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Vitrification Technologies for Weldon Spring Raffinate Sludges and Contaminated Soils Phase 2 Report: Screening of Alternatives

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Richland, Washington 99352

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SUMMARY

A report was prepared to aid the Weldon Spring Project Management Contractor in screening two vitrification technologies developed by Pacific Northwest Laboratory (PNL) for the remediation of raffinate sludges and contaminated soils at the Weldon Spring Site in St. Charles County, Missouri. The report describes laboratory and bench-scale treatability tests conducted by PNL with actual raffinate sludge, clay liner, and uncontaminated soil from the Weldon Spring site to evaluate the joule-heated ceramic melter (JHCM) and in situ vitrification (ISV) processes. The vitrified product from the JHCM and ISV treatability tests was analyzed for a wide range of characteristics, including durability (leach resistance), strength, and toxicity. The treatability test results and the product analyses from those tests show that both the ISV and JHCM processes are effective in producing a high-quality product suitable for long-term isolation of the hazardous and radioactive constituents of the raffinate sludges, clay liner, and soils from the environment.

The effectiveness of the ISV process in treating Weldon Spring raffinate sludge and soils was demonstrated in a bench-scale ISV test using actual samples of Weldon Spring materials. The test showed that the processing parameters such as power consumption and temperature were in the normal range for good ISV operation, there was no detectable migration of contaminants into the soil during the test, off-gas emissions were below detectable levels, and a strong, high-quality product was produced which passed the EP Toxicity test and performed well in leach testing. Several options were identified for implementing the ISV processes to the raffinate sludge, vicinity soils, clay liner, and quarry refuse. The most attractive options for ISV involve staging the wastes into a pit and performing successive ISV melts to better utilize the electrodes and set-up time. A 50:50 mixture of the raffinate sludge and soil or clay liner is needed to prevent excessive devitrification. Mixing contaminated soil or clay liner with the sludge will be more efficient than individual processing of the sludge, soil, and liner. An on-site pilot-scale ISV tests is recommended before full-scale implementation of the ISV process. The cost of remediating the 358,000 m^3 raffinate sludge, contaminated soil, clay liner, and quarry refuse with ISV is estimated to be from $86M to $105M. The lower cost assumes that the sludge is

dewatered to 35% solids before ISV and that contaminated soil is utilized in the raffinate sludge processing, thereby lowering the cost of processing the soil separately.

The JHCM evaluation and crucible tests showed that the raffinate sludge, clay liner, and soils are amenable to JHCM processing. The optimum flowsheet for processing is to blend the soils and sludge together. This would result in a glass containing 75% waste and 25% glass formers. A total volume reduction of about 50% would be achieved. These streams can also be processed separately with the penalty of additional process time and glass produced. A processing flowsheet that incorporates coprocessing of the Weldon Spring wastes generates approximately 25% less glass, reduces the processing duration by 1 year, and saves $14M when compared with processing each waste stream separately. The cost of processing the raffinate sludge, contaminated soil, clay liner, and quarry refuse is estimated at $95M to $109M depending on whether or not the wastes are blended. Two options that will decrease the projected costs are to dewater the sludge and to use a high-temperature melter. Dewatering the sludge will reduce the low-end cost to $85M. Cost savings for using a high-temperature melter are primarily a result of reduced chemical additive costs and higher throughput. Use of the high-temperature melter could reduce costs by an additional $10M to $20M, resulting in a minimum estimated cost of $65M to $75M. An engineering-scale JHCM test using an existing PNL melter is recommended to characterize process conditions, confirm production rates, and obtain off-gas data.

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1.0 INTRODUCTION

This report is intended to aid the Weldon Spring Project Management Contractor in screening two vitrification technologies developed by Pacific Northwest Laboratory (PNL) for the remediation of raffinate sludges and contaminated soils at the Weldon Spring Site in St. Charles County, Missouri. A previous report (Koegler, Oma, and Perez 1988) described the joule-heated ceramic melter (JHCM) and in situ vitrification (ISV) processes and their applicability to remediation of the Weldon Spring site based on existing information and previous PNL experience with similar wastes. Subsequent treatability tests and product analysis were conducted by PNL to further evaluate the JHCM and ISV processes. The treatability tests involved laboratory and bench-scale tests with actual raffinate sludge and uncontaminated soil from the Weldon Spring site. The vitrified product from the JHCM and ISV treatability tests was analyzed for a wide range of characteristics, including durability (leach resistance), strength, and toxicity. Both the process performance test and product quality were used to assess the two PNL vitrification technologies to determine their effectiveness, implementability, and cost.

Descriptions and results of the treatability tests, including product analysis, are given in the sections on process effectiveness. Case studies, based on the treatability test results, appear in the implementation sections and discuss various options for remediation of the raffinate sludge and soils. Cost estimates for each of the options in the implementation section are given in the cost analysis sections.

2.0 CONCLUSIONS AND RECOMMENDATIONS

The treatability test results and the product analyses from those tests show that both the ISV and JHCM processes are effective in producing a high-quality product suitable for long-term isolation of the hazardous and radioactive constituents of the raffinate sludges and soils from the environment. In addition, several case studies demonstrate the implementability of the JHCM and ISV technologies and provide a basis for preliminary cost estimates. Specific conclusions for the JHCM and ISV technologies are presented here.

2.1 IN SITU VITRIFICATION

2.1.1 ISV Process Effectiveness

The effectiveness of the ISV process in treating Weldon Spring raffinate sludge and soils was demonstrated in a 10 kg bench-scale ISV melt or test using actual samples of Weldon Spring materials. An analysis of the processing behavior during the test and the vitrified product from the test led to the following specific conclusions:

- Electrical power density, power consumption, temperature, and other ISV process parameters are within the expected operating ranges for good ISV performance.

- The ISV bench-scale test produced a high-quality vitrified mass from vitrification of raffinate sludge, soil, and clay liner. The product passed the EP Toxicity test and was very durable (leach resistant), exceeding the durability of many high-level nuclear waste glasses. The product is strong, exceeding both the tensile and compressive properties of non-reinforced concrete.

- Off-gas analyses from the bench-scale ISV test indicated that the radioactive or hazardous materials emissions are expected to be below the DOE-established Derived Concentration Guides (DCGs) for stack emissions during large-scale ISV operation at the Weldon Spring site. Analyses of the soil surrounding the vitrified soil and sludge showed that there was no detectable thermal transport of contaminants during the bench-scale ISV test.

2.1.2 ISV Implementability

Five options were identified for implementing the ISV process to the raffinate sludge, vicinity soils, clay liner and quarry refuse. The most attractive options involve staging the wastes into a pit and performing successive ISV melts to better utilize the electrodes and reduce equipment set-up time. Specific conclusions and recommendations are as follows:

- Because of the high lime content, the sludge cannot be vitrified alone. A 50:50 mixture of the raffinate sludge and soil or clay liner is needed to prevent excessive devitrification and crystallization in the melt. Use of contaminated soil or clay liner to mix with the sludge will be more efficient than individual processing of the sludge, soil, and liner.

