The design of the solidification, high-level, and off-gas treatment cells is similar to that proposed for the spray calcine feed/borosilicate glass monolith waste form with the following exceptions:

- The size of the solidification cell is increased to allow for the installation of the calciner surge tank, increased volume of off-gas processing equipment, turbulator or disc pelletizer, the drying and sintering furnace, the pellet storage tank, and matrix formation furnace.
- Water-cooling for the canister storage rack is not required; a zone-cooled furnace is required.
- Additional storage space must be provided outside of the solidification cell for the chemical addition tank and lead shot storage and metering.
- One additional power manipulator and two additional master-slave manipulators are required in the solidification cell.
- The size of the high-level cell is increased due to the larger feed prep tank and calciner feed tanks.
- The VOG cell is larger due to the larger size of the VOG processing equipment.

4.0 CAPITAL COSTS

4.1 Introduction

The development of facility costs in a definitive manner requires six distinct steps to be taken prior to the assignment of cost to the facility. These steps include:

1. Site (field) surveys that include subsurface investigations as well as surface investigations to define civil and structural engineering requirements for the facility.
2. The establishment of engineering and architectural design criteria for the facility. These would include process and facility design objectives as a part of the design criteria.
3. Studies on the implementation of the design criteria producing preliminary system descriptions and sketches showing preliminary layouts considered for the facility.
4. Further studies quantifying the advantages of design alternatives resulting in the selection of the preferred alternative.

5. Preparation of the necessary drawings such as plant layouts, piping and instrumentation drawings, flow diagrams, electrical schematics, logic diagrams, etc., as well as outlining specifications for the major pieces of equipment, civil construction, and equipment installation.
6. Preparation of cost and time schedules for (a) the completion of design drawings and specifications, (b) procurement, (c) construction, and (d) startup.

Upon completion of these six steps, the facility cost can be determined from a sufficient information base to assure that the cost is a realistic representation of the expected actual cost. In the absence of a complete facility design process such as described above, order-of-magnitude cost estimates can be made by use of cost studies previously performed for similar facilities. The latter approach was used in this study to derive the costs presented.

The shortcomings of such order-of-magnitude estimates must be understood so that the estimates can be evaluated in proper perspective. First, this estimating technique propagates the errors or uncertainties present in the cost studies which are the basis for the order-of-magnitude estimates. Also, when processes are developed from conceptual waste-product forms, without detailed engineering studies to support the proposed processes, certain necessary process and equipment detail may be lacking. For these reasons, such cost studies should not be regarded as of budgetary quality.

The inherent error in an order of magnitude cost estimate can be minimized by the use of sound engineering judgment and by the prudent selection of processing steps and components that utilize proven technology where possible. Such an approach was taken in this study. To this extent, it is believed that such an approach yields an estimate that is within 30 percent of an estimate which would result from more detailed engineering studies. Figure 22 shows the relationship between percent of engineering complete and the uncertainty in the estimate [MAPLES].

4.2 Waste Processing System Costs

From the conceptual flow diagrams described in Section 3, equipment lists were developed of the major components shown for each of the waste-form alternatives. The equipment sizing shown on the equipment lists was based on the processing rates and capacities shown on each alternative flow diagram. The equipment lists are included as Appendix E. Based on the equipment lists, capital equipment cost estimate sheets were generated for each alternative. The estimate sheets included the component costs and the installation costs for each component. The complete estimate sheets are included in Appendix G.

Table 4 provides a summary of the equipment costs, installation man-hours and installation direct costs, and total field cost for each waste alternative evaluated. The estimated equipment costs were derived from other cost studies, vendor quotes, and engineering estimates. The installation man-hours were derived from other cost studies and engineering estimates. Installation man-hours were charged at \$13.50/h direct cost. Total process equipment field

Table 4. Process Equipment and Installation Cost Summary (1979 dollars)

	Cost, \$K			
	Borosilicate Glass/Spray Calcine Feed	Borosilicate Glass/Direct Liquid Feed	Glass Bead-Metal Composite	Ceramic Pellet- Metal Matrix Composite
Process Equipment ^a	1,392	978	1,358	2,103
Installation				
Direct Cost ^b	324	189	243	494
Total Installation ^c	616	359	462	939
Total Process Equipment Field Cost	2,008	1,337	1,820	3,042

^aProcess equipment costs are detailed in Appendix G.

^bDirect installation costs are detailed in Appendix G.

^cTotal installation costs are calculated as 1.9 times the direct cost.

Fig. 22. The Relation of Percent of Engineering Completed to Cost Estimate Accuracy [MAPLES]

costs were computed by summing the equipment costs and the total installation cost, which is the direct installation cost multiplied by 1.9--a factor used to account for field indirect costs. The indirect cost factor is based on nuclear power facility experience. Field indirect costs include wages and payroll additives, fringe benefits, and miscellaneous supplies (such as welding rods) used in equipment installation.

In addition to process equipment costs and installation costs for that process equipment, the complete system costs include those costs associated with piping and valves, instrumentation, and electrical equipment. These items were treated as percentages (or allowance factors) of the equipment costs and installation costs for each waste alternative. The allowance factors used in this study are presented in Table 5. The allowance factors are derived from nuclear power facility experience. Total system costs for

Table 5. Allowance Factors

	Equipment Cost ^a	Installation ^b
Piping & Valves	18%	79%
Instrumentation	12%	21%
Electrical	6%	26%

^aEquipment cost allowance factors are used to multiply total process equipment costs to determine subcomponent costs.

^bInstallation cost allowance factors are used to multiply total equipment installation costs in order to get direct costs for piping and valves, instrumentation, and electrical components.

each waste processing alternative are the sum of the total field cost for equipment purchase and installation of the equipment, piping and valves, instrumentation, and electrical equipment. The total field costs for piping and valves, instrumentation, and electrical equipment are computed in the same manner as the total field cost for the process equipment itself, as discussed in the preceding paragraphs. Total system costs for each waste processing system are presented in Table 6.

4.3 Solidification Facility Costs

In addition to waste processing system costs, costs were developed for the solidification facility which would contain each processing system developed. The following major assumptions were used in developing the entire solidification facility costs:

- The reference solidification facility is similar in design to the facility proposed for the AGNS plant [HALL]
- The waste processing system for the borosilicate glass monolith/spray calcine feed is the reference system contained within the reference solidification facility
- The only quantifiable differences impacting the waste solidification facility size (and hence costs) are those associated with the equipment for the four different waste processing systems and the canister storage space requirements

The cost of the reference Waste Solidification Facility was divided into four major components:

- Concrete
- Structural steel
- Building services
- Stainless Steel Liner Plate

Table 6. Waste Processing System Costs (1979 dollars)

	Cost, \$K			
	Borosilicate Glass/Spray Calcine Feed	Borosilicate Glass/Direct Liquid Feed	Glass Bead- Metal Matrix Composite	Ceramic Pellet- Metal Matrix Composite
Equipment ^a				
Process Equipment	1,392	978	1,358	2,103
Piping and Valves	251	176	244	379
Instrumentation	167	117	163	252
Electrical	84	59	81	126
Total Equipment	1,894	1,330	1,846	2,860
Installation:				
Total Direct ^b	732	427	549	1,116
Total Installation ^c	1,391	811	1,043	2,121
Total System Cost	3,285	2,141	2,889	4,981

^aEquipment costs calculated using allowance factors given in Table 5.

^bTotal direct installation costs are for complete processing system using allowance factors of Table 5.

^cTotal installation costs are calculated as 1.9 times the total direct costs.

Concrete includes the bulk quantity of structural concrete (including that for shielding used to construct the solidification facility structure.) The structural steel consists of the steel structural members (I-beams, etc.) used for structural support. Building services are the miscellaneous systems required to complete the facility design, including HVAC, plumbing, fire protection, electrical distribution, cooling water piping, compressed air, demineralized water, etc. Stainless steel is used to line the process equipment cells and the canister storage pool. The bulk quantities of the materials and labor for the reference waste solidification facility are given in Table 7. The bulk quantities listed in Table 7 were derived from the AGNS facility in conjunction with nuclear power plant experience. Building volume, quantity of concrete emplaced in the structure, and surface area for cells lined with stainless steel were determined explicitly for the AGNS conceptual facility design [HALL] by scaling dimensions from the layout drawings of the WSF presented in Section 2.0. The amount of structural steel and quantities of building services were then obtained by extrapolating from nuclear power facilities of comparable design (radwaste processing buildings, reactor auxiliary building and spent fuel building) to obtain the quantities for the reference solidification facility. The gross volume of the reference solidification facility was estimated to be $8.5 \times 10^4 \text{ m}^3$ ($3 \times 10^6 \text{ ft}^3$). Based on the parameters in Table 7, an average volumetric building cost, not including any stainless steel liner plate costs, was calculated (for calculational purposes only) to be \$585 per cubic meter. The cost for stainless steel liner plate (installed) was assumed to be \$150 per square foot.

Table 7. Bulk Material and Labor Quantities for Reference Waste Solidification Facility (1979 dollars)

	Quantity	Cost, \$K		Man-Hours
		Field Cost ^a	Factory Cost ^b	
Concrete	31,550 m^3 (41,000 cubic yards)	6,200	--	1.1×10^6
Structural Steel	—	2,100	—	4.7×10^4
Building Services	—	1,500	1,800	3.5×10^5
Stainless Steel Liner Plate ^c	6,654 m^2 (71,600 ft^2)	10,740		

^aCapital cost of those materials purchased at the jobsite.

^bCapital cost of those materials fabricated completely at the factory and shipped for installation at the solidification facility.

^cTotal installed cost including materials and labor was estimated to be \$150 per square foot.

For each waste processing alternative considered, the building volume required to house the solidification equipment and provide for canister storage was determined. To estimate the different building volume requirements for the high-level, solidification, and VOG cells, the volume ratio of equipment to building was assumed to be 0.38; this is similar to the proposed EXXON design [EXXON] for the high-level, solidification, and VOG cells. The different amounts of stainless steel liner plates required to line these volumes were also determined. Canister storage pool differentials were calculated from the dimensions discussed in Section 3. The differential quantities (volumes and stainless steel lined surface areas) were then compared to quantities for the reference borosilicate glass monolith/spray calcine feed alternative. Differential costs (based upon the \$585/m³ value for volumes and \$150/ft² for liner) were then assigned on a linear ratio of volumes and surface areas relative to the reference facility cost. A summary of the differential quantities calculated for all alternatives is presented in Table 8.

Table 8. Differential Volume and Surface Area Quantities for Four Waste Processing Alternatives

	Borosilicate Monolith/ Spray Calcine Feed	Borosilicate Monolith/ Direct Liquid Feed	Glass Bead-Metal Matrix Composite Lead Encapsulated Glass Beads	Ceramic Pellet-Metal Matrix Composite Lead Encapsulated Supercalcine Pellets
DIFFERENTIAL BUILDING VOLUME QUANTITIES, m ³				
High-Level Cell	BASE	1	1	10
Solidification Cell	BASE	(79) ^a	(37)	56
VOG Cell	BASE	(24)	(24)	42
Storage Pool	BASE	0	4,892	2,732
Other ^b	BASE	0	6	10
TOTALS	0	(102)	4,838	2,850
DIFFERENTIAL SURFACE AREA QUANTITIES, m ²				
High-Level Cell	BASE	6	6	28
Solidification Cell	BASE	(110)	(20)	89
VOG Cell	BASE	(50)	(17)	73
Storage Pool	BASE	0	1,009	605
TOTALS		(154)	978	795

^aParentheses represent a negative value.

^bThese areas, such as the service area, are part of the WSF but are not lined with stainless steel.

The total system cost (Table 6) was added to the total building field cost estimates, with adjustments made for each alternative to determine the total facility field cost. This total facility field cost was multiplied by 2.27 to compute the total facility capital costs for the alternatives. The 2.27 factor includes 20% home office support, 20% contingency and 58% interest (12% compounded for four years) during construction (IDC). The cost summaries for the four waste solidification processes are given in Tables 8 through 12.

Table 9. Borosilicate Glass/Spray Calcine Feed, Total Capital Cost Summary (1979 dollars)

EQUIPMENT		
Process Equipment	\$1,392,000	
Piping & Valves	251,000	
Electrical	84,000	
Instrumentation	167,000	
Total Equipment		\$1,894,000
INSTALLATION		
Direct	732,000	
Total Installation		1,391,000
BUILDING		
Concrete	34,415,000	
Structural Steel	3,306,000	
Building Services	12,278,000	
Liner Plate	10,740,000	
Differential Volume Cost (0 m ³)	0	
Differential Liner Plate Cost (0 ft ²)	0	
Total Building Cost		60,739,000
TOTAL FACILITY FIELD COST		64,024,000
HOME OFFICE, IDC, CONTINGENCIES		<u>81,310,000</u>
TOTAL FACILITY CAPITAL COST		<u>\$145,334,000</u>

Table 10. Borosilicate Glass/Direct Liquid Feed, Total Capital Cost Summary (1979 dollars)

EQUIPMENT

Process Equipment	\$978,000	
Piping & Valves	176,000	
Electrical	59,000	
Instrumentation	117,000	
Total Equipment		\$1,330,000

INSTALLATION

Direct	427,000	
Total Installation		811,000

BUILDING

Concrete	34,415,000	
Structural Steel	3,306,000	
Building Services	12,278,000	
Liner Plate	10,740,000	
Differential Volume Cost	(60,000) ^a	
Differential Liner Plate Cost	(249,000)	
Total Building Cost		<u>60,430,000</u>

TOTAL FACILITY FIELD COST	<u>62,571,000</u>
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HOME OFFICE, IDC, CONTINGENCIES	<u><u>79,465,000</u></u>
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TOTAL FACILITY CAPITAL COST	<u><u>\$142,036,000</u></u>
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^aParentheses represent a cost savings or negative value.

Table 11. Glass Bead-Metal Matrix Composite, Total Capital
Cost Summary (1979 dollars)

EQUIPMENT		
Process Equipment	\$1,358,000	
Piping & Valves	244,000	
Electrical	81,000	
Instrumentation	163,000	
Total Equipment		\$1,846,000
INSTALLATION		
Direct	549,000	
Total Installation		1,043,000
BUILDING		
Concrete	34,415,000	
Structural Steel	3,306,000	
Building Services	12,278,000	
Liner Plate	10,740,000	
Differential Volume Cost	(2,830,000) ^a	
Differential Liner Plate Cost	(1,578,000)	
Total Building Cost		<u>65,147,000</u>
TOTAL FACILITY FIELD COST		68,036,000
HOME OFFICE, IDC, CONTINGENCIES		<u>86,406,000</u>
TOTAL FACILITY CAPITAL COST		<u>\$154,442,000</u>

^aParentheses represent a cost savings or negative value.

Table 12. Ceramic Pellet-Metal Matrix Composite, Total Capital Cost Summary (1979 dollars)

EQUIPMENT

Process Equipment	\$2,103,000	
Piping & Valves	379,000	
Electrical	126,000	
Instrumentation	252,000	
Total Equipment		\$2,860,000

INSTALLATION

Direct	1,116,000	
Total Installation		2,120,000

BUILDING

Concrete	34,415,000	
Structural Steel	3,306,000	
Building Services	12,278,000	
Liner Plate	10,740,000	
Differential Volume Cost	1,667,000	
Differential Liner Plate Cost	1,283,000	
Total Building Cost		<u>63,689,000</u>

TOTAL FACILITY FIELD COST 68,669,000

HOME OFFICE, IDC, CONTINGENCIES 87,210,000

TOTAL FACILITY CAPITAL COST \$155,879,000

5.0 OPERATING AND MAINTENANCE COSTS

5.1 Introduction

This section describes the estimates developed to identify annual operating and maintenance (O&M) costs of the four waste-form alternatives. The estimates for the O&M costs for the four alternatives include: (a) costs of labor for operating and maintenance, (b) maintenance material costs, (c) costs of consumables, and (d) cost of utilities and related services. The annual O&M cost estimate sheets for the four alternatives are shown in Tables 13 through 16. The cost categories identified are discussed below.

Table 13. Annual Operating & Maintenance Costs, Borosilicate Glass Monolith/Spray Calcine Feed (1979 dollars)

Item	Cost, \$K	Basis
Labor	1,849.3	Table 17
Maintenance Materials	554.8	Allowance, 30% of Labor Cost
Consumables		
Canisters	750.0	300 canisters/year at \$2,500 each
Chemicals	90.0	Figure 6, Table 18
Utilities		
Cooling Water	80.5	
Electricity	266.5	Table E-5, \$.05/kW·h
TOTAL	3,591.1	

5.2 Operating and Maintenance Labor Costs

Operating and maintenance labor costs are a function of the number of personnel required to support the waste solidification facility, the range of the personnel requirements of the facility, and the wages and fringe benefits paid to each category of personnel employed at the facility. The size of the operating and maintenance staffs was based on modifications of projections made by PNL for a borosilicate glass monolith/spray calcine feed, in-can-melting waste solidification facility [LARSON-1978]. Adjustments to these projections for other waste solidification alternatives were made based on process complexity and the number of process components in the solidification system. These adjustments are treated as allowances on the personnel requirements projected by [LARSON-1978].

Four personnel categories were defined for the purpose of determining facility staffing requirements: (1) Operations, (2) Technical Support, (3) Administrative, and (4) Maintenance. Of the four groups considered, only the maintenance personnel were considered to be a part of the entire facility

Table 14. Annual Operating & Maintenance Costs, Borosilicate Glass Monolith/Direct Liquid Feed (1979 dollars)

Item	Cost, \$K	Basis
Labor	1,738.5	Table 17 2 less plant mechanical maintenance 1 less electrical, 1 less instrumentation
Maintenance Materials	521.6	Allowance, 30% of Labor Cost
Consumables		
Canisters	750.0	300 canisters/year at \$2,500 each
Chemicals	90.0	Figure 12, Table 18
Utilities		
Cooling Water	80.5	
Electricity	75.5	Table E-5, \$.05/kW·h
TOTAL	3,256.1	

Table 15. Annual Operating & Maintenance Costs, Glass Bead-Metal Matrix Composite Lead-Encapsulated Glass Beads (1979 dollars)

Item	Cost, \$K	Basis
Labor	2,136.3	Table 17, 3 additional operators, 2 additional technicians, 2 additional Plant maintenance, 2 additional Contract Mechanical maintenance
Maintenance Materials	640.9	Allowance, 30% of Labor Cost
Consumables		
Canisters	1,050.0	300 canisters/year at \$3,500 each
Chemicals	811.9	Figure 14, Table 18
Utilities		
Cooling Water	80.5	
Electricity	132.5	Table E-5, \$.05/kW·h
TOTAL	4,852.1	

Table 16. Annual Operating & Maintenance Costs, Ceramic Pellet-Metal Matrix Composite Lead-Encapsulated Supercalcine Pellets (1979 dollars)

Item	Cost, \$K	Basis
Labor	2,253.9	Table 17, 3 additional operators, 6 additional technicians, 2 additional Plant maintenance, 2 additional Contract maintenance
Maintenance Materials	676.2	Allowance, 30% of Labor Cost
Consumables		
Canisters	900.0	300 canisters/year at \$3,000 each
Chemicals	507.6	Figure 19, Table 18
Utilities		
Cooling Water	80.5	
Electricity	308.0	Table E-5, \$.05/kW·h
TOTAL	4,726.2	

work force; the other three groups were assumed to be dedicated to the Waste Solidification Facility. For reasons associated with personnel radiation exposure and craft skill requirements beyond those of the permanent facility staff, the maintenance work force consists of approximately 70 percent permanent employees of the facility owner and 30 percent employees obtained from outside (or contract) organizations. This framework is consistent with experience gained in commercial nuclear power facilities. The distribution of personnel for the reference borosilicate glass monolith/spray calcine feed waste alternative for the four personnel categories is given in Table 17.

The wage structure of the personnel employed to operate and maintain the solidification facility is presented in Table 17. Annual compensation is based on a survey taken at 13 operating nuclear power facilities by the Atomic Industrial Forum [AIF]. In addition to the direct compensation to the employee, there is a fringe benefit factor of 0.38 of the annual wage to account for vacation, sick leave, life and health insurance, and other benefits provided to the employee. Contract workers' compensation is defined as the total cost to the facility owner including fringe benefits to the employee and profit to the contracting organization.

5.3 Maintenance Costs

The maintenance costs include only the cost of minor repair parts, melter liner materials, filter elements, calciner nozzles, furnace heater elements,

Table 17. Facility Staffing Requirements for Reference WSF (1979 dollars)

Category	Number of Equivalent Full-Time Personnel	Annual Compensation
OPERATIONS		
Process Operators	15	\$21,500
Radiation Monitors	3	21,300
Supervisor		29,800
TECHNICAL SUPPORT		
Engineers	4	27,500
Technicians	10	21,300
ADMINISTRATIVE		
Manager	1	45,000
Others	4	12,500
MAINTENANCE		
Plant		
Mechanical	7	19,300
Electrical	2	20,300
Instrumentation	2	21,400
Labor	3	15,200
Supervisor	2	27,100
Contract ^a		
Mechanical	3	43,000
Electrical	1	36,500
Instrumentation	1	38,500
Labor	2	27,400

^aAnnual compensation for contract workers is defined as annualized cost to facility owner. Fringe factor of 0.38 does not apply to these compensation values.

ferric oxide and silver zeolite replacement, and other materials such as piping, cabling or valve-packing materials. The costs developed are allowances of approximately thirty percent of the direct labor costs based on adjustments to DOE projections [DOE-1979].

5.4 Consumables Costs

The cost of consumables includes the chemical canister costs. The chemical quantities for each alternative were taken from the flow diagrams developed for each alternative. Chemical suppliers were contacted to obtain chemical costs for industrial grade chemicals. Many of the chemicals were not available in grades other than reagent grades and consequently their costs were extremely high. Quality assurance (QA) and quality control (QC) requirements for the chemicals to be used in the process are at this point

undefined. It was assumed that QA and QC requirements will raise the chemical unit prices to levels consistent with reagent-grade material. Assumed chemical unit costs are given in Table 18.

Table 18. Chemical Unit Prices

Item	\$/kg
SiO ₂	0.04
B ₂ O ₃	1.62
CaO	0.05
Na ₂ O (as NaOH)	0.32
ZnO	0.99
Ca(NO ₃) ₂	0.77
Sr(NO ₃) ₂	0.53
Al(NO ₃) ₃	3.97
Pb	1.06

The canister costs were derived from a recent BNWL study [MC ELROY]. Other studies have estimated canister costs to be somewhat higher than the \$2500 per canister cost assumed in this study for the glass monoliths. However, on a quantity basis, it is assumed that the canister costs will be reduced so that \$2500 per canister is an acceptable estimate. For the metal matrix waste forms, a more complex canister would be required. A cost of \$3,000 per canister was assigned to ceramic pellet-metal matrix composite alternative. A cost of \$3,500 per canister was assigned to the glass bead-metal matrix alternative which has the largest canister.

5.5 Utilities Costs

The cooling water and electricity requirements for each alternative were taken from the flow diagrams. Using the 5760 operating hours (80 percent capacity) per year, the quantity of each utility was computed. The cooling water costs are based on a total heat removal rate of 4.74×10^7 W of heat, 1.63×10^4 gal/min of cooling flow at a head of 60 feet of water. The electricity was charged at \$0.05/kW·h. The electricity costs were based on the full kW ratings of the equipment, which are greater than the actual power usage. Cooling water requirements for the process equipment and storage pool cooling systems were determined from the decay heat curves for the fission-product spectrum assumed for the fuel burnup in this study. Power requirements for building services were excluded from this evaluation since they are essentially the same for all alternatives.

6.0 COST SUMMARIES

Annual fixed costs for each waste processing alternative were calculated by use of a capital recovery factor. No decontamination and decommissioning costs (D&D) are included in any part of this study.

The capital recovery factor is an annual charge which takes into account the cost of borrowed money and the depreciation of assets. It is calculated from the expression:

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

where

CRF = capital recovery factor
i = cost of borrowed money expressed as a decimal
n = plant operating lifetime (y)

The capital recovery factor multiplied by the total capital cost will give the annual dollar charges and capital-related expenses. In this analysis, the plant operating life is assumed to be 15 years (similar to that utilized by DOE) and the cost of borrowed money is 12%, therefore, the capital recovery factor is 0.147. Annual costs for each alternative are given in Table 19; annual cost differences are given in Table 20 for the four alternatives.

A review of the annual cost summaries for the waste solidification alternatives reveals that the differences of Table 20 are within about ten percent of the base case. This indicates that cost is not necessarily the most critical factor or criterion in the choice of a waste form. Indeed, variations in facility construction duration, interest rates (hence, interest during construction), or any of the other factors which make up and influence annual costs can overshadow the cost differences between alternatives shown in Table 20.

For example, a change of the interest during construction (IDC) to reflect either fluctuation in interest rates or an extension of the construction period can have a large impact. Increasing the factor for IDC from 1.58 (12% for four years) to 1.70 (12% for 4.7 years or 14% for four years) increases the total capital cost of the reference borosilicate glass/spray calcine feed alternative from \$145,334,000 to \$156,372,000. This differential is \$11,038,000 which is greater than any of the total cost differences between any alternatives given in Table 20.

Table 19. Annual Cost Summary (Absolute 1979 dollars)

	Borosilicate Glass Monolith/ Spray Calcine Feed, \$K	Borosilicate Glass Monolith/ Direct Liquid Feed, \$K	Glass Bead-Metal Matrix Composite, Lead-Encapsulated Glass Beads, \$K	Ceramic Pellet-Metal Matrix Composite, Lead-Encapsulated Supercalcine Pellets, \$K
Annual Operating ^a and Maintenance Cost	3,591.1	3,256.1	4,852.1	4,726.2
Annualized Capital ^b Cost	<u>21,364.1</u>	<u>20,879.3</u>	<u>22,703.0</u>	<u>22,914.2</u>
Total Annual Cost	24,955.2	24,135.4	27,555.1	27,640.4

^aFrom Tables 13 to 16.

^bFrom Tables 9 to 12 after applying the capital recovery factor (CRF).

Table 20. Annual Cost Differentials (Relative 1979 dollars)

Waste Form	Cost Difference	
	\$K	%
Borosilicate Glass Monolith/ Spray Calcine Feed	BASE ^a	0
Borosilicate Glass Monolith/ Direct Liquid Feed	(819.8) ^b	(3.2)
Glass Bead-Metal Matrix Composite, Lead-Encapsulated Glass Beads	2,599.9	10.4
Ceramic Pellet-Metal Matrix Composite, Lead-Encapsulated Supercalcine Pellets	2,685.2	10.7

^aBase equals \$24,955,200; the other values in this column are added to this value to convert to absolute values

^bParentheses represent a negative cost difference.

7.0 SUMMARY AND CONCLUSIONS

It is concluded in this study that:

- The largest single cost component of a high-level waste solidification facility (WSF) is the cost of the building structure and support facilities for the solidification process.
- The costs for total process equipment and its installation for the various solidification system alternatives are between about three and one-half and eight percent of the total (unannualized) WSF Building costs, depending upon the specific solidification alternative.
- The annual operating and maintenance costs for the various solidification alternatives are between 14 and 18 percent of the total annualized capital costs, based on a 15-year plant operating life.
- Based on an annualized (15-year) cost, the borosilicate glass monolith/direct liquid feed waste form has the lowest cost. However, because of the uncertainties of this cost study, we cannot treat this statement definitively. Thus, given the current uncertainties of these estimates, all processes could be concluded to cost the same.

Because of general uncertainty of the cost estimates and the use of many assumptions and derived factors, we conclude that, within the likely errors,

no difference in total cost among the four processes can be considered reliable. As is evident from Tables 9-12, building costs and costs associated with overall expenses ("house office," IDC, contingencies) constitute more than 95% of the total facility capital cost; these, in turn, constitute more than 80% of the annual cost of Table 19. If it is assumed that uncertainties among the various categories of costs are comparable, it is also instructive to examine the relative cost data after removing the major, and generally invariant, fraction that is attributed to the building. Costs for selected aspects, normalized to unity for the liquid-fed borosilicate glass monolith process, are shown below:

	Spray Calcine Feed/Glass Monolith	Liquid Feed/ Glass Monolith	Glass Bead- Metal Matrix	Ceramic Pellet- Metal Matrix
Installed Process Equipment Costs (Table 6)	1.53	1.00	1.35	2.33
Annual Labor Cost (Tables 13-16)	1.06	1.00	1.23	1.30
Annual Consumables (Tables 13-16)	1.00	1.00	2.22	1.68
Total Annual Cost (Table 19)	1.034	1.000	1.142	1.145

We conclude from the trend in these data that Process Equipment and Consumables for the metal matrix processes are more costly than for the liquid-fed glass monolith process. Further, consumable costs for both metal matrix processes are also significantly greater. It is not clear, however, whether some of the increases in estimated equipment and consumable costs are only the result of less-developed technology for the metal matrix processes. Even if the cost differences singled out for attention are assumed to be reliable, their impact on total costs, as noted above, is negligible. Consumable costs are about 7% of the total annual cost for the glass bead-metal matrix process and less than 4% for the glass monolith processes (i.e., Table 19).