- An on-site pilot-scale ISV test is recommended before full-scale implementation of the ISV process to 1) demonstrate multiple batch ISV melts at a single setting and determine electrode corrosion, 2) deter-mine whether pre-mixing of sludge and soil prior to ISV can be eliminated, 3) demonstrate ISV off-gas performance, especially radon, thorium, and uranium release levels, and 4) produce a larger vitrified block for product characterization.

2.1.3 ISV Cost

The total estimated cost for ISV remediation of the raffinate sludge, soils, and quarry refuse ranged from $86.2M to $105M, which includes $17.5M in ISV equipment costs. The cost of remediating the raffinate sludges alone is estimated at $39M. The use of contaminated soil and liner as mixing agents would use the entire inventory of vicinity soils (21,000 m^3) and approximately 15% of the clay liner material and would reduce the cost of vitrifying these materials by $8.8M from $105M to $96.2M. Filtering the raffinate sludge to increase the solids content from 25 to 35% would further reduce the cost of treating the raffinate sludge by $10M to $86.2M.

2.2 JHCM VITRIFICATION

2.2.1 JHCM Process Effectiveness

An evaluation of the effectiveness, implementability, and costs associated with JHCM vitrification of Weldon Spring materials was conducted based

on crucible melt tests and subsequent characterization of the glass product. Based on this evaluation, the following conclusions and recommendations can be drawn.

Several glass compositions were developed and tested on a laboratory scale to determine an optimum waste loading and minimal glass former addition requirements. These tests culminated with the testing of actual Weldon Spring raffinate sludge, clay liner, and site soils. Results of these investigations led to the following specific conclusions:

- Raffinate pit sludge, clay liner, vicinity soils, and quarry refuse are amenable to JHCM processing. These materials can be blended together or processed separately within the constraints of conventional JHCM equipment.
- The optimum Weldon Spring glass is a glass composed of 75% waste and 25% glass forming additive. A waste to glass volume reduction of 50% is estimated.
- The glass produced with Weldon Spring materials exhibited splitting tensile and compressive strength in excess of those reported for unreinforced concrete.
- The JHCM crucible melt tests produced a high-quality glass from a blend of raffinate sludge, soil, and clay liner. The product passed the EP toxicity test, and its durability (leach resistance) was comparable to that of many high-level nuclear waste glasses.

2.2.2 JHCM Implementability

Based on the results of testing and engineering analyses, blending of the raffinate sludge, clay liner, and vicinity soils is both feasible and preferred for economic reasons. Specific conclusions and recommendations follow.

- A processing flowsheet that incorporates blending of the Weldon Spring wastes generates approximately 25% less glass, reduces the processing duration by 1 year, and saves almost $14M when compared with processing each of the waste streams separately.
- An engineering-scale test, using Weldon Spring materials, is recommended to accurately characterize off-gas effluents and glass product quality. This test would support the detailed evaluation of JHCM vitrification by establishing process rates and off-gas treatment requirements; results would also verify the crucible melt tests.

2.2.3 JHCM Cost

Treatment of the Weldon Spring wastes, including quarry waste range from $95M to $109M. The low-end cost of processing blended Weldon Spring materials (raffinate sludge, soil, and clay liner) could be reduced by as much as $10M to $85M with dewatering of the raffinate sludge prior to vitrification. Additional cost savings are considered possible if a high-temperature melter is used. Potential cost savings associated with high-temperature processing are estimated to be between $10M and $20M. A detailed evaluation of the JHCM processing flowsheet, including the potential cost saving scenarios identified, is recommended to more accurately establish costs and aid the PMC with evaluating the JHCM vitrification alternative.

3.0 BACKGROUND

The Weldon Spring site comprises a 9-acre former limestone quarry, a 52-acre raffinate disposal area, and a 169-acre mothballed uranium feed materials plant. The quarry contains an estimated 95,000 cubic yards of rubble and soils contaminated with trinitrotoluene (TNT), dinitrotoluene (DNT), uranium, thorium, and their decay products (Bechtel 1985). The quarry is located about 4 miles south of the main site. The waste material is piled 40 feet above the floor of the quarry, with most of the waste covered by several feet of soil. Vegetation covers the quarry surface and the lowest area is covered by water. Where a cross section is visible, a large amount of metal (e.g., crushed drums, sheet metal, structural building iron, and process equipment) protrudes from the soil. Large pieces of equipment such as tanks, a fork-lift truck, and up to 3000 drums are also buried, although ground-penetrating radar or similar techniques have not been used to locate these large items. The water table is about 15 feet above the floor of the quarry, and the standing water level is about 6 feet above the water table.

There is much interest in moving the rubble from the quarry to the main site because of its proximity to public areas and water supplies, and to permit geological characterization and estimates of contaminant migration in the underlying fractured limestone. Late in 1986, eighteen boreholes were drilled into the quarry to chemically characterize the quarry for PCBs, TNT, and other hazardous chemicals (Bechtel 1987). The drilling operation was extremely difficult and exposed metal, pieces of concrete, bricks, rebar, and other building materials.

The raffinate disposal area includes four open pits covering a total area of 27 acres and containing about 220,000 cubic yards of sludge (U.S. DOE 1987a). Below the sludge is an estimated 130,000 cubic yards of contaminated soil. The sludge is a lime-neutralized material from uranium and thorium processing operations and contains uranium, thorium, radium, and their decay products. The sludge in the pits is about 10 feet deep and is presently covered by 1 to 3 feet of water. The pits are lined with a low permeability clay-soil that has not been sampled for fear of destroying the pit's integrity. Vegetation has been removed from the sides of the pits, leaving only

grass. Radiological characterization data exist from previous studies, and additional chemical and physical characterization of the sludges is being performed by the Weldon Spring PMC. The main portion of the site is an inactive uranium feed materials plant consisting of about 50 deteriorating buildings and an estimated 337,000 cubic yards of contaminated soil, equipment, and facilities.

4.0 DESCRIPTION OF THE VITRIFICATION TECHNOLOGIES

Pacific Northwest Laboratory has extensive experience in vitrification technologies, beginning with in-can and small-scale joule-heated melter development in the early 1970's. Two vitrification technologies have matured to the point of large-scale deployment: in situ vitrification and the joule-heated ceramic melter.

4.1 IN SITU VITRIFICATION

In situ vitrification is a patented process originally developed by PNL for providing enhanced environmental stability to contaminated soils without the need for exhumation (Buelt et al. 1987). Figure 4.1 illustrates the progressive stages of ISV processing. To begin the process, electrodes are inserted in the ground in a desired array (depth and spacing). A graphite-containing starter material is placed on the surface of the soil between the electrodes to form a conductive path. An electric current is passed between the electrodes, creating temperatures high enough to melt the soil (typically about 1700°C). The molten zone grows downward and outward (beyond the electrodes), encompassing the contaminated soil and contained waste materials.

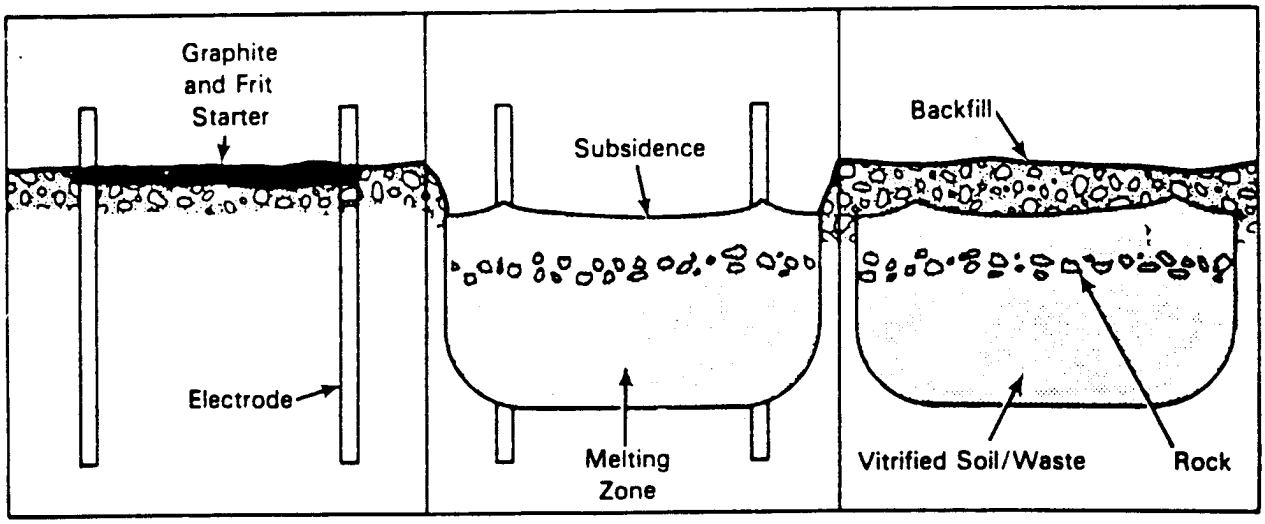

FIGURE 4.1. ISV Processing Sequence

Figure 4.2 depicts the large-scale process equipment required for in situ vitrification of radioactive wastes. The process immobilizes contaminated soil and isolates it from the surrounding environment. Controlled electrical power is distributed to the electrode, and special equipment contains and treats the gaseous effluents. Four major subsystems comprise the process equipment to perform those functions: 1) electrical power supply, 2) off-gas hood, 3) off-gas treatment, and 4) process control. Except for the off-gas hood, all components are contained in three transportable trailers. The effluents exhausted from the hood are cooled and treated in the off-gas treatment system. The off-gas hood and off-gas lines are dismantled and placed on a flatbed trailer for transport between the sites to be treated. The entire process is monitored and controlled from the process control trailer.

The resulting ISV product is a glass and crystalline mass resembling natural glass (obsidian). For typical earthen materials within the United States, the final density of the ISV block varies from 2.3 to 2.5 g/cm^3 (144 to 156 lb/ft^3). Although the block is only 3% to 11% heavier than concrete, it possesses about 5 to 10 times the strength of unreinforced concrete in both tension and compression. The ISV block is extremely inert, with a chemical leach resistance approaching that of Pyrex glass. Some crystallization may be present in the block, which results in even greater leach resistances.

The ISV process was developed specifically to incorporate long-lived radioactive waste materials into a glass waste form. The U.S. Department of Energy (DOE) has supported the development and performance of field-scale demonstrations of the basic ISV technology. In addition, PNL has performed several bench- and pilot-scale tests on process sludges and other hazardous materials. The tests have shown that the ISV process destroys and/or removes organic and volatile inorganic contaminants from the soil. Any remaining hazardous inorganic materials (e.g., heavy metals or radioactive materials) are incorporated into a final product that prevents releases of contaminants into the environment.