Transportation costs were not included in the present study. The data in a previous cost estimate [ERDA-1977B] appeared to show a significant cost penalty for transport of metal matrix waste. Closer examination of this work revealed, however, that the comparisons are not valid, and hence the conclusions are not justifiable. When appropriately corrected, the revisions tend to be similar to the conclusions of the present work, namely, that total cost differences among the processes are not significant at the present level of process refinement.

In summary, the costs for the equipment and its installation for any one given waste solidification system studied do not dominate the waste solidification facility costs. Depending upon the choice for annualizing the capital

costs, the annual operating and maintenance costs for a given waste solidification alternative form a significant portion of the total annual costs for a complete WSF. Differences between the estimated operating and maintenance costs for the various alternatives cannot be regarded as significant because of the lack of experience with process reliability and ease of remote maintenance. The final selection of a waste form should be decided based on other factors (beyond the scope of this study) such as:

- Process operability and reliability
- Ease of remote maintenance
- Methods of satisfying QA/QC requirements
- Considerations of waste-form handling during transportation and terminal storage
- Level of protection given to the health and safety of the public

APPENDIX A

SUPERCALCINE MONOLITH

A-1.0 Introduction

This waste-form alternative involves the formation of a supercalcine monolith within the stainless steel waste canister. The supercalcine product is a crystalline ceramic waste form prepared by modifying the HLLW with selected additives so that when it is calcined and given additional heat treatment, an assemblage of thermodynamically stable crystalline phases will be formed which are more refractory and leach-resistant than ordinary oxide calcine formed without additives and heat treatment. The flow diagram for this conceptual alternative is given in Fig. A-1. This alternative is not being currently developed, but was partially analyzed as a possible simplified HLLW solidification process. The data and results presented here represent only preliminary analysis of the supercalcine monolith and as such should not be compared with other processes.

A-2.0 Feed Preparation

Feed to the solidification process is prepared in the high-level cell where the supercalcine formation additives (Sr, Ca, Al nitrates and SiO_2) are added to the HLLW in the feed prep tank. The additives are in a slurry that has been prepared in the chemical addition tank located outside of the high-radiation areas of the facility and transferred to the feed prep tank. Once mixing of the tank is completed, the solution is sampled and further chemical adjustments made if necessary, or the waste can be transferred back to the HLLW storage for additional treatment or dilution.

Once the acceptability of the waste for processing has been determined, the waste is transferred to the calciner feed tank. Both the 4,750-L feed prep tank and the 4,750-L calciner feed tank are equipped with cooling coils to remove decay heat and agitators to mix the tanks and maintain any particulate material in suspension.

This system design is basically the same as that discussed in Section 3.4.1.

A-3.0 Solidification

Solidification of the HLLW is by spray calcination of the HLLW supercalcine additive mixture similar to the spray calcination performed for the borosilicate glass monolith/spray calcine feed waste form. The calciner product is fed in the next step directly to the stainless steel canister. After the formation of the supercalcine product (*i.e.*, heating to $1,200^\circ\text{C}$ for several hours), the material is compacted with a hydraulic ram compactor to achieve a greater product density to increase the thermal conductivity of the canister product. The operation would probably involve partial filling following by compaction and repeating until the canister is filled. All operations which result in canister temperatures above the sensitization temperature of stainless steel are performed in an inert atmosphere. This includes the supercalcine sintering.

ITEM	STREAM	1	2	3	4	5	6	7	8	9	10
DESCRIPTION	Supercalcine Additives	HLW	Calciner Feed	Calciner Feed	Atomizing Air	Calciner Product	Calciner Effluent	Ruthenium Adsorbent	Off Gas	Calciner Exhaust	Calciner Exhaust
RATE m ³ /min	50.0 L/hr	90.0 L/hr	150.7 L/hr	150.7 L/hr	25.0 m ³ /min	...	71.0 m ³ /min	...	11.5 m ³ /min	100.0 m ³ /min	100.0 m ³ /min
TEMP °C	ambient	60	60	60	0	1100	150	...	60	60	60
PH. SLURRY	0.0	0.0	0.0 psig	0.0 psig	700 psig	600 psig	600 psig	...	700 psig	700 psig	700 psig
DENSITY g/cm ³	1.15	1.30	1.20	1.20	1.20	0.45 g/cm ³	0.45 g/cm ³	...	1.00 g/cm ³	1.00	1.00
WATER %	...	7.0	...	...	...	...	...	...	...	...	...
CALCINER RATES %	6.3	23.9	30.2	30.2	...	...	...	...	...	...	...
WATER %	55.2	90.0	100	100	...	...	100	100	0.22	100	100
NO ₂ %	...	...	...	...	...	...	10.5	10.5	10.5	10.5	10.5
NO _x %	...	...	...	...	...	...	...	...	...	...	...
O ₂ %	...	...	...	...	150	...	150	150	150	...	...
H ₂ %	...	...	...	...	420	...	420	420	420	...	...
WATER %	7.0	12.0	20.0	20.0	...	11.0	0.030	0.030	0.030	...	...

Fig. A-1. Flow Diagram for Supercalcine Monolith

2	3	4	5	6	7	8	9	10
HLW	Calcliner Feed	Calcliner Feed	Atomizing Air	Calcliner Product	Calcliner Effluent	Ru Adsorber Effluent	Off Gas	Calcliner Combustion
1.6 L/hr.	150.2 L/hr	150.2 L/hr	25 m ³ /min	...	23.4 /min	...	11.5 m ³ /min	106 L/hr
60	60	60	0	1100	350	...	60	60
60	60 psig	60 psig	760 psig	600 psig	600 psig	...	760 psig	760 psig
1.30	1.24	1.24	1.79 kg/m	...	0.69 kg/m	...	1.01 kg/m	1.01
...	...	...	...	...	...	...	...	...
23.9	30.2	30.2	...	...	...	...	...	...
...	...	...	...	...	106	106	0.13	106
...	...	...	...	...	10	1	...	9.48 x 10 ⁴
...	...	...	1500	...	1500	1500	1500	...
...	...	...	674	...	674	674	674	...
...	12.8	20.6	20.6	11.4	0.034	0.016	...	0.016

Fig. A-1. Flow Diagram for Supercalcine Monolith

A-4.0 Off-Gas Treatment

The off-gas treatment system is identical in concept to that of the calcine-fed borosilicate glass waste form. Figure A-2 shows the VOG system for this waste solidification process. The VOG system design is discussed in Section 3.1.3, and the VOG equipment sizing is given in Table A-1. The flow rate from the VOG preprocessing is 31.5 m³/min at 60°C and 740 torr.

Table A-1. Major Equipment Listing for Supercalcine Monolith
(Preliminary)

Item	Number Required
1. Feed Preparation Tank	1
Capacity: 4750 L	
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Dimensions: 1.82 m height, 1.82 m diameter	
2. Calciner Feed Tank	1
Capacity: 4750 L	
Materials of Construction: 304L SS	
Design Pressure: 100 psig	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Feed pump mounting	
Dimensions: 1.82 m height x 1.82 m diameter	
3. Ruthenium Adsorber	7
Capacity: 11.3 m ³ /min - module	
5.1 cm x 20.3 cm x 2.74 m	
Design Temp: 800°C	
Design Pressure: 25 psig	
Materials of Construction: 304L SS	
Geometry: Rectangular finned vessel	

(contd)

Table A-1. (contd)

Item	Number Required
4. Quench Tower	1
Countercurrent Spray Tower Design Pressure: 25 psig Design Temp: 700°C Materials of Construction: 304L SS Geometry: Right cylinder Conical bottom Appurtenances: Spray header 4 Vessel connections Bottom drain screen Size: 1.9 m OD x 3 m Ht.	
5. Quench Tower Surge Tank	1
Materials of Construction: 304L SS Design Pressure: Atmospheric Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Size: 4.0 m OD x 4.3 m Ht. Appurtenances: Cooling coils Agitator mounting Recycle pump mounting	
6. Chemical Addition Tank	1
Capacity: 1800-L volume Design Pressure: Atmospheric Materials of Construction: 304L SS Geometry: Right cylinder Dished head bottom Closed top Dimensions: 1.32 m x 1.32 m Design Temp: 100°C	
7. Pumps	
A. Calciner Feed Pumps 6 L/min ~ 1/2 hp	2
B. Quench Solution Recycle Pumps 300 L/min ~ 6 hp	2

(contd)

Table A-1. (contd)

Item	Number Required
8. Agitators	
A. Calciner Feed Tank	2
B. Feed Preparation Tank	2
C. Chemical Addition Tank	1
9. VOG Adsorber	1
Type: Bubble Cap Tray Capacity: 31.5 m ³ /min Size: 0.4 m OD x 4.6 m Ht. Material of Construction: 304L SS Geometry: 8 Trays, Right cylinder Design Pressure: 25 psig Design Temp: 130°C	
10. VOG Cooler	1
Type: Glycol Cooled Capacity: 31.5 m ³ /min Size: 0.6 m OD x 1.5 m long Shell and Tube Design Temp: 130°C Design Pressure: 25 psig Material of Construction: 304L SS	
11. VOG De-entrainer	1
Type: Knockout Pot Design Pressure: 25 psig Design Temp: 130°C Material of Construction: 304L SS	
12. VOG Heater	2
Type: Resistance, 1 Zone Rating: 9 kW Material of Construction: 304L SS Nichrome heating element	

(contd)

Table A-1. (contd)

Item	Number Required
13. VOG Filters	2
Type: Deep bed fiberglass Material of Construction: 304L SS Design Pressure: 25 psig Design Temp: 200°C Size: 0.3 m OD x 2.2 m Right cylinder Dished head bottom Capacity: 40.1 m ³ /min	
14. VOG Iodine Adsorber	3
Type: Silver zeolite bed Material of Construction: 304L SS Design Temp: 200°C Design Pressure: 25 psig Geometry: Right cylinder, hemisphere head, bottom - 4 Nozzles Capacity: 40.1 m ³ /min Vessel Size: 0.6 m OD x 2 m Ht.	
15. VOG Blowers	2
Type: Centrifugal blower, direct drive Capacity: 40.1 m ³ /min Material of Construction: 304L SS Static Pressure: 42 mm Hg	
16. NO _x Feed Effluent Heat Exchanger	1
Type: Shell and Tube Hx Capacity: 33.2 m ³ /min Design Temp: 450°C Design Pressure: 25 psig Material of Construction: 304L SS	
17. NO _x Reactor	1
Type: Platinum - Palladium catalyst S.S. Vessel, 0.8 m OD x 1 m Ht. 190 kg Catalyst	

(contd)

Table A-1. (contd)

Item	Number Required
18. NO _x Reactor Heater	1
Type: Resistance, 1-Zone Rating: 8 kW Material of Construction: 304L SS Nichrome heating element	
19. Denitrification Furnace	1
Type: Electrical Resistance 8-Zone Rating: 250 kW Materials: Silicone Carbide Size: 0.5 m OD x 5.5 m Ht.	
20. Spray Calciner	1
Capacity: 158.2 L/h Calcining Chamber: 1.0 m OD x 3.0 m Ht. Overall Height: 5.3 m Material: 304L SS Design Pressure: 40 psig Design Temp: 800°C Heaters: 500 kW	
21. Power Manipulators	1
PAR 3000 or equivalent	
22. Canister Rack/Transport	1
Storage, cooling and transport capability Pneumatic actuation Remote maintenance	
23. Weld Station	1
Capability to cap canister in one pass Drive for weld wire outside of cell Console located outside cell Remote maintenance and repair Welding electrode rotates to produce weld	

(contd)

Table A-1. (contd)

Item	Number Required
24. Master-Slave Manipulators	2
Central Research Laboratories Model F or equivalent	
25. Hydraulic Ram Compactor	1
Capacity: 2000 psi	
Material: 304L SS	
Motor-Driven	

A-5.0 Canister Handling

The waste canister is constructed of Type 304L stainless steel. The size of the canister is based on minimizing the canister's length-to-diameter ratio, and maintaining the canister heat load at five kilowatts per canister at ten years decay after the spent fuel is discharged from the reactor. Canister centerline temperatures do not exceed 700°C. Details of the canister size determination are given in Appendix F. The resultant canister is 0.19 m in diameter and 4.84 m long. Canister handling operations are similar to those for the calcine-fed ceramic melter, except that the coupling to the canister is to the calciner directly.

A-6.0 Canister Storage

Storage of the canister containing this waste-form product is similar to that for the calcine-fed borosilicate glass waste form discussed previously in Section 3.1, except that the canisters are stored in single-storage tier racks. The size of the storage pool is 26 m wide by 33 m long by 10.6 m deep.

A-7.0 Solidification, High-Level, and Off-Gas Treatment Cell Designs

The design of the solidification, high-level, and off-gas treatment cells is similar to that proposed for the spray calcine feed/borosilicate glass waste form with the following exceptions:

- The ceramic melter is not required in this waste process
- A denitrification furnace is required for this process
- The hydraulic ram compactor is required for this waste form process

The preliminary capital equipment cost estimates for this process are given in Table A-2. They cannot be compared with other alternatives developed in this report.

ITEM	1	2	3	4	5	6	7	8	9
DESCRIPTION	Solidification Off Gas	Absorber Off Gas	Condensate	Non-Cond. Off Gas	Filter Off Gas	Indirect Absorber Effluent	NOx Reactor Effluent	NOx Reactor Feed	NOx Reactor Feed
RATE m ³ /min	31.5	31.5	2.17×10^{-3}	26.3	40.1	40.1	33.2	50.8	29.7
TEMP °C	60	60	4.4	4.4	150	150	150	450	150
PRESSURE, torr	760	760	760	760	760	760	900	1000	1000
DENSITY g/l	1.03	1.03	1000 kg/m^3	1.22	0.80	0.80	0.98	0.61	1.08
PHO ₂ (at)	--	--	--	--	--	--	--	--	--
CATION INTRATES kg/hr	--	--	--	--	--	--	--	--	--
WATER kg/hr	0.13	0.13	0.13	--	--	--	11.1	--	--
NO kg/hr	18.5	18.5	--	18.5	18.5	18.5	--	18.5	18.5
NH ₃ kg/hr	--	--	--	--	--	--	--	--	--
N ₂ kg/hr	1500	1500	--	1500	1500	1500	1518	1500	1500
O ₂ kg/hr	424	424	--	424	424	424	424	424	424

Fig. A-2. Flow Diagram for Supercalcine Monolith-VOG System

Fig. A-2. Flow Diagram for Supercalcine Monolith-VOG System

Table A-2. Preliminary Capital Equipment Cost Estimate Sheet, Supercalcine Monolith

Item Description	Quantity	Unit Cost \$K	Man- Hours	C o s t	
				Material	Labor
Feed Prep Tank	1	21	1,300	\$21,000	\$17,600
Calciner Feed Tank	1	21	1,300	21,000	17,600
Ruthenium Adsorber	7	10	820	70,000	77,500
Quench Tower	1	60	1,300	60,000	17,600
Quench Tower Surge Tank	1	60	1,300	60,000	17,600
Chemical Addition Tank	1	10	180	10,000	2,400
Calciner Feed Pumps	2	2	160	4,000	4,300
Quench Tower Recycle Pumps	2	10	250	20,000	6,800
Agitators	5	6	80	30,000	5,400
VOG Adsorber	1	30	980	30,000	13,200
VOG Cooler	1	4	410	4,000	5,500
VOG De-entrainer	1	2	160	2,000	2,200
VOG Heater	2	5	160	10,000	4,300
VOG Filters	2	4	250	8,000	6,800
VOG Iodine Adsorber	3	28	440	84,000	17,800
VOG Blowers	2	5	660	10,000	17,800
NO _x Feed Effluent Heat Exchanger	1	6	320	6,000	4,300
NO _x Reactor	1	27	490	27,000	6,600
NO _x Reactor Heater	1	4	180	4,000	2,400
Denitrification Furnace	1	232	2,000	232,000	27,000
Spray Calciner	1	420	8,400	420,000	113,400
Power Manipulator	1	170	1,100	170,000	14,900
Canister Rack/Transport	1	330	2,000	330,000	27,000
Weld Station	1	110	600	110,000	8,100
Master-Slave Manipulators	2	30	330	60,000	8,900
Hydraulic Ram Compactor	1	42	980	42,000	7,200
TOTAL				\$1,845,000	\$460,200

APPENDIX B

LWR SPENT FUEL INVENTORY

B-1.0 LWR Spent Fuel Inventory

The estimated cumulative inventory of spent fuel discharged from light-water power reactors is summarized in Table B-1 and Fig. B-1. Five sources of estimated quantities of spent fuel from light-water reactors (LWRs) were compared for the purposes of defining the most likely age* of the waste generated from the commercial reprocessing of spent fuel. Four factors influence the age of spent fuel reprocessing wastes which are to be solidified:

1. The rate at which spent reactor fuel is accumulated
2. The rate at which spent fuel is reprocessed
3. The point in time at which reprocessing of spent reactor fuel is initiated, i.e., storage time as spent fuel
4. Storage time of liquid high-level waste after reprocessing prior to solidification

Based on current institutional obstacles and the lead times required for waste solidification process development and demonstration, plant design, licensing, equipment procurement, and plant construction, it is unlikely that reprocessing of spent reactor fuel and the subsequent solidification of the reprocessing wastes could be started before at least 1990. As shown in Table B-2, the minimum mass-weighted average age of the spent reactor fuel at that time is five years using the five projections of spent fuel quantities. Thus, there will be a sufficient supply of spent fuel of age equal to or greater than five years that would be available for reprocessing. Thus the use of liquid wastes to be solidified for the reference-case age of three years is very plausible. Further, assuming that reprocessing is initiated in 1990 and the reprocessing capacity of the U.S. expands at a rate of 1000 MTU/y every year, almost eight years would be required to reprocess the existing inventory of spent reactor fuel. With more realistic reprocessing capability growth rates (e.g., 300-500 MTU/y every year), the existing 1990 inventory would take over a decade to reprocess.

Using the derived parameters previously described, it can be seen that waste solidification technologies that could reasonably be expected to be implemented by the year 1990 would handle any wastes that have decayed for at least 6.3 years after discharge from a reactor. For the process evaluations performed, the assumption of three-year-old waste as a design basis is reasonable and conservative.

*"Age" is defined as the time elapsed between discharge from the reactor and spent fuel reprocessing.

Table B-1. Cumulative Spent Fuel Discharged (in MTU)

Year	Source				
	ERDA-Low [ERDA-1977A]	NRC [DOE-1978]	DOE-1977 [DOE-1978]	BLOMEKE [DOE-1978]	NAC [DOE-1978]
1976	1814	2500	2000	2200	1925
1977	2635	3440	3000	3313	2959
1978	3614	4550	4000	4538	4316
1979	4690	5810	5300	5921	5841
1980	5864	7220	6600	7432	7704
1981	7126	8880	8000	9090	9600
1982	8541	10830	9600	10876	12073
1983	10190	12940	11500	12869	14949
1984	12080	15200	13700	15148	18189
1985	14257	17540	16400	17768	22170
1986	16791	19880	19300	20811	26486
1987	19673	22130	22700	24256	31217
1988	22847	25340	26300	28047	36255
1989	26292	28900	30200	32162	41484
1990	30015	32860	34400	36606	46674
1991	34033	37220	39000	41402	51925
1992	38365	41960	43900	46573	57585
1993	43024	47170	49100	52137	63700
1994	48020	52830	54800	58102	70250
1995	52743	58920	60800	64494	77257
1996	59111	65440	67300	71346	84763
1997	65042	72380	74200	78670	92772
1998	71762	79690	81500	86457	101282
1999	78662	87320	89300	94706	110292
2000	85937	95230	97400	103405	119802

Fig. B-1. Five Estimates of Spent Fuel Discharged

Table B-2. Characteristics of Cumulative Spent Fuel Discharged by 1990

	Average Age, ^a y	Minimum Time to Process ^b Backlog @ 1000 MTU/y per y
ERDA-Low[ERDA-1977A]	6.3	7.8
NRC[DOE-1978]	5.6	8.1
DOE-1977[DOE-1978]	5.2	8.3
Blomeke[DOE-1978]	5.3	8.6
NAC[DOE-1978]	5.0	9.7

^aThe mass-weighted average age of the spent fuel based on projections given in Table B-1 at 1990

^bReprocessing capability is assumed to be installed and increased every year at a rate of 1000 MTU/y beginning in 1990.

APPENDIX C

HIGH-LEVEL LIQUID WASTE (HLLW) CHARACTERIZATION

C-1.0 Bases

The PWR spent fuel from the uranium cycle is assumed reprocessed after irradiation of 33,000 MWd/MTU at 30 MW/MTU. Spent fuel properties are discussed in detail elsewhere [ERDA-1977A, DOE-1978]. The HLLW is aged for at least three years prior to solidification. Aging may be done by storing spent fuel or by the less likely option of reprocessing and storing the HLLW. A preconcentration and nitric acid recovery step is performed prior to solidification processing. The HLLW assumed for this study is raffinate from the first-stage extraction in the Purex Process and does not include intermediate or low-level liquid wastes.

C-2.0 Assumptions

The concentrated HLLW feed rate to the solidification process is 378 L/MTU [AGNS, ERDA-1977A]. HLLW density is 1.2 g/cm³ and is saturated with air. HLLW composition is assumed similar to the reference PW-7 composition [RUSIN]. The composition is assumed to be 100 percent of the fission products (except for 0.1 percent of the iodine and no noble gases), 0.5 percent uranium and plutonium, and 100 percent of the remaining actinides from the spent fuel. The nitrate composition in the solidification feed is 3.9M which includes 2M as nitric acid and 1.9M as metal salts. The bases of PWR spent fuel irradiated for 33,000 MWd/MTU at a specific power of 30 MW/MTU represent expected values for PWRs that are currently commercially available. Properties of the spent fuel are given in Table C-1. From the assumed waste composition and the spent fuel properties given in Table C-1, the HLLW properties in Table C-2 were calculated. Details of the waste composition other than nitrates do not impact this study. Typical waste nitrate composition and the composition of the oxide form of the waste are given in Tables C-3 and C-4 and are based upon composition given in [RUSIN].

Table C-1. Spent Fuel Properties [ALEXANDER]

Years After Discharge	Decay Heat, W/MTU	Radioactivity, Ci/MTU
160 days	1.97×10^6	2.00×10^8
1	1.04×10^4	2.45×10^6
2	5.39×10^3	1.36×10^6
5	1.84×10^3	5.78×10^5
10	1.14×10^3	3.95×10^5

Table C-2. HLLW Properties

Years After Discharge	Decay Heat, W/MTU	Radioactivity, Ci/MTU
160 days	1.89×10^6	2.00×10^8
1	1.02×10^4	2.45×10^6
2	5.17×10^3	1.36×10^6
5	1.66×10^3	5.78×10^5
10	1.00×10^3	3.95×10^5

Table C-3. Nitrate Composition in HLLW

Component	Chemical Form	Molarity	g Nitrate/L
Ag	AgNO ₃	0.002	0.12
Ba	Ba(NO ₃) ₂	0.027	3.35
Cd	Cd(NO ₃) ₂	0.002	0.25
Cr	Cr(NO ₃) ₃	0.012	2.23
Cs	CsNO ₃	0.054	3.35
Fe	Fe(NO ₃) ₃	0.153	28.46
H	HNO ₃	2.000	124.00
Na	NaNO ₃	0.01	0.62
Ni	Ni(NO ₃) ₂	0.005	0.62
Rb	RbNO ₃	0.010	0.62
Ru	Ru(NO)(NO ₃) ₃	0.059	10.97
Sr	Sr(NO ₃) ₃	0.027	3.35
Zr	ZrO(NO ₃) ₂	0.106	13.14
Gd	Gd(NO ₃) ₃	0.153	28.46
Nd	Nd(NO ₃) ₃	0.071	8.80
Re+U	Re+U(NO ₃) ₄	0.236	14.63
			243 g/L

Total nitrate composition is 0.24 kg/L waste

Table C-4. Oxide Composition in HLLW [RUSIN]

Oxide	g/L of Calcined Solution
Re ₂ O ₃	34.07
Gd ₂ O ₃	27.69
ZrO ₂	13.04
Fe ₂ O ₃	8.00
P ₂ O ₅	7.10
MoO ₃	13.68
Cs ₂ O	7.61
BaO	4.13
SrO	2.81
Cr ₂ O ₃	0.91
Rb ₂ O	0.94
Na ₂ O	0.31
RuO ₂	7.90
NiO	0.38
CdO	0.26
Ag ₂ O	0.23
U ₃ O ₈	33.6
PdO	3.9
TeO ₂	1.9
Rh ₂ O ₃	1.3
TOTAL	169.76

APPENDIX D

REPROCESSING FACILITY DESIGN

D-1.0 Introduction

The conceptual design of the reprocessing plant is that of a modular facility for the various process steps. This is consistent with the design concept incorporated in the Allied-General Nuclear Services Barnwell Nuclear Fuel Plant at Barnwell, South Carolina [AGNS]. By using a modular facility as a basis, the solidification portion of the facility can be viewed as a stand-alone unit and evaluated as such. Shared facilities would then be limited to auxiliary services such as electrical power, makeup water, ventilation treatment, cooling water, etc. [HALL].

The solidification facility is then defined as that facility which converts concentrated high-level liquid wastes (HLLW) into a solid form. All process steps from the HLLW transfer through feed preparation, waste processing, and canister storage are included in the solidification facility.

D-2.0 Reprocessing Facility Design

The reprocessing facility has eight major process units:

- Spent Fuel Receiving and Storage Facility
- Central Reprocessing Facility
- Liquid Waste Storage Facility
- Uranium Hexafluoride Conversion Facility
- Plutonium Conversion Facility
- Solid Waste Storage Area
- Waste Solidification Facility
- Auxiliary System Facility

The reprocessing facility is designed, constructed, and operated to minimize the release of radioactive materials during normal operation and under accident conditions by the use of multiple barriers and administrative controls. The primary barrier is the process equipment itself which is designed for the range of operating conditions (i.e., temperature, pressure, radiation level, pH, etc.) expected, thereby ensuring that a barrier to the release of radioactive material exists. Once the equipment design bases are established, strict quality assurance programs are established to monitor the design, construction, and installation of the equipment to ensure that the design bases have been adequately implemented.

Structural barriers are designed to contain process materials if primary equipment barriers are breached. The principal structural barriers

are constructed of heavily reinforced concrete. The process structural barriers are generally termed "radioactive process cells" and are usually surrounded by maintenance or operating areas. The process cell where the spent fuel is chopped and dissolved and high-level liquid wastes are concentrated contains very high radiation levels. This cell is designed for remote maintenance (i.e., maintenance from outside the cell by the use of in-cell cranes, shielding windows, and manipulators). Similarly, a cell for remote packaging of radioactive wastes and for performing remote decontamination and maintenance of equipment removed from other process cells is also provided. The rest of the process cells are designed to permit direct personnel entry and contact maintenance, but only after appropriate remote decontamination has been completed. These cells are designed to minimize maintenance requirements.

The process and support equipment used in handling the radioactive materials are contained in cells or glove boxes. Spent fuel bundles are stored and transported under water. The cells, glove boxes and pools provide a barrier between the highly contaminated or radioactive environment within and the outside habitable environment. Cells with heavy shielding walls or pools with deep water cover are provided where protection against penetrating radiation is required. Glove boxes are used when radiation levels are low and hand operations are permitted.