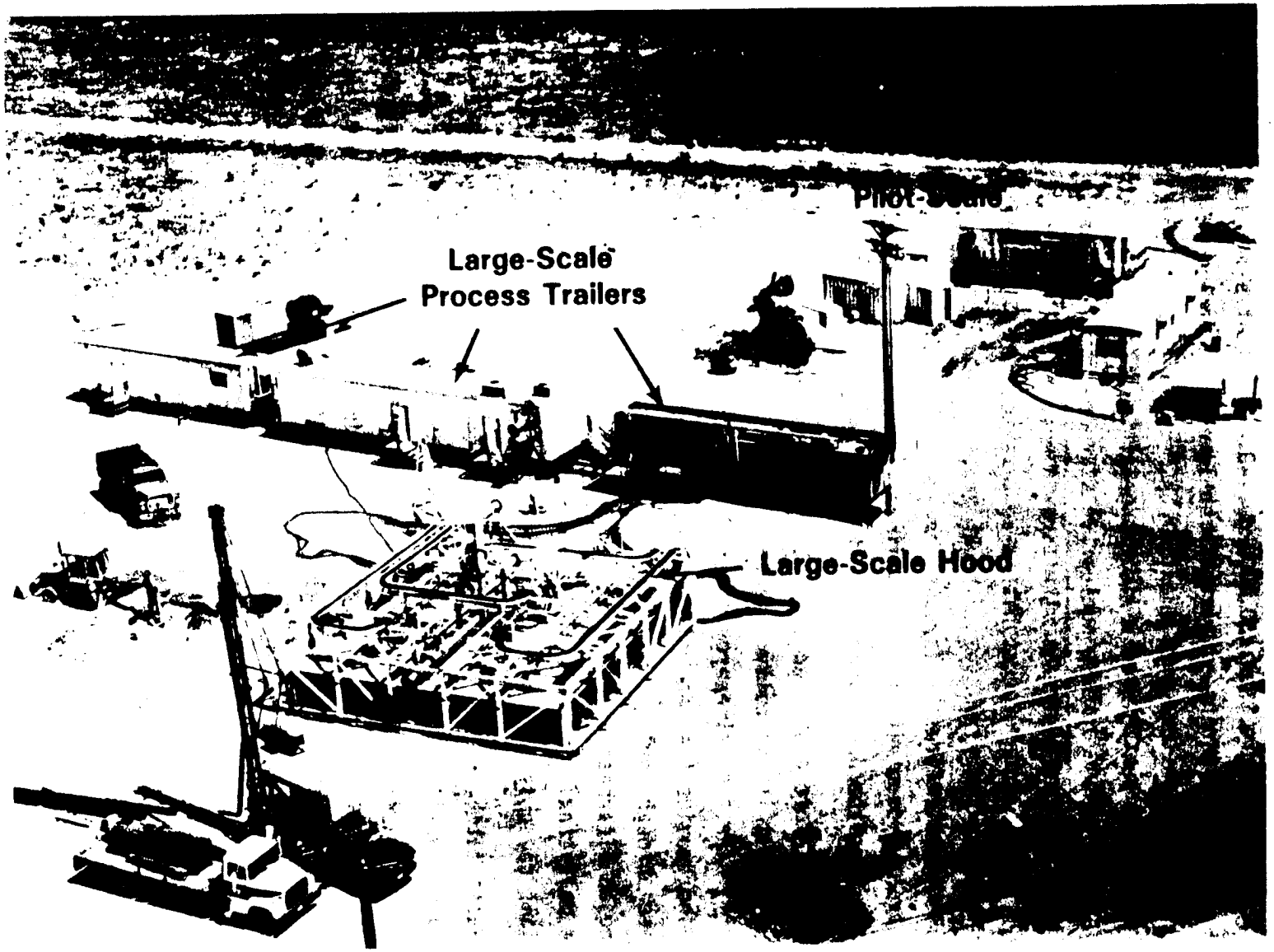

FIGURE 4.2. Equipment Setup for In Situ Vitrification

4.2 JOULE-HEATED CERAMIC MELTER TECHNOLOGY

Since 1973, more than 200,000 kg (440,000 lb) of simulated and actual waste glasses containing simulated high-level radioactive wastes have been produced at PNL-in the development of JHCM technology. Vitrification research at PNL has covered a wide range of waste stream compositions for both commercial and defense nuclear reactor operations (Chapman, Pope, and Barnes 1986). Waste streams vitrified in existing developmental melters include high fission product nitric acid wastes and alkaline sludges containing refractory materials (e.g., high iron, chromium, alumina, zirconium, and zeolite concentrations). In addition, more than 50 million curies of radioactivity have been vitrified in radioactive process demonstrations. Figure 4.3 shows the JHCM process as it might be applied to Weldon Spring.

The JHCM process is an adaptation of commercial glass-making technology. The glass melt is typically operated between 1000°C (1800°F) and 1300°C (2400°F). The thermal energy required to maintain the temperature of the glass and provide the heat to decompose and melt the soils and sludges is supplied through joule heating of the glass. Joule heating is achieved by passing an alternating electric current between submerged electrodes located in the melt tank. The melt tank is lined with high-temperature refractory materials to resist corrosion and contain the molten glass.

Waste materials are fed into the high-temperature furnace, where they decompose and the residual oxides and any ash material melt to form a glass product. The waste materials are mixed with the appropriate glass-forming chemicals, typically silica, soda ash, and lime. This mixture forms the basic glass structure that allows the inorganic waste materials to be dissolved. The glass formers and waste can be mixed in a batch tank prior to feeding the melter, or in the melt cavity itself.

To process wastes that are liquids or sludges, the mixture of wastes and glass-forming chemicals is deposited directly on the glass surface. The water evaporates and the waste materials decompose to form oxides. Mixtures of solids, such as contaminated soils, incinerator ash, or combustibles, can be deposited on top of, or below, the glass surface. As the waste particles rise to the glass surface, they undergo pyrolysis. Organic compounds are

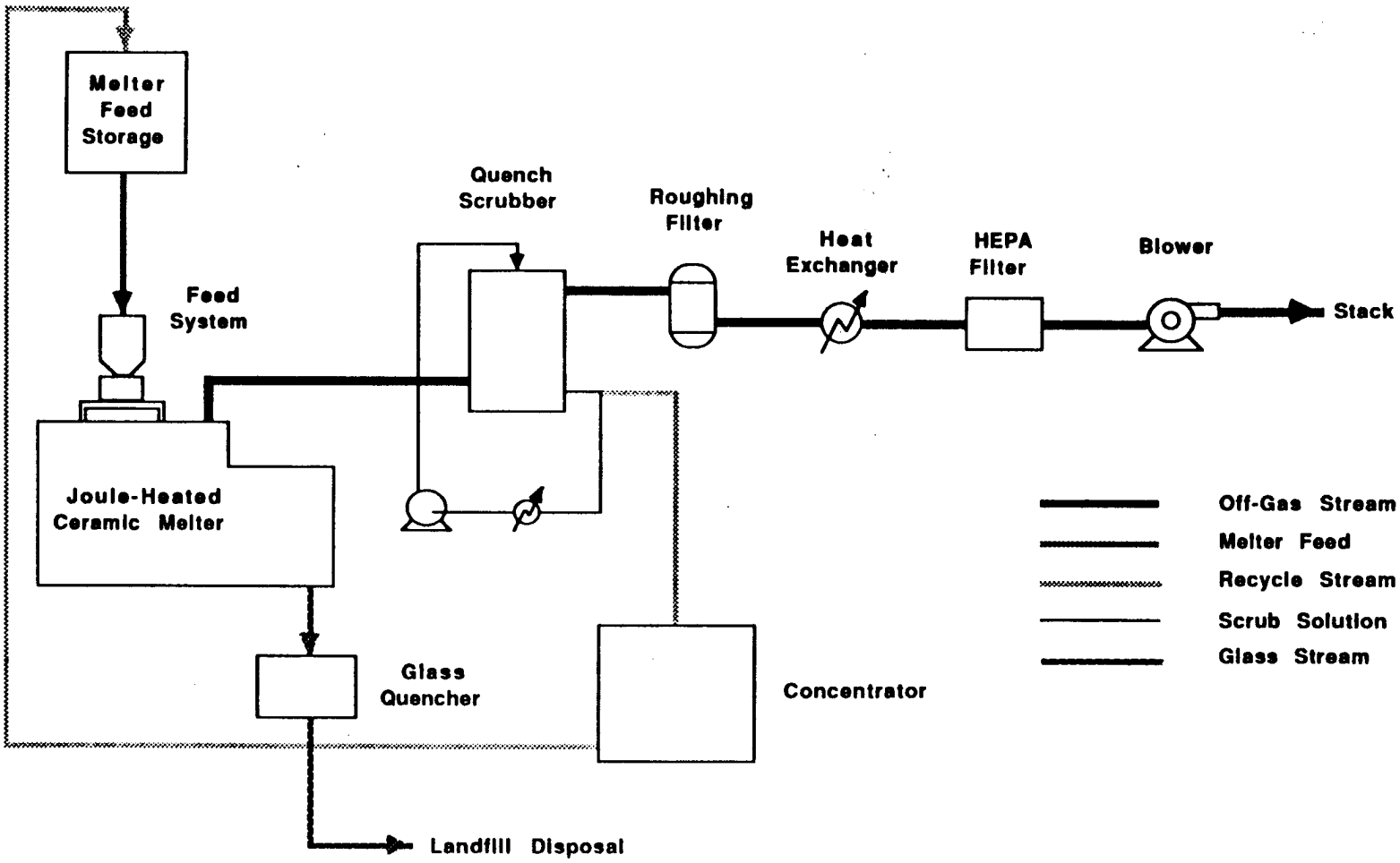

FIGURE 4.3. Typical JHCM Process Flowsheet

thermally degraded to low carbon chain gases that readily burn in the plenum space or secondary combustion chamber above the melt surface, where additional air is added. Glass is discharged from the melt tank into disposal containers by way of an overflow section, or quenched in water ("fritted") to produce a granular product for bulk disposal.

The necessary components of the off-gas treatment system will depend on the specific waste stream. The components are selected from commercially available equipment. The decomposition of some waste species will result in the generation of hazardous gases such as NO_x or HCl, which escape from the melt and must be treated. The resultant waste streams from off-gas treatment, such as concentrated scrub solutions or filter media, can be recycled to the melter or disposed of directly if they are of low toxicity.

5.0 EVALUATION OF IN SITU VITRIFICATION

This section discusses the feasibility of applying in situ vitrification (ISV) to remediation of the raffinate sludge pits, quarry wastes, and contaminated soils at the Weldon Spring site. The section is broken down into subsections on process effectiveness, implementability, and cost. Each subsection discusses the raffinate sludge pits, contaminated soils, and quarry wastes.

5.1 PROCESS EFFECTIVENESS

The effectiveness of the ISV process on raffinate sludge pit, soil, and liner stabilization was determined by a bench-scale ISV test of actual materials from the Weldon Spring site. The bench-scale ISV test vitrified a mixture of raffinate sludge and uncontaminated site soil, surrounded by Weldon Spring Soil, and a layer of clay liner material. Included in this work was a determination of the sludge/soil mix ratio required for vitrification, an evaluation of system performance, and a determination of the vitrified product's quality and durability, based on post-test analytical results.

5.1.1 Preliminary Waste Analysis

Elemental analyses were conducted on the three test material samples received from the Weldon Spring site: raffinate sludge, the clay liner, and uncontaminated soil. Inductively coupled plasma atomic emission spectroscopy (ICP) was used to obtain most of the elements. Ion chromatography (IC) was used for fluorine, chlorine, nitrate and sulfate analysis. The as-analyzed results are presented in Table 5.1. Values are reported in terms of weight percent oxides. Blank values in the Table 5.1 indicate that the concentration of the element was below detection limits. The composition of the clay liner and the soil were found to be essentially the same. Both were high in silica, alumina, and iron while low in fluxes such as the alkalies and alkaline earths. The composition of the sludge was significantly different, containing mostly alkaline earths with major amounts of silicon, aluminum, iron and sulfate. The relatively high amount of sulfate (9.4 wt%) and low amount of fluorine (0.078) were unexpected.

TABLE 5.1. Weldon Spring Site Material Analyses

Oxide	Raffinate Sludge, wt%	Uncontaminated Clay Liner, wt%	Uncontaminated Site Soil, wt%
Al_2O_3	4.26	13.7	12.4
As_2O_3	0.204	--(a)	--
B_2O_3	--	0.337	0.159
BaO	0.081	0.044	0.071
CaO	27.5	0.643	0.845
Cr_2O_3	0.031	--	--
CuO	0.115	--	--
Fe_2O_3	6.16	4.2	4.66
K_2O	0.41	1.3	1.64
MgO	8.83	0.842	0.958
MnO2	4.56	0.024	0.097
MoO_3	0.513	--	--
Na_2O	1.60	1.04	1.16
NiO	0.066	0.043	0.037
P_2O_5	3.21	--	--
SiO_2	11.4	73.4	71.4
SrO	0.022	0.038	0.061
ThO_2	0.625	--	--
TiO_2	0.268	0.680	0.741
V_2O_3	2.25	0.015	0.018
Y_2O_3	0.058	--	--
ZnO	0.065	--	--
ZrO_2	0.351	0.038	0.061
Total Oxides	68.4	96.4	94.3
Cl	0.045	*(b)	*
F	0.078	*	*
NO_3	7.54	*	*
SO_4	9.40	*	*
Density (g/ml)	1.18	2.1	*
Percent Moisture	75.6	20.9	20.9

(a) Below detection limit.
(b) Analysis not available.

The radioactive raffinate sludge sample used in this evaluation is a composite sample of material from the four raffinate pits at Weldon Spring. The composite sample was prepared at Oak Ridge National Laboratories (ORNL). An isotopic analysis of the sample, prepared by ORNL, is shown in Table 5.2. The isotopic analysis showed that the primary radioactive contaminant in the raffinate sludge sample is thorium (89.4%) and that 99.6% of the thorium is ^{230}Th. The radionuclide contents of uranium and radium in the raffinate sludge are 7.0% and 3.6%, respectively.

5.1.2 Preliminary Melt Tests

Crucible melting tests were conducted to provide an estimate of the ISV melting properties of the soil and sludge and to determine if soil and sludge should be blended to give a more desirable product. Samples of the soil and sludge were placed in separate crucibles and observed with increasing temperature to estimate their fusion and melt temperatures, as well as the viscosities of each melt. Because of the chemical similarity of the soil and clay liner, their melting properties were similar after calcining. The Weldon Spring soil sintered together at approximately 1300°C and melted at

TABLE 5.2. Radionuclide Content of the Weldon Spring Raffinate Sludge Sample

Isotope	Radionuclide Content, pCi/g
Radium-226	300
Radium-228	300
Thorium-230	15,900
Thorium-232	100
Uranium-234	640
Uranium-235	30
Uranium-238	580
Total Radionuclide Content	17,900

1440°C. The molten glass exhibited a viscosity ≥3000 poise at 1480°C. After cooling, the samples appeared glassy. These results show that the soil and clay liner materials can be processed by ISV.

The Weldon Spring raffinate sludge shrank in volume and sintered together after heating to 1120°C. At 1200°C, the sludge was completely molten and appeared very fluid, with a viscosity of approximately 1 poise. The 1200°C sludge was also very corrosive. During cooling, the melt was soft and granular, and the final product was nearly completely devitrified. The devitrification was caused by the very low silica content and high alkaline earth levels in the melt. Although some degree of devitrification or crystallization is always present in ISV product, excess devitrification can result in poor ISV product strength, higher surface area, and therefore, poorer leach resistance. For the ISV process, a portion of clay liner or soil material should be added to the sludge to decrease its degree of devitrification.

A mixture of 50% soil and 50% sludge (based on dry weight) was evaluated to determine if this ratio would produce an acceptable ISV product. The two wastes were mixed together and dried, then placed in a high-temperature furnace. At 1100°C, the mixture sintered together and slumped to the bottom of the crucible. Melting was initiated at 1150°C, but the melt did not become completely molten until after the furnace temperature had reached 1250°C. The melt exhibited a viscosity of 800 to 1000 poise at 1250°C, and a viscosity of approximately 200 poise at 1475°C. Based on the viscosity and melting behavior observed, this mixture was used for the bench-scale ISV test.