The process equipment, piping, buildings and structures, casks, storage tanks and fuel element cladding (prior to shearing) provide barriers for the confinement of radioactive materials. Essential confinement systems are designed to maintain their function under normal operating conditions, abnormal operations, upper-limit accident conditions, and adverse environmental conditions throughout the life of the facility. Hatches and penetrations, which are an integral part of the structure, do not compromise the confinement and shielding functions.

The floors of all cells are covered with continuous (welded) stainless steel liners. These liners serve to contain all liquids within the cells in the event of a primary vessel leak. Process cells are also equipped with sump systems for the control of spilled solutions. The walls of the cells are covered with either stainless steel or a radiation-resistant paint. The choice of cell wall covering depends on the nature of the material to be processed within the particular cell. The wall covering serves to seal the concrete structural material from the corrosive atmosphere and radionuclides and, hence, facilitate decontamination.

D-2.1 Spent Fuel Receiving and Storage Facility

The Spent Fuel Receiving and Storage Facility is designed to receive and store irradiated fuel elements from light water reactors. The spent fuel assemblies would be received in shielding casks, transported by either truck or rail and unloaded under water. The fuel elements would be stored under water to provide cooling and shielding. Facilities for decontaminating the shipping casks before they leave the plant and equipment to circulate, filter, deionize, and cool the storage pool water are provided. The major areas of the facility and their primary functions are listed in Table D-1.

Table D-1. Primary Functions of Areas in Spent Fuel Receiving and Storage Facility

Area	Process Functions	Remarks
Vehicle unloading bays (2)	Receive rail and truck casks; unload casks from transport vehicle; load casks on transport vehicle	
Test and decontamination pit	Prepare casks for unloading in the cask unloading pool	Stainless steel floor pan
Cask unloading pools (2) (CUP)	Remove fuel from casks; place solidified waste canisters in casks	Stainless steel liner
Decontamination pit	Decontaminate casks after removal from CUP	Stainless steel floor pan
Fuel storage pool	Store fuel assemblies and solidified waste canisters	Stainless steel liner; aluminum storage racks
Fuel transfer pool	Transfer fuel assemblies to Central Reprocessing Facility	Stainless steel liner
Deionization area	Circulate, filter, deionize, and cool pool water	

The facility is connected to the Central Reprocessing Facility by the fuel transfer conveyor tunnel and will be connected to the conceptual waste solidification plant by an underwater transfer aisle. The pool walls and liners are designed to maintain their containment integrity during a design-basis earthquake or tornado.

D-2.2 Central Reprocessing Facility

The Central Reprocessing Facility is the functional center of the reprocessing plant. The uranium and plutonium are chemically separated from the spent fuel in this building. This processing is carried out in a series of main process cells that occupy a major portion of the building. The Central Reprocessing Facility also contains a wide variety of facilities and equipment that are used to monitor and control the process, maintain the equipment, carry out auxiliary operations and treat gaseous effluents from the processes carried out in the building.

The primary functions of the main process cells are listed in Table D-2. Most of the building is constructed of reinforced concrete designed to remain intact during a design-basis earthquake or tornado. Process cell walls are up to 2-m thick to provide shielding of personnel from radioactivity.

Table D-2. Primary Functions of Main Process Cells

Cell	Primary Process Functions	Remarks
Remote process cell (RPC)	Shear and dissolve fuel; concentrate high-level waste	Stainless steel floor pan; remote liquid waste maintenance
Remote maintenance and scrap cell (RMSC)	Package leached hulls and other solid waste; remotely maintain contaminated equipment	Stainless steel walls and floor
High-level cell (HLC)	Accountability for dissolver solution; chemically adjust dissolver solution; centrifuge dissolver solution	Stainless steel floor pan; contact maintenance; centrifuge replaceable without cell entry
High-intermediate level cell (HILC)	Separate uranium and plutonium from high-level waste; separate uranium from plutonium, treat dissolver off-gas; solvent cleanup; concentrate intermediate-level waste	Stainless steel floor pan; contact maintenance
Intermediate-level cell (ILC)	Treat vessel off-gas; recover nitric acid; concentrate low-level waste; burn used solvent	Stainless steel floor pan; contact maintenance
Uranium product cell (UPC)	Purify uranium stream; clean up solvent	Stainless steel floor pan; contact maintenance
Plutonium product cell (PPC)	Purify plutonium stream	Stainless steel floor pan; contact maintenance
Plutonium nitrate storage and loadout (PNSL)	Store plutonium nitrate solutions; transfer plutonium nitrate to Plutonium Oxide Conversion Facility	Stainless steel floor pan; contact maintenance

The areas outside the main process cells are generally divided into regions called "galleries," "areas," or "stations." These areas enclose and protect service piping, process support equipment, instrumentation components, and some operating areas. Radioactivity levels in these areas range from essentially background to modest levels.

Other pertinent features of the Central Reprocessing Facility are discussed briefly below.

D-2.2.1 Control Room Area (CRA)

The control room area houses the process-control and safety-related instrumentation for the plant. It serves as the communications center from which operators can be directed to perform manual functions. The control room area is not expected to be contaminated, since the only process connections to other facility areas are electrical.

D-2.2.2 Sample and Analytical Cells (SAC)

The SAC is a shielded facility designed to facilitate radiochemical analyses of samples from the more highly radioactive portions of the process. The cells provide a shielded area for remote sampling and analysis of these materials, and for preparation of samples to be analyzed in the plant analytical laboratories. Operation is through the use of either shielded cells with viewing windows and manipulators or glove boxes.

D-2.3 Liquid Waste Storage Facility

High- and intermediate-level liquid wastes from the reprocessing operations would be concentrated and stored in large underground tanks until they could be solidified and shipped off-site for disposal. The Liquid Waste Storage complex is composed of high-level liquid waste (HLLW) tanks, intermediate-level liquid waste (ILLW) tanks and a waste tank equipment gallery (WTEG) that provides services for the tanks.

The WTEG is a concrete building located near the Central Reprocessing Facility. It houses the control room, heat exchangers, coolant circulating pumps, off-gas treatment equipment, and ventilation filters for the waste storage tanks. These tanks are connected through a small diverter cell beneath the WTEG and through underground pipe vaults to the Central Reprocessing Facility and the future waste solidification plant.

All tanks are constructed of stainless steel and are designed to store acidic aqueous solutions. All of the tanks have smooth bottoms with cooling coils and circulators hung from the ceiling to facilitate decontamination and cleanout. Each tank is contained within its own underground concrete vault. The vaults are lined with stainless steel. The tanks are supported off the floors of the vaults by stainless steel strips. The vault is sloped slightly from one side to the other, and a flushing pipe header is installed on the high side of the vault floor. The stainless steel strips supporting the tanks are arranged to channel the flush solution from the header to the vault sump.

The HLLW and ILLW tanks differ mainly in their internals. The HLLW tanks contain a densely packed array of cooling coils to remove the decay heat from the waste solution; in addition, a system of air-operated ballast tanks and circulators constantly and thoroughly mixes the solution in the tank to prevent accumulation of waste solids on the tank bottom. Each HLLW tank contains multiple external temperature sensing points and is provided with ten

instrument dip tubes. The ILLW tank has no cooling coils and is provided with fewer temperature sensing points than the HLLW tanks. It has a system of air spargers (rather than air-lift circulators and ballast tanks as in the HLLW tanks) to mix the solution in the tank.

D-2.4 Uranium Hexafluoride Conversion Facility

The major structures consist of two buildings, both of standard chemical plant construction. The main building is a multi-story structure containing the principal process areas. A second building located near the main process area is used for fluorine generation. The UF₆ Facility is located near the Central Reprocessing Facility to eliminate the need for shipment of uranyl nitrate to a distant conversion plant. The elimination of the shipping requirement saves time, reduces the cost to the nuclear power industry, and lessens the chances of radiological hazard to the public.

D-2.5 Plutonium Conversion Facility

A Plutonium Conversion Facility is added to: (1) convert aqueous plutonium nitrate solutions to solid plutonium oxide and (2) provide storage of plutonium oxide. The process facilities would be located in a separate building immediately adjacent to the Central Reprocessing Facility.

Most of the operations and maintenance in the facility would be carried out in glove boxes. Lead gloves would be used to protect against the low-level gamma radiation, and relatively thin concrete and other hydrogeneous shields would be used to protect against the alpha-neutron radiation from ²³⁸Pu.

D-2.6 Solid Waste Storage Area

The Solid Waste Storage Area is a facility designed to provide shielding and isolation of miscellaneous radioactive solid wastes that result from spent fuel reprocessing. Three types of wastes have been identified for storage in this facility:

- Spent fuel cladding hulls
- High-level general process trash
- Low-level general process trash

The facility consists of a series of concrete vaults for storage of spent fuel cladding hulls and high-level general process trash. Low-level general process trash would be stored in earth-covered containers.

D-2.7 Waste Solidification Facility

The Waste Solidification Facility (WSF) would be located adjacent to the Central Reprocessing Facility. It would receive liquid waste solutions from the waste tank farm complex, convert the liquids to a solid, and facilitate the transfer of solidified high-level wastes for storage and eventual shipment off-site.

The WSF would contain the waste solidification equipment, canister sealing, inspection and decontamination equipment, off-gas treatment equipment, and remote maintenance facilities in four process cells. The primary process functions performed in each of the cells are presented in Table D-3. All process cells in the WSF would be completely lined with stainless steel. The cells would be surrounded by limited access areas for operating and controlling the processes in the cells. All operational and maintenance activities in the process cells would be performed remotely using viewing windows, manipulators and cranes. Details of the WSF for the five waste-form alternatives are discussed in Section 3.

Table D-3. Primary Functions of Major Process Cells in the Waste Solidification Facility (WSF)

Area	Function
High-level cell	Prepare solidification system feed
Off-gas treatment cell	Treat off-gas from WSF process vessels
Waste solidification cell	Solidify liquid waste; weld canisters closed
Canister decontamination cell	Decontaminate outer surfaces of canisters; transfer filled canisters to facility
Hot maintenance cell	Perform remote maintenance on contaminated equipment

D-2.8 Auxiliary System Facilities

The Auxiliary System Facilities encompass the support systems required to make the entire plant operational such as:

- Ventilation
- Demineralized water
- Fire protection
- Electrical power
- Hot and cold laboratories
- Ventilation treatment
- Cooling water

These systems are located throughout the entire facility. Where possible, major components are centralized and distributional networks of the services are provided. Nonradioactive components are separated and isolated from radioactive components where practical to minimize radiation exposure to personnel.

APPENDIX E

WASTE SOLIDIFICATION ALTERNATIVES--EQUIPMENT LISTS

E-1.0 Introduction

This appendix presents tabulations of the major equipment and components for each of the conceptual solidification flowsheets developed in Section 3. This conceptual design effort has resulted in the preliminary definition of the equipment, materials of construction, equipment dimensions, and other factors necessary to allow for estimation of the cost of conceptual design components based on cost data from other available equipment cost and construction cost studies.

Tables E-1 through E-4 present the equipment lists for the four solidification alternatives analyzed.

Table E-1. Major Equipment Listing for Borosilicate Glass
Monolith/Spray Calcine Feed

Item	Number Required
1. Feed Preparation Tank	1
Capacity: 2960 L	
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Dimensions: 1.56 m x 1.56 m	
2. Calciner Feed Tank	1
Capacity: 2960 L	
Materials of Construction: 304L SS	
Design Pressure: 100 psig	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Feed pump mounting	
Dimensions: 1.56 m x 1.56 m	

(contd)

Table E-1. (contd)

Item	Number Required
3. Ruthenium Adsorber Capacity: 11.3 m ³ /min per module Size: 5 cm x 20.3 cm x 2.74 m Design Temp: 800°C Design Pressure: 25 psig Materials of Construction: 304L SS Geometry: Rectangular finned vessel	4
4. Quench Tower Countercurrent Spray Tower Design Pressure: 25 psig Design Temp: 700°C Materials of Construction: 304L SS Geometry: Right cylinder Conical bottom Appurtenances: Spray header 4 vessel connections Bottom drain screen Size: 1.4 m OD x 3.1 m Ht.	1
5. Quench Tower Surge Tank Materials of Construction: 304L SS Design Pressure: Atmospheric Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Size: 2.7 m OD x 4.3 m Ht. Appurtenances: Cooling coils Agitator mounting Recycle pump mounting	1
6. Frit Hopper with Feeder Capacity: 1000 kg of frit 562-L volume Materials of Construction: Carbon steel Geometry: Right cylinder with cone bottom Dimensions: 0.9 m x 0.9 m	1

(contd)

Table E-1. (contd)

Item	Number Required
7. Pumps	
A. Calciner feed pumps 6 L/min - 1/2 hp	2
B. Quench solution recycle pumps 60 L/min - 1 hp	2
8. Agitators	
A. Calciner feed tank	2
B. Feed preparation tank	2
9. VOG Adsorber	1
Type: Bubble cap tray Capacity: 21.8 m ³ /min Size: 0.3 m OD x 4.6 m Ht. Material of Construction: 304L SS Geometry: 8 trays, Right cylinder Design Pressure: 25 psig Design Temp: 130°C	
10. VOG Cooler	1
Type: Glycol-cooled Capacity: 21.8 m ³ /min Size: 0.5 m OD x 1.2 m long Shell and Tube Design Temp: 130°C Design Pressure: 25 psig Material of Construction: 304L SS	
11. VOG Deentrainer	1
Type: Knockout pot Design Pressure: 25 psig Design Temp: 130°C Material of Construction: 304L SS	

(contd)

Table E-1. (contd)

Item	Number Required
12. VOG Heater	2
Type: Resistance, 1-zone Rating: 5 kW Material of Construction: 304L SS Nichrome Heating Element	
13. VOG Filters	2
Type: Deep bed fiberglass Material of Construction: 304L SS Design Pressure: 25 psig Design Temp: 200°C Size: 0.3 m OD x 2.1 m Geometry: Right cylinder Dished head bottom Capacity: 27 m ³ /min	
14. VOG Iodine Adsorber	2
Type: Silver zeolite bed Material of Construction: 304L SS Design Temp: 200°C Design Pressure: 25 psig Geometry: Right cylinder, hemisphere head, bottom - 4 nozzles Capacity: 27 m ³ /min Vessel Size: 0.5 m OD x 2 m Ht.	
15. VOG Blowers	2
Type: Centrifugal blower, direct drive Capacity: 27 m ³ /min Material of Construction: 304L SS Static Pressure: 42 mm Hg	
16. NO _x Feed Effluent Heat Exchanger	1
Type: Shell and Tube H _x Capacity: 34 m ³ /min Design Temp: 450°C Design Pressure: 25 psig Material of Construction: 304L SS	

(contd)

Table E-1. (contd)

Item	Number Required
17. NO _x Reactor	1
Type: Platinum-Palladium Catalyst S.S. Vessel, 0.8 m OD x 1 m Ht 120 kg Catalyst	
18. NO _x Reactor Heater	1
Type: Resistance, 1-zone Rating: 7 kW Material of Construction: 304L SS Nichrome heating element	
19. Spray Calciner	1
Capacity: 98 L/h Calcining Chamber: 1.0 m OD x 2.6 m Ht. Overall Height: 5.0 m Material: 304L SS Design Pressure: 40 psig Design Temp: 800°C Heaters: 500 kW	
20. Ceramic Melter	1
Capacity: 100 kg/h Tilt Screw: Overflow Joule Heated: 200 kW Size: 2.5 m x 2.5 m x 2.5 m	
21. Power Manipulator	1
PAR 3000 or equivalent	
22. Canister Rack/Transport	1
Storage, cooling and transport capability Pneumatic actuation Remote maintenance and repair	

(contd)

Table E-1. (contd)

Item	Number Required
23. Weld Station	1
Capability to cap canister in one pass	
Drive for weld wire outside of cell	
Console located outside cell	
Remote maintenance and repair	
Welding electrode rotates to produce weld	
24. Master-Slave Manipulators	2

Table E-2. Major Equipment Listing for Borosilicate Glass
Monolith/Direct Liquid Feed

Item	Number Required
1. Feed Preparation Tank	1
Capacity: 3150 L	
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Dimensions: 1.56 m x 1.66 m	

(contd)

Table E-2. (contd)

Item	Number Required
2. Melter Feed Tank	1
Capacity: 3150 L Materials of Construction: 304L SS Design Pressure: 100 psig Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Appurtenances: Cooling coils Agitator mounting Feed pump mounting Dimensions: 1.56 m x 1.66 m	
3. Ruthenium Adsorber	1
Capacity: 11.3 m ³ /min per module Size: 5.1 cm x 20.3 cm x 2.74 m Design Temp: 800°C Design Pressure: 25 psig Materials of Construction: 304L SS Geometry: Rectangular finned vessel	
4. Quench Tower	1
Countercurrent Spray Tower Design Pressure: 25 psig Design Temp: 700°C Materials of Construction: 304L SS Geometry: Right cylinder Conical bottom Appurtenances: Spray Header 4 vessel connections Bottom drain screen Size: 0.8 m OD x 2 m Ht.	

(contd)

Table E-2. (contd)

Item	Number Required
5. Quench Tower Surge Tank	1
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Size: 1.6 m OD x 3.3 m Ht.	
Appurtenances: Cooling coils	
Agitator mounting	
Recycle pump mounting	
6. Frit Hopper and Feeder	1
Capacity: 1000 kg of frit	
562-L volume	
Materials of Construction: Carbon steel	
Geometry: Right cylinder with	
cone bottom	
Dimensions: 0.9 m x 0.9 m	
7. Pumps	
A. Melter feed pumps	2
3 L/min - 1/2 hp	
B. Quench solution recycle pumps	2
60 L/min - 1 hp	
8. Agitators	
A. Melter Feed Tank	2
B. Feed Preparation Tank	2
9. VOG Adsorber	1
Type: Bubble Cap Tray	
Capacity: 0.2 m ³ /min	
Size: 0.2 m OD x 2.0 m Ht.	
Material of Construction: 304L SS	
Geometry: 8 Trays,	
Right cylinder	
Design Pressure: 25 psig	
Design Temp: 130°C	

(contd)

Table E-2. (contd)

Item	Number Required
10. VOG Cooler	1
Type: Glycol-cooled Capacity: 0.2 m ³ /min Size: 0.2 m OD x .5 m long Shell and Tube Design Temp: 130°C Design Pressure: 25 psig Material of Construction: 304L SS	
11. VOG Deentrainer	1
Type: Knockout Pot Design Pressure: 25 psig Design Temp: 130°C Material of Construction: 304L SS	
12. VOG Heater	2
Type: Resistance, 1-Zone Rating: 1 kW Material of Construction: 304L SS Nichrome heating element	
13. VOG Filters	2
Type: Deep bed fiberglass Material of Construction: 304L SS Design Pressure: 25 psig Design Temp: 200°C Size: 0.3 m OD x 1 m Geometry: Right cylinder Dished head bottom Capacity: 0.23 m ³ /min	
14. VOG Iodine Adsorber	1
Type: Silver zeolite bed Material of Construction: 304L SS Design Temp: 200°C Design Pressure: 25 psig Geometry: Right cylinder, hemisphere head, bottom - 4 nozzles Capacity: 0.23 m ³ /min Vessel Size: 0.2 m OD x 1 m Ht.	

(contd)

Table E-2. (contd)

Item	Number Required
15. VOG Blowers	2
Type: Centrifugal blower, direct drive Capacity: 0.23 m ³ /min Material of Construction: 304L SS Static Pressure: 42 mm Hg	
16. NO _x Feed Effluent Heat Exchanger	1
Type: Shell and Tube H _x Capacity: 0.23 m ³ /min Design Temp: 450°C Design Pressure: 25 psig Material of Construction: 304L SS	
17. NO _x Reactor	1
Type: Platinum-Palladium Catalyst S.S. Vessel, 0.5 m OD x 1 m Ht. 70 kg Catalyst	
18. NO _x Reactor Heater	1
Type: Resistance, 1-zone Rating: 1 kW Material of Construction: 304L SS Nichrome heating element	
19. Ceramic Melter	1
Capacity: 100 kg/h Tilt Screw, Overflow weir Joule-Heated: 200 kW Size: 2.5 m x 2.5 m x 2.5 m	
20. Power Manipulator	1
PAR 3000 or equivalent	

(contd)

Table E-2. (contd)

Item	Number Required
21. Canister Rack/Transport	1
Storage, cooling and transport capability	
Pneumatic actuation	
Remote maintenance and repair	
22. Weld Station	1
Capability to cap canister in one pass	
Drive for weld wire outside of cell	
Console located outside cell	
Remote maintenance and repair	
Welding electrode rotates to produce weld	
23. Master-Slave Manipulators	2
Central Research Laboratories Model F or equivalent	

Table E-3. Major Equipment Listing for Glass Bead-Metal
Matrix Composite

Item	Number Required
1. Feed Preparation Tank	1
Capacity: 3150 L	
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Appurtenances: Cooling coils	
Agitator mounting	
Dimensions: 1.56 m x 1.66 m	

(contd)

Table E-3. (contd)

Item	Number Required
2. Melter Feed Tank	1
Capacity: 3150 L Materials of Construction: 304L SS Design Pressure: 100 psig Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Appurtenances: Cooling coils Agitator mounting Feed pump mounting Dimensions: 1.56 m x 1.66 m	
3. Ruthenium Adsorber	1
Capacity: 11.3 m ³ /min per module Size: 5.1 cm x 20.3 cm x 2.74 m Design Temp: 800°C Design Pressure: 25 psig Materials of Construction: 304L SS Geometry: Rectangular finned vessel	
4. Quench Tower	1
Countercurrent Spray Tower Design Pressure: 25 psig Design Temp: 700°C Materials of Construction: 304L SS Geometry: Right cylinder Conical bottom Appurtenances: Spray Header 4 vessel connections Bottom drain screen Size: 0.8 m OD x 2 m Ht.	

(contd)

Table E-3. (contd)

Item	Number Required
5. Quench Tower Surge Tank	1
Capacity: 9463 L Materials of Construction: 304L SS Design Pressure: Atmospheric Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Size: 1.6 m OD x 3.3 m Ht. Appurtenances: Cooling coils Agitator mounting Recycle pump mounting 9 tank connections	
6. Frit Hopper with Feeder	1
Capacity: 1000 kg of frit 562-L volume Materials of Construction: Carbon steel Geometry: Right cylinder with cone bottom Dimensions: 0.9 m x 0.9 m	
7. Pumps	
A. Melter feed pumps 3 L/min - 1/2 hp	2
B. Quench solution recycle pumps 60 L/min - 1 hp	2
8. Agitators	
A. Melter Feed Tank	2
B. Feed Preparation Tank	2

(contd)

Table E-3. (contd)

Item	Number Required
9. VOG Adsorber Type: Bubble Cap Tray Capacity: 0.2 m ³ /min Size: 0.2 m OD x 2.0 m Material of Construction: 304L SS Geometry: 8 Trays, Right cylinder Design Pressure: 25 psig Design Temp: 130 °C	1
10. VOG Cooler Type: Glycol-cooled Capacity: 0.2 m ³ /min Size: 0.2 m OD x 0.5 m long Shell and Tube Design Temp: 130 °C Design Pressure: 25 psig Material of Construction: 304L SS	1
11. VOG Deentrainer Type: Knockout Pot Design Pressure: 25 psig Design Temp: 130 °C Material of Construction: 304L SS	1
12. VOG Heater Type: Resistance, 1-Zone Rating: 1 kW Material of Construction: 304L SS Nichrome heating element	2
13. VOG Filters Type: Deep bed fiberglass Material of Construction: 304L SS Design Pressure: 25 psig Design Temp: 200 °C Size: 0.3 m OD x 1 m Geometry: Right cylinder Dished head bottom Capacity: 0.23 m ³ /min	2

(contd)

Table E-3. (contd)

Item	Number Required
14. VOG Iodine Adsorber	1
Type: Silver zeolite bed Material of Construction: 304L SS Design Temp: 200°C Design Pressure: 25 psig Geometry: Right cylinder, hemisphere head, bottom - 4 nozzles Capacity: 0.23 m ³ /min Vessel Size: 0.2 m OD x 1 m Ht.	
15. VOG Blowers	2
Type: Centrifugal blower, direct drive Capacity: 0.23 m ³ /min Material of Construction: 304L SS Static Pressure: 42 mm Hg	
16. NO _x Feed Effluent Heat Exchanger	1
Type: Shell and Tube H _x Capacity: 0.23 m ³ /min Design Temp: 450°C Design Pressure: 25 psig Material of Construction: 304L SS	
17. NO _x Reactor	1
Type: Platinum-Palladium Catalyst S.S. Vessel, 0.5 m OD x 1 m Ht. 70 kg Catalyst	
18. NO _x Reactor Heater	1
Type: Resistance, 1-zone Rating: 1 kW Material of Construction: 304L SS Nichrome heating element	

(contd)

Table E-3. (contd)

Item	Number Required
19. Ceramic Melter	1
Capacity: 100 kg/h Tilt Screw, Overflow weir Joule-Heated: 200 kW Size: 2.5 m x 2.5 m x 2.5 m	
20. Power Manipulator	2
PAR 3000 or equivalent	
21. Canister Rack/Transport	1
Storage and transport capability Pneumatic actuation Remote maintenance and repair	
22. Weld Station	1
Capability to cap canister in one pass Drive for weld wire outside of cell Console located outside cell Remote maintenance and repair Welding electrode rotates to produce weld	
23. Master - Slave Manipulators	4
Central Research Laboratories Model F or equivalent	
24. Glass-Bead-Making Machine	1
Chain drive, aluminum molds Remote maintenance, repair Vibrator motor located outside cell Size: 3 m x 2 m x 1 m	

(contd)

Table E-3. (contd)

Item	Number Required
25. Lead Shot Storage	
Capacity: 2400 kg of lead	
Material: Carbon steel	
Geometry: Right circular cylinder Conical bottom	
Size: 0.9 m OD x 0.9 m	
26. Bead Storage Tank	1
Capacity: 600 L	
Material: 304L SS	
Geometry: Right circular cylinder Conical bottom Cooling water jacket	
Size: 1 m OD x 0.8 m Ht.	
27. Matrix Formation Furnace	1
Type: Electrical Resistance 4 Zone	
Rating: 150 kW	
Materials: Silicone Carbide	
Size: 1.2 m OD x 1.5 m Ht.	

Table E-4. Major Equipment Listing for Ceramic Pellet -
Metal Matrix Composite

Item	Number Required
1. Feed Preparation Tank	1
Capacity: 4750 L	
Materials of Construction: 304L SS	
Design Pressure: Atmospheric	
Design Temp: 120°C	
Geometry: Right cylinder Dished head bottom Closed top	
Appurtenances: Cooling coils Agitator mounting	
Dimensions: 1.82 m x 1.82 m	

(contd)

Table E-3. (contd)

Item	Number Required
2. Calciner Feed Tank	1
Capacity: 4750 L Materials of Construction: 304L SS Design Pressure: 100 psig Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Appurtenances: Cooling coils Agitator mounting Feed pump mounting Dimensions: 1.82 m x 1.82 m	
3. Ruthenium Adsorber	7
Capacity: 11.3 m ³ /min per module Size: 5.1 cm x 20.3 cm x 2.74 m Design Temp: 800°C Design Pressure: 25 psig Materials of Construction: 304L SS Geometry: Rectangular finned vessel	
4. Quench Tower	1
Countercurrent Spray Tower Design Pressure: 25 psig Design Temp: 700°C Materials of Construction: 304L SS Geometry: Right cylinder Conical bottom Appurtenances: Spray Header 4 vessel connections Bottom drain screen Size: 1.9 m OD x 3 m Ht.	
5. Quench Tower Surge Tank	1
Materials of Construction: 304L SS Design Pressure: Atmospheric Design Temp: 120°C Geometry: Right cylinder Dished head bottom Closed top Size: 4.0 m OD x 4.3 m Ht. Appurtenances: Cooling coils Agitator mounting Recycle pump mounting	

(contd)

Table E-3. (contd)