5.1.3 ISV Bench-Scale Test

The ISV bench-scale test used the engineering-scale power supply and off-gas system and a 30-gal metal drum that was placed in the engineering-scale processing container. The engineering-scale container (illustrated in Figure 5.1) measured 1.8 m (6 ft) in diameter by 2.4 m (8 ft) tall. The processing container provided sealed containment of the soil vitrification and off-gas vacuum during the bench-scale melting process. The bench-scale

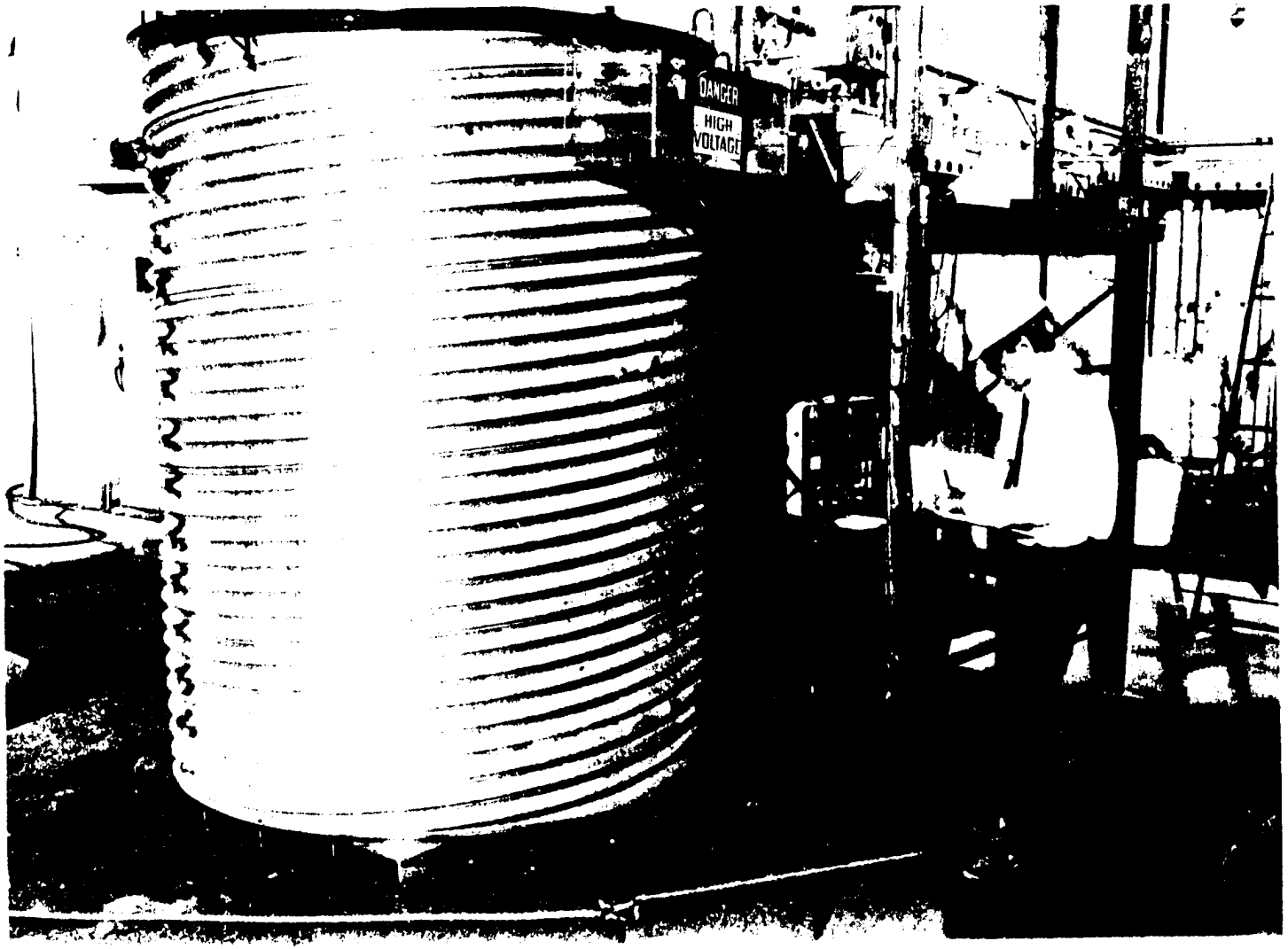

FIGURE 5.1. Engineering-Scale ISV Processing Container

test was performed using a 10-kW transformer with five voltage taps (400, 320, 240, 160, and 80 volt) and silicon-controlled rectifier control.

Figure 5.2 shows the configuration for the Weldon Spring bench-scale test. Two molybdenum electrodes, 1.3 cm (0.5 in.) in diameter, were inserted 20 cm (8 in.) into the test soil. Each electrode was surrounded by a 3.8-cm (1.5-in.) diameter graphite collar, inserted to a depth of 30 cm (12 in.). The electrodes were spaced 14 cm (5.5 in.) apart. The 50:50 mixture of radioactive sludge and uncontaminated soil was buried in a 4-in.-long by 2-in.-wide zone between the two electrodes. The zone had a height of 4 in. and was covered by 2 in. of sand. (Sand has typically been added as a soil cover during ISV processing of clay soils to promote ISV start-up.) Uncontaminated soil from the Weldon Spring site surrounded the sludge/soil mixture perimeter, and a 2-in. layer of uncontaminated clay liner was placed under the uncontaminated soil and sludge/soil mixture. Uncontaminated non-Weldon Spring soil was used to fill the 30-gal drum underneath the 2-in. layer of clay liner.

Type K thermocouples were incrementally positioned along the centerline and side of the two containers to monitor the progress of the melt and the surrounding temperature profiles. In addition, a high-temperature Type C thermocouple was placed 14 cm (5.5 in.) below the soil surface in the radial center of the melt. The high-temperature thermocouple was used to determine the operating melt temperatures during ISV processing.

The ISV melt was started using a 2.5-cm (1-in.)-deep, 2.5-cm (1-in.)-thick conductive path of graphite/frit mixture between the two electrodes. During testing, the melt area was covered with 5.1 cm (2 in.) of blanket insulation to minimize surface heat loss and promote melt surface subsidence during processing.

Off gasses from the vitrification zone were isokinetically sampled during the test. The sampling train consisted of an EPA Reference Method 5 sampling scheme to sample off-gas particulates and semivolatiles (40 CFR 60, Appendix A), and a large activated carbon tube on the end to capture radon. The off-gas flow was measured with a wet test meter.

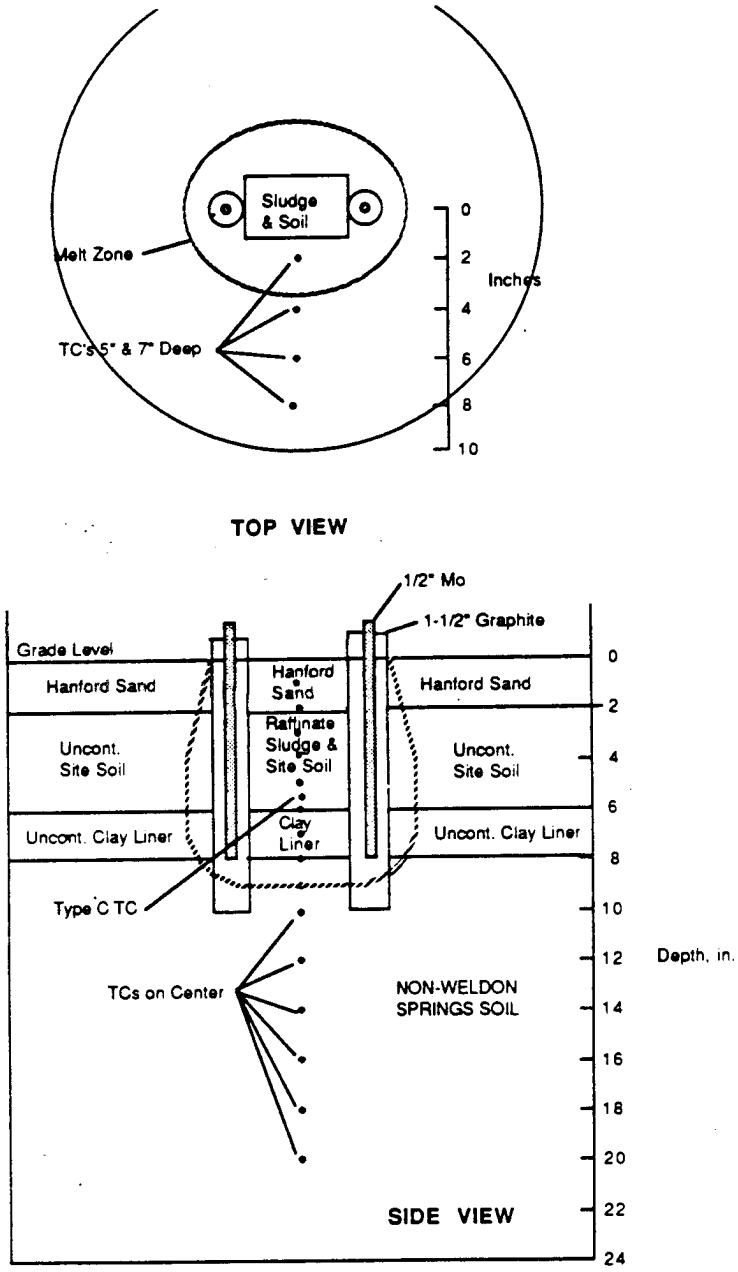

FIGURE 5.2. ISV Bench-Scale Test Configuration: Sediment Placement and Thermocouple and Electrode Locations

Note: The 30-gal drum was placed inside the engineering-scale ISV processing container (see Figure 5.1).

The bench-scale ISV test, conducted on February 23, 1989, vitrified 13.8 kg of soil, clay liner, and raffinate sludge, which included 600 ml (710.5 g) of sludge that had been mixed with 219 g of uncontaminated Weldon Spring soil. The high moisture content (63 wt%) of the soil/sludge mixture did not appear to hinder the test operation, as indicated by the lack of any power surges or other operational problems during the test run. The melt proceeded to a depth of approximately 30.5 cm (12 in.) and produced a 10.0 kg (22 lb) block over a 5-h period. The resultant glass block is shown in Figure 5.3. The resultant block was elliptical, with a maximum diameter of 23 cm (9 in.) and a height of 28 cm (11 in.). Very little void volume was observed in the resultant glass block.

Electrical power data for the bench-scale ISV test is plotted in Figure 5.4. The total energy consumed during the test was 18.6 kW-h, which resulted in an energy-to-mass ratio of 1.3 kW-h/kg. This ratio is slightly above typical energy-to-mass ratios for previous ISV tests, that have ranged from 0.8 to 1.1 kW-h/kg for dry soils and slightly higher for high-moisture soils and sludges.

Power to the electrodes was controlled to provide an accurate scale-down of the power density from the large-scale ISV system. The maximum power density of the large-scale system is 286 kW/m^2 (26.6 kW/ft^2), which is based on a 3500-kW power supply and a minimum surface area between the electrodes of 12.25 m^2 (131.9 ft^2). During the latter portion of the test, the power level averaged 4.72 kW. Assuming an elliptical melt cross-sectional geometry with an area of 124 cm^2 (19.2 $in.^2$), the actual power density for this test was 380.6 kW/m^2 (35.4 kW/ft^2). Although somewhat high, the power density is still within acceptable power density limits to ensure that the tests were operated under representative conditions.

Data on the operating melt temperatures for the bench-scale ISV test were limited because the high-temperature Type C thermocouple failed after 3.6 h of testing. However, melt temperatures of 1710°C to 1760°C were recorded by the Type C thermocouple for 1.2 h before it oxidized (2.4 to

FIGURE 5.3. Vitrified Product Resulting from the Bench-Scale ISV Test

3.6 h after initiating power). These melt temperatures are typical of ISV molten soil and indicate that a high-quality product could be expected, and indeed, was produced in the test.

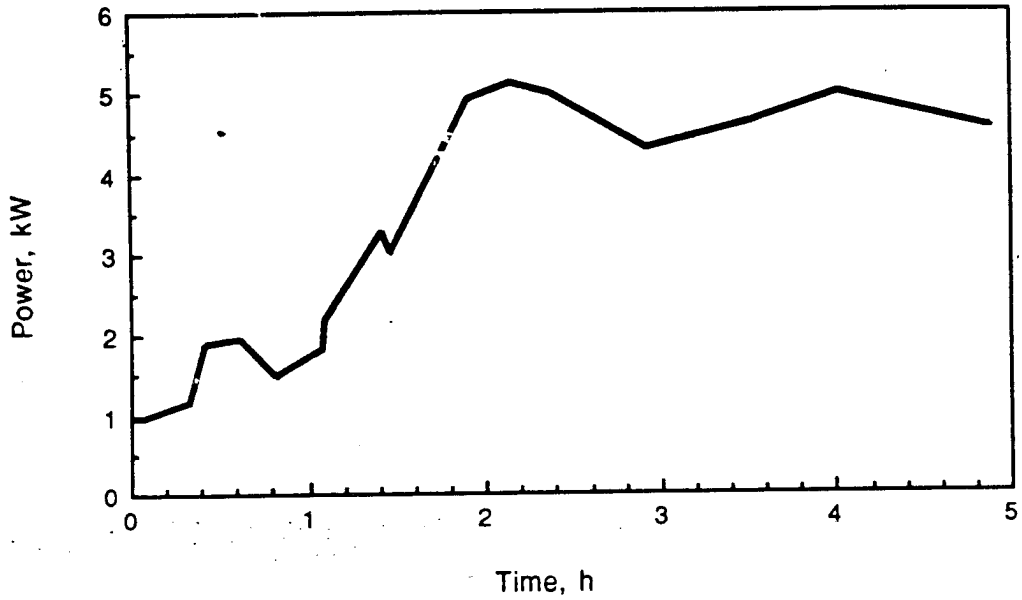

FIGURE 5.4. Electrical Power Performance for the Weldon Spring Bench-Scale ISV Test

5.1.4 Off-Gas Performance

The average off-gas flow during the test was 595 L/min (21 scfm). From this flow, an isokinetic sample was drawn through the off-gas sample train to determine the amount and composition of particulate, semivolatiles, and radon that was released to the off-gas during vitrification. A sketch of the off-gas sample apparatus is shown in Figure 5.5. The flow rate through the sampling train ranged from 11.6 to 14.7 L/min (0.41 to 0.52 scfm), with an average flow rate of 13.6 L/min (0.48 scfm). The 13.6 L/min average flow rate results in a linear flow velocity that is within 5% of the isokinetic linear flow velocity (approximately 13 L/min). As a result, the amount and size distribution of off-gas particulate that was entrained on the sampling filters should be representative of the particulate loadings and size distributions in the 21 scfm off-gas flow.