Item	Number Required
6. Chemical Addition Tank	1
Capacity: 1300 L	
Materials of Construction: 304L SS	
Geometry: Right cylinder	
Dished head bottom	
Closed top	
Dimensions: 1.32 m x 1.32 m	
Design Temperature: 100°C	
Design Pressure: Atmospheric	
7. Pumps	
A. Calciner Feed Pumps	2
6 L/min - 1/2 hp	
B. Quench Solution Recycle Pumps	2
300 L/min - 6 hp	
8. Agitators	
A. Calciner Feed Tank	2
B. Feed Preparation Tank	2
C. Chemical Addition Tank	1
9. VOG Adsorber	1
Type: Bubble Cap Tray	
Capacity: 31.5 m ³ /min	
Size: 0.4 m OD x 4.6 m Ht.	
Material of Construction: 304L SS	
Geometry: 8 Trays	
Right cylinder	
Design Pressure: 25 psig	
Design Temp: 130°C	
10. VOG Cooler	1
Type: Glycol-cooled	
Capacity: 31.5 m ³ /min	
Size: 0.6 m OD x 1.5 m long	
Shell and Tube	
Design Temp: 130°C	
Design Press: 25 psig	
Material of Construction: 304L SS	

(contd)

Table E-3. (contd)

Item	Number Required
11. VOG Deentrainer	1
Type: Knockout Pot Design Pressure: 25 psig Design Temp: 130°C Material of Construction: 304L SS	
12. VOG Heater	2
Type: Resistance, 1-zone Rating: 9 kW Material of Construction: 304L SS Nichrome heating element	
13. VOG Filters	2
Type: Deep bed fiberglass Material of Construction: 304L SS Design Pressure: 25 psig Design Temp: 200°C Size: 0.4 m OD x 2.2 m Right cylinder Dished head bottom Capacity: 40.1 m ³ /min	
14. VOG Iodine Adsorber	3
Type: Silver zeolite bed Material of Construction: 304L SS Design Temp: 200°C Design Pressure: 25 psig Geometry: Right cylinder, hemisphere head, bottom - 4 nozzles Capacity: 40.1 m ³ /min Vessel Size: 0.6 m OD x 2 m Ht.	
15. VOG Blowers	2
Type: Centrifugal blower, direct drive Capacity: 40.1 m ³ /min Material of Construction: 304L SS Static Pressure: 42 mm Hg	

(contd)

Table E-3. (contd)

Item	Number Required
16. NO _x Feed Effluent Heat Exchanger	1
Type: Shell and Tube H _x Capacity: 33.2 m ³ /min Design Temp: 450°C Design Pressure: 25 psig Material of Construction: 304L SS	
17. NO _x Reactor	1
Type: Platinum-Palladium catalyst S.S. Vessel, 0.8 m OD x 1 m Ht. 190 kg Catalyst	
18. NO _x Reactor Heater	1
Type: Resistance, 1-zone Rating: 13 kW Material of Construction: 304L SS Nichrome heating element	
19. Drying and Sintering Furnace	1
Type: Electrical resistance 8-zone Rating: 250 kW Materials: Silicone carbide Size: 1 m OD x 1.3 m Ht.	
20. Spray Calciner	1
Capacity: 158.2 L/h Calcining Chamber: 1.1 m OD x 3.0 m Ht Overall Height: 5.3 m Material: 304L SS Design Pressure: 40 psig Design Temp: 800°C Heaters: 650 kW	
21. Power Manipulators	2
PAR 3000 or equivalent	

(contd)

Table E-3. (contd)

Item	Number Required
22. Canister Rack/Transport	1
Storage and transport capability Pneumatic actuation Remote maintenance and repair	
23. Weld Station	1
Capability to cap canister in one pass Drive for weld wire outside of cell Console located outside cell Remote maintenance and repair Welding electrode rotates to produce weld	
24. Master-Slave Manipulators	4
Central Research Laboratories Model F or equivalent	
25. Lead Shot Storage	1
Capacity: 1400 kg of lead Material: Carbon steel Geometry: Right circular cylinder Conical bottom Size: 0.6 m OD x 0.6 m Ht.	
26. Matrix Formation Furnace	1
Type: Electrical resistance 4-zone Rating: 150 kW Materials: Silicone carbide Size: 1 m OD x 1.3 m Ht.	
27. Calciner Surge Tank	1
Capacity: 500 L Material: 304L SS Geometry: Right circular cylinder Conical bottom Cooling water jacket Size: 0.9 m OD x 0.9 m Ht.	

(contd)

Table E-3. (contd)

Item	Number Required
28. Pellet Storage Tank	1
Capacity: 700 Liters Material: 304L SS Right circular cylinder Conical bottom Cooling water jacket Size: 1 m OD x 1 m Ht.	
29. Turbulator	1
Pin Mixer Material: 304L SS Capacity: 34 kg/h Size: 2 m x 1.8 m x 1 m	

E-2.0 Equipment Comparisons

The development of the waste solidification alternatives for each of the conceptual flowsheets was dictated by the study bases, process requirements, and necessary engineering evaluations and judgment performed for each alternative. Some alternatives were more sensitive to the study bases than others.

E-2.1.1 Feed Preparation and Feed Tanks

These tanks were sized somewhat arbitrarily for a single batch, where the batch is one canister filling. This resulted in tanks of reasonable size which compared quite closely with the AGNS tank sizes. The tank costs were adjusted to account for the increased nondestructive examination, QA, and remote-maintenance features of these tanks, as compared to nuclear plant tanks. The installation man-hours were based on engineering estimates for similar-sized tanks in nuclear plants.

E-2.1.2 Calciners

The spray calciner costs for the two required cases were approximated by extrapolating using ratios formed from existing calciners of smaller size. The diameters of the calciner units were increased by the ratio of the feed rates to the 0.5 power. The costs were estimated by multiplying the costs for similar equipment of smaller size by the ratio of the processing rates raised to the 0.7 power. The installation man-hours were based on engineering estimates for similar equipment in nuclear plants.

E-2.1.3 Furnaces

For the furnaces, the sizes were determined by multiplying the furnace size for smaller applications by the ratio of the process flow

rates. The process furnace costs were based on the furnace sizes in [LARSON-1976]. The installation man-hours were based on engineering estimates.

E-2.1.4 Ceramic Melter

For the ceramic melter, melting data were used to scale-up to the melting rate required for the borosilicate glass alternative [BUELT, CHAPMAN]. The melter cost was based on vendor pricing estimates. The installation man-hours are engineering estimates.

E-2.1.5 Quench Towers

Using a 6°C temperature rise, the quench spray rate was determined for each alternative's heat load. Using a constant spray flow rate per unit area, the sizes of the quench towers were determined. The unit area spray flow rate was taken from the EXXON PSAR [EXXON]. The costs of the quench towers were based on cost estimates for similar equipment in nuclear power plants. The installation man-hours were derived from the same source.

E-2.1.6 Quench Tower Surge Tanks

The quench tower surge tanks for the alternatives were sized by providing a 20-min residence time of the quench spray flow rate. The tank costs were determined from tank costs for nuclear power plants. The installation man-hours were based on typical tank installation man-hours experienced in nuclear plants.

E-2.1.7 Ruthenium Adsorber

A ruthenium adsorber module concept was taken from the EXXON PSAR [EXXON]. The module was designed for a superficial flow velocity of 1.7 m/s which resulted in a flow rate of 11.3 m³/min per module. The incremental number of modules were determined for alternatives on the basis of the required off-gas flow associated with each alternative. The module cost and installation man-hours were based on engineering estimates.

E-2.1.8 VOG System

The components in the VOG system for each alternative are relatively small components and correspondingly have small costs associated with them. The component sizing for all the components was done on the basis of off-gas flow rate. The flows-per-unit-area for the components were taken from the EXXON PSAR, and the component sizes were adjusted for the individual flow rate for each alternative. The component and installation costs were derived from engineering estimates for nuclear plants.

E-2.1.9 Miscellaneous Components

Miscellaneous components such as pumps, blowers, feeders, etc., have been sized and cost estimates prepared based upon similar components in use in nuclear power facilities. Scaling of size and cost are based upon common engineering practices similar to those described in engineering handbooks such as [PERRY].

E-3.0 Equipment Power Ratings

The electrical consumption rate of each major process component was tabulated. These data are summarized in Table E-5 for the four alternatives. Annual power costs were derived by assuming a usage of 5760 hours per operating year at full-rated power. Miscellaneous components such as small pumps, blowers, etc. were assumed to add an additional 30 percent to the total annual power consumption of all major components given in Tables E-1 through E-4.

Table E-5. Equipment Power Consumption

Alternative	Equipment	Rating	
Borosilicate Monolith/ Spray Calcine Feed	VOG Heater	5	kW
	NO _x Reactor Heater	7	kW
	Spray Calciner	500	kW
	Ceramic Melter	200	kW
	TOTAL	712	kW
Annual Power Consumption ^a = 5.33×10^6 kW·h			
Borosilicate Monolith/ Direct Liquid Feed	VOG Heater	1	kW
	NO _x Reactor Heater	1	kW
	Ceramic Melter	200	kW
	TOTAL	202	kW
Annual Power Consumption ^a = 1.51×10^6 kW·h			
Glass Bead-Metal Matrix Composite Lead-Encapsulated Glass Beads	VOG Heater	1	kW
	NO _x Reactor Heater	1	kW
	Ceramic Melter	200	kW
	Matrix Formation Furnace	150	kW
	TOTAL	352	kW
Annual Power Consumption ^a = 2.64×10^6 kW·h			
Ceramic Pellet-Metal Matrix Composite Lead- Encapsulated Super- Calcine Pellets	VOG Heater	9	kW
	NO _x Reactor Heater	13	kW
	Spray Calciner	650	kW
	Matrix Formation Furnace	150	kW
	TOTAL	822	kW
Annual Power Consumption ^a = 6.16×10^6 kW·h			

^aIncludes an additional factor of 1.3.

APPENDIX F

WASTE CANISTER THERMAL ANALYSIS

Solidified HLW has a heat generation rate that is a function of the reactor fuel burnup from which the HLW was created, the decay period after discharge of the spent fuel from the reactor, and the form or composition of the HLW. One of the bases for this study is a constant value of heat generation in each waste canister at a designated time, i.e., 5 kW at ten years after spent fuel is discharged from a reactor. This defines the volumetric heat generation rate for each waste form considered. Each waste form has assumed temperature limitations in order to maintain product stability. These considerations, coupled with the properties of the waste product, control the geometry of the waste canister.

From a handling point of view it was assumed that a minimum length-to-diameter ratio of the waste canister was desirable. Two modes of storage have been defined for which the canister temperature profiles were determined. The two storage modes are:

1. In a water basin with the solidified HLW aged three years after reactor discharge
2. In air with the HLW aged ten years after reactor discharge

The canister was assumed to be a right circular cylinder made of stainless steel. The waste product was assumed to be in intimate contact with the canister wall. Analyses of the canister temperature profile were performed using the computer code HEATING-5 [TURNER], a general-purpose three-dimensional heat transfer computer code. Parameters used in the analyses are given in Table F-1. Natural convection heat transfer coefficients were determined by the methods given by Sparrow and Gregg [SPARROW] for laminar flow and the method of Kato et al., [KATO] for turbulent flow. Holding the volumetric heat generation rate and consequently the volume constant, the radius of the canister was varied (effectively varying the L/D ratio), and the resultant centerline temperature was determined. An interpolation was performed to determine the maximum canister radius which did not result in the centerline temperature limit to be exceeded. The results are presented in Table F-2.

For the borosilicate glass monolith waste forms, centerline temperatures were limiting during water basin storage, with the waste being aged three years after reactor discharge. The metal matrix waste forms approach maximum centerline temperatures during the air storage, with the waste aged ten years after reactor discharge.

Table F-1. Heat Transfer Parameters

	Canister Volume, ^a m ³	Maximum Allowable Centerline Temperature [TERA]	Thermal Conductivity [NRC-1977A]
Borosilicate Glass Monoliths	0.29	700°C ^b	1.1 W/m°C
Metal Matrix Composites:			
Glass Beads	0.50	300°C	10.0 W/m°C
Supercalcine Pellets	0.30	300°C	10.0 W/m°C

^aDerived from conceptual process flowsheets. The corresponding values for the supercalcine monolith alternative described in Appendix A are 0.14 m³ canister volume, 0.4 W/m°C thermal conductivity, and a centerline limitation of 700°C.

^bIt is likely the maximum allowable temperature in glass will be lower. Internal fins (not considered here) are one engineering method being examined to reduce centerline temperature. Such methods could be used to allow use of the canister sizes derived in this appendix with lower maximum temperatures.

Table F-2. Canister Dimensions^a

	Diameter	Height	Maximum Centerline Temperature
Borosilicate Glass Monoliths	0.46 m	1.81 m	680°C ^b
Metal Matrix Composites:			
Glass Beads	0.86 m	0.86 m	270°C ^c
Supercalcine Pellets	0.73 m	0.73 m	270°C ^c

^aThe final solidified waste forms were assumed to occupy 60 L/MTU for both glass monolith and for supercalcine pellets (bulk) in a lead matrix; a value of 100 L/MTU was assumed for glass beads (bulk) in a lead matrix with 40 percent void fraction by volume.

The canister size for the conceptual supercalcine monolith of Appendix A is calculated to be 0.19 m OD by 4.84 m in height; this assumes a solid supercalcine waste volume of 36 L/MTU.

^bWater basin storage at three years age.

^cStorage in air at ten years age.

APPENDIX G

WASTE SOLIDIFICATION ALTERNATIVES--CAPITAL EQUIPMENT COST

G-1.0 Introduction

This appendix presents tabulations (Tables G-1 through G-4) of the capital equipment cost estimates for the four solidification alternatives analyzed in Section 3. These equipment costs were developed in conjunction with the process descriptions given in Section 3, the equipment list given in Appendix E, and the approach discussed in Section 4.

Table G-1. Capital Equipment Cost Estimate Sheet^a, Borosilicate Glass
Monolith/Spray Calcine Feed (1979 dollars)

Item Description	Quantity	Unit Cost, \$K	Man- Hours	Cost	
				Material	Labor
Feed Prep Tank	1	13	410	\$13,000	\$ 5,500
Calciner Feed Tank	1	13	410	13,000	5,500
Ruthenium Adsorber	4	10	820	40,000	44,300
Quench Tower	1	45	1,000	45,000	13,500
Quench Tower Surge Tank	1	54	1,100	54,000	14,900
Frit Hopper and Feeder	1	2	160	2,000	2,200
Calciner Feed Pumps	2	2	160	4,000	4,300
Quench Solution Recycle Pumps	2	8	200	16,000	5,400
Agitators	4	6	80	24,000	4,300
VOG Adsorber	1	25	940	25,000	12,700
VOG Cooler	1	4	410	4,000	5,500
VOG Deentrainer	1	2	160	2,000	2,200
VOG Heater	2	4	160	8,000	4,300
VOG Filters	2	4	250	8,000	6,800
VOG Iodine Adsorber	2	26	410	52,000	11,000
VOG Blowers	2	5	660	10,000	17,800
NO _x Feed Effluent H _x	1	5	250	5,000	3,400
NO _x Reactor	1	23	400	23,000	5,400
NO _x Reactor Heater	1	4	180	4,000	2,400
Spray Calciner	1	300	6,600	300,000	89,100
Ceramic Melter	1	120	660	120,000	8,900
Power Manipulator	1	170	1,100	170,000	14,900
Canister Rack/Transport	1	280	1,700	280,000	23,000
Weld Station	1	110	600	110,000	8,100
Master-Slave Manipulators	2	30	330	60,000	8,900
TOTAL				\$1,392,000	\$324,300

^aAll costs rounded to nearest \$100.

Table G-2. Capital Equipment Cost Estimate Sheet^a, Borosilicate Glass
Monolith/Direct Liquid Feed (1979 dollars)

Item Description	Quantity	Unit Cost, \$K	Man- Hours	Cost	
				Material	Labor
Feed Prep Tank	1	13	410	\$13,000	\$5,500
Melter Feed Tank	1	13	410	13,000	5,500
Ruthenium Adsorber	1	10	820	10,000	11,100
Quench Tower	1	19	820	19,000	11,100
Quench Tower Surge Tank	1	48	900	48,000	12,200
Frit Hopper and Feeder	1	2	160	2,000	2,200
Melter Feed Pumps	2	2	160	4,000	4,300
Quench Solution Recycle Pumps	2	5	160	10,000	4,300
Agitators	4	6	80	24,000	4,300
VOG Adsorber	1	18	900	18,000	12,200
VOG Cooler	1	4	410	4,000	5,500
VOG Deentrainer	1	2	160	2,000	2,200
VOG Heater	2	3	160	6,000	4,300
VOG Filters	2	3	250	6,000	6,800
VOG Iodine Adsorber	1	24	410	24,000	5,500
VOG Blowers	2	5	660	10,000	17,800
NO _x Feed Effluent H _x	1	5	250	5,000	3,400
NO _x Reactor	1	17	360	17,000	4,900
NO _x Reactor Heater	1	3	150	3,000	2,000
Ceramic Melter	1	120	660	120,000	8,900
Power Manipulator	1	170	1,100	170,000	14,900
Canister Rack/Transport	1	280	1,700	280,000	23,000
Weld Station	1	110	600	110,000	8,100
Master-Slave Manipulators	2	30	330	60,000	8,900
TOTAL				\$978,000	\$118,900

^aAll costs are rounded to the nearest \$100.

Table G-3. Capital Equipment Cost Estimate Sheet^a, Glass Bead-Metal Matrix Composite (1979 dollars)

Item Description	Quantity	Unit Cost, \$K	Man- Hours	Cost	
				Material	Labor
Feed Prep Tank	1	13	410	\$ 13,000	\$ 5,500
Melter Feed Tank	1	13	410	13,000	5,500
Ruthenium Adsorber	1	10	820	10,000	11,100
Quench Tower	1	19	820	19,000	11,100
Quench Tower Surge Tank	1	48	900	48,000	12,200
Frit Hopper and Feeder	1	2	160	2,000	2,200
Melter Feed Pumps	2	2	160	4,000	4,300
Quench Solution Recycle Pumps	2	5	160	10,000	4,300
Agitators	4	6	80	24,000	4,300
VOG Adsorber	1	18	900	18,000	12,200
VOG Cooler	1	4	410	4,000	5,500
VOG Water Separator	1	2	160	2,000	2,200
VOG Heater	2	3	160	6,000	4,300
VOG Filters	2	3	250	6,000	6,800
VOG Iodine Adsorber	1	24	410	24,000	5,500
VOG Blowers	2	5	660	10,000	17,800
NO _x Feed Effluent H _x	1	5	250	5,000	3,400
NO _x Reactor	1	17	360	17,000	4,900
NO _x Reactor Heater	1	3	150	3,000	2,000
Ceramic Melter	1	120	660	120,000	8,900
Power Manipulators	2	170	1,100	340,000	29,700
Canister Rack/Transport	1	40	750	40,000	10,100
Weld Station	1	110	600	110,000	8,100
Master-Slave Manipulators	4	30	330	120,000	17,800
Glass-Bead-Making Machine	1	140	1,800	140,000	24,300
Bead Storage Tank	1	8	400	8,000	5,400
Lead Shot Storage	1	2	200	2,000	2,700
Matrix Formation Furnace	1	240	800	240,000	10,800
TOTALS				\$1,358,000	\$242,900

^aAll costs are rounded off to the nearest \$100.

Table G-4. Capital Equipment Cost Estimate Sheet^a, Ceramic Pellet-Metal Matrix Composite (1979 dollars)

Item Description	Quantity	Unit Cost, \$K	Man-Hours	Cost	
				Material	Labor
Feed Prep Tank	1	21	1,300	\$ 21,000	\$ 17,600
Calciner Feed Tank	1	21	1,300	21,000	17,600
Ruthenium Adsorber	7	10	820	70,000	77,500
Quench Tower	1	60	1,300	60,000	17,600
Quench Tower Surge Tank	1	60	1,300	60,000	17,600
Chemical Addition Tank	1	10	180	10,000	2,400
Calciner Feed Pumps	2	2	160	4,000	4,300
Quench Solution Recycle Pumps	2	10	250	20,000	6,800
Agitators	5	6	80	30,000	5,400
VOG Adsorber	1	30	980	30,000	13,200
VOG Cooler	1	4	410	4,000	5,500
VOG Deentrainer	1	2	160	2,000	2,200
VOG Heater	2	5	160	10,000	4,300
VOG Filters	2	4	250	8,000	6,800
VOG Iodine Adsorber	3	28	440	84,000	17,800
VOG Blowers	2	5	660	10,000	17,800
NO _x Effluent Heat Exchanger	1	6	320	6,000	4,300
NO _x Reactor	1	27	490	27,000	6,600
NO _x Reactor Heater	1	4	180	4,000	2,400
Drying and Sintering Furnace	1	232	2,000	232,000	27,000
Spray Calciner	1	420	8,400	420,000	113,400
Power Manipulators	2	170	1,100	340,000	29,700
Canister Rack/Transport	1	40	750	40,000	10,100
Weld Station	1	110	600	110,000	8,100
Master-Slave Manipulators	4	30	330	120,000	17,800
Lead Shot Storage	1	2	20	2,000	2,700
Matrix Formation Furnace	1	240	800	240,000	10,800
Calciner Surge Tank	1	15	600	15,000	8,100
Pellet Storage Tank	1	13	500	13,000	6,800
Turbulator (or Pelletizer)	1	90	860	90,000	11,600
				<u>\$2,103,000</u>	<u>\$493,800</u>

^aAll costs are rounded off to the nearest \$100.

REFERENCES

AGNS

Allied General Nuclear Services, Final Safety Analysis Report, Barnwell Nuclear Fuel Plant, Separations Facility, Docket No. 50-332 (October 1978).

AIF

Potential Benefits of Reducing Occupational Radiation Exposure, Atomic Industrial Forum Report AIF/NESP-010 (1978).

Alexander

C. W. Alexander et al., Projections of Spent Fuel to be Discharged by the Nuclear Power Industry, Oak Ridge National Laboratory Report ORNL/TM-6008 (1977).

ANL-79-29

M. J. Steindler et al., Fuel Cycle Programs Quarterly Progress Report October-December 1978, Argonne National Laboratory Report ANL-79-29 (January 1980).

Bjorklund

W. J. Bjorklund, Development and Use of Sintered Metal Filters with Fluidized Bed and Spray Calcination of Simulated High-Level Waste, Battelle Pacific Northwest Laboratories Report BNWL-2024 (July 1976).

Bonner

W. F. Bonner et al., Spray Calcination of Nuclear Waste, Battelle Pacific Northwest Laboratories Report BNWL-2059 (August 1976).

Buel

J. L. Buel and C. C. Chapman, Liquid Bed Ceramic Melter--a General Description Report, Pacific Northwest Laboratories Report PNL-2735 (October 1978).

CFR

Code of Federal Regulations, Title 10, Part 50, Appendix F.

Chapman

C. C. Chapman, Experience with a Joule Heated Ceramic Melter While Converting Simulated High-Level Waste to Glass, Battelle Pacific Northwest Laboratories Report BNWL-2071 (August 1976).

Deutch

J. M. Deutch et al., Report to the President by the Interagency Review Group on Nuclear Waste Management, TID-28817 (October 1978).

DOE-1978

Draft Environmental Impact Statement: Storage of U.S. Spent Power Reactor Fuel, DOE/EIS-0015-D (August 1978).

DOE-1979

Technology for Commercial Radioactive Waste Management, DOE/ET-0028, Volume 2 (May 1979).

ERDA-1976

Alternatives for Managing Waste from Reactors and Post-Fission Operations in the LWR Fuel Cycle, ERDA-76-43 (May 1976).

ERDA-1977A

LWR Spent Fuel Disposition Capabilities 1977-1986, ERDA 77-25 (May 1977).

ERDA-1977B

Alternatives for Long-Term Management of Defense High-Level Radioactive Waste, Idaho Chemical Processing Plant, ERDA 77-43 (1977).

EXXON

EXXON Nuclear Co., Inc., Nuclear Fuel Recovery and Recycling Center, PSAR, XW-FR-32, Docket 50-564.

Hall

J. C. Hall, Conceptual Liquid Waste Storage and Solidification Baseline Description, Allied General Nuclear Services Report NMS-7 (September 1977).

Harmon

Harmon International Source Book: Radioactive Waste Management Research and Development, Compiled by K. M. Harmon, Pacific Northwest Laboratories Report PNL-2478 (1978).

Holley

Personal communication, Carl Holley, Ferro-Tech., Inc., August 1979.

IAEA

International Atomic Energy Agency, Techniques for the Solidification of High-Level Wastes, Technical Review Series 176, Vienna (1977).

Jardine-1978

L. J. Jardine and M. J. Steindler, A Review of Metal-Matrix Encapsulation of Solidified Radioactive High-Level Waste, Argonne National Laboratory Report ANL-78-19 (May 1978).

Jardine-1979A

L. J. Jardine and M. J. Steindler, Metal Encapsulation of Ceramic Nuclear Waste, Scientific Bases for Nuclear Waste Management, Vol. 1, G. J. McCarthy, Ed., Plenum Press, New York, p. 191 (1979).

Jardine-1979B

Unpublished results, L. J. Jardine, Argonne National Laboratory, 1979.

Kato

H. Kato, N. Nishiwaki, and M. Hirata, On the Turbulent Heat Transfer by Free Convection from a Vertical Plate, Int. J. Heat Mass Transfer II, 1117 (1968).

Lamb

K. M. Lamb, Final Report: Development of a Metal Matrix for Incorporating High-Level Commercial Waste, Idaho Chemical Processing Plant Report ICP-1144 (March 1978).

Larson-1976

D. E. Larson and W. F. Bonner, High-Level Waste Vitrification by Spray Calcination/In-Can Melting, Battelle Pacific Northwest Laboratories Report BNWL-2092 (November 1976).

Larson-1978

D. E. Larson et al., Conceptual Design of Nuclear Waste Vitrification Facility, Pacific Northwest Laboratories Report PNL-2690 (May 1978).

Maples

R. E. Maples and M. J. Hyland, What is Involved in Major Venture Financing?, Chem. Eng. Prog., (January 1980).

McElroy

J. L. McElroy, Quarterly Progress Report Research and Development Activities Waste Fixation Program, Battelle Pacific Northwest Laboratories Report BNWL-1949 (January 1976).

NRC-1973

Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors, Nuclear Regulatory Commission Report NUREG-0002, Vol. 3 (August 1973).

NRC-1977A

Determination of Performance Criteria for High-Level Solidified Nuclear Waste, Nuclear Regulatory Commission Report NUREG-0279 (July 1977).

NRC-1977B

Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes, Nuclear Regulatory Commission Report NUREG-0170 (December 1977).

NRC-1978

Proceedings on the Conference on High-Level Radioactive Solid Waste Forms, Nuclear Regulatory Commission Report NUREG/CP-0005, December 19-21, 1978, Denver, CO.

NRC-1979

Solidification of High-Level Radioactive Wastes, National Academy of Sciences, Nuclear Regulatory Commission Report NUREG/CR-0895 (July 1979).

Nuclear News

Nuclear News 22(7), 94-98 (May 1979).

Perry

J. H. Perry, Chemical Engineer's Handbook, Fourth Edition, McGraw-Hill Book Co. (1963).

Rusin

J. M. Rusin et al., Multibarrier Waste Forms, Part I: Development, Pacific Northwest Laboratories Report PNL-2668-1 (September 1978).

Slate

Personal communication, Stephen Slate, Pacific Northwest Laboratories, 1979.

Sparrow

E. M. Sparrow and J. L. Gregg, Trans. ASME 78, 1823-1829(1956).

TERA

Production of Solidified High-Level Wastes--A Cost Comparison of Solidification Processes, prepared by TERA Corporation for Lawrence Livermore Laboratory (August 1977).

TID

Western New York Nuclear Service Center Study, TID-28905-2 (1979).

Turner

W. D. Turner and M. Siman-Tov, Heating-5, an IBM 360 Heat Conduction Code, Oak Ridge National Laboratory Report ORNL-TM-3208 (1971).

Wheelwright

E. J. Wheelwright et al., Technical Summary Nuclear Waste Vitrification Project, Pacific Northwest Laboratories Report PNL-3038 (May 1979).

Van Geel-1975

Jacques Van Geel et al., Conditioning of High-Level Waste Products by Dispersion into Metal Matrices, presented at the AIChE annual meeting, Los Angeles, CA, November 18, 1975.

Van Geel-1980

J. Van Geel, H. Eschrich, F. Dabbels, P. Favre, and H. Sterner, Embedding of Solid High-Level Wastes into Metal and Non-Metal Matrices, European Company for the Chemical Processing of Irradiated Fuels Report ETR-296 (March 1980).