The filters in the off-gas sampling train were used to estimate the amount and composition of larger, entrained particulate in the system off-gas filters before the off-gas stream enters the off-gas scrub solutions. The scrub solutions were used to capture the remaining particulate. In addition, samples of the entrained particulate that plated out in front of the

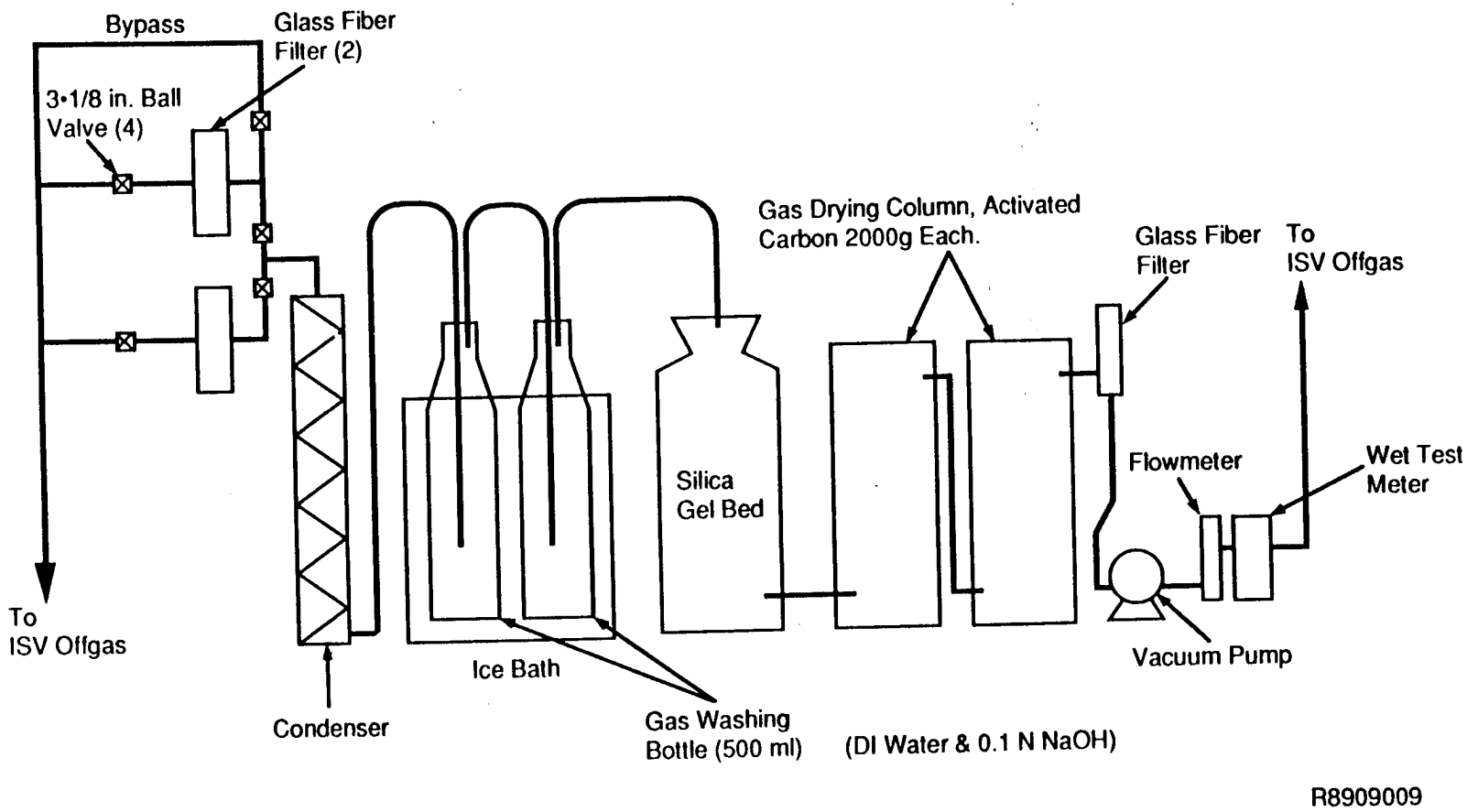

FIGURE 5.5. ISV Bench-Scale Off-Gas Train

off-gas filters were also collected and analyzed using ICP. The composition of filtered particulate, gas scrub solutions, and plated-out particulate in the off-gas sampling train are shown in Table 5.3. These numbers need to be multiplied by approximately 43.75 to account for the difference in flow volume between the off-gas sampling train and the full engineering-scale off gas system.

The amount of thorium (the primary radioactive component in the Weldon Spring sludge) collected in the off-gas sampling train was below ICP detection limits, as was the amount of uranium that was collected in the impinger solutions. Assuming that the thorium released to the off-gas system is just below detection limits (0.04 μg/ml), the amount of thorium released to the engineering-scale off-gas system would be 1.83 mg. This value is only 0.4% of the original amount of thorium present in the 600 ml of Weldon Spring of vitrified raffinate sludge (4.44 g). This is in accordance with previous studies that have shown over 99.96% of uranium retained in the vitrified block (Koegler and Bates 1988). Moreover, it is expected that radionuclide retention in the large-scale ISV process will be much better than the bench-scale test since retenticn improves dramatically with an increase in melt depth (Buelt et al. 1987).

In addition, the off-gas sampling system used 4 kg of activated carbon to determine the amount of radon-222 emanation that occurred during vitrification. This was necessary to estimate the amount of radon released during large-scale remediation of the Weldon Spring site. The amount of radon-222 collected during the 5.6-h bench-scale test (corrected for analysis time lag) was less than 3 dpm or 3 nCi/kg of sludge/soil mixture. Extrapolated to the large-scale ISV equipment, the radon emanation rate during ISV processing is estimated to be less than 8 μCi/h. At a projected large-scale off-gas flow rate of 50 std. m^3/min, this results in an estimated radon concentration of less than 2.7×10^{-9} μCi/ml. The stack release criteria for radon is 5×10^{-5} μCi/ml (DOE order 5484.1).

5.1.5 ISV Product Quality

Following bench-scale ISV testing, analyses were conducted on samples of the vitrified block to determine its quality and durability. The product

TABLE 5.3. Off-Gas Sample Compositions

Element	Amount of Element in Collected Particulate, mg			
	Plated-Out	Off-Gas Filters	H_2O Scrub	NaOH Scrub
Al	0.08	5.93	--	0.035
B	0.021	2.29	<0.22	<0.04
Ba	0.0004	0.066	--	0.018
Ca	0.042	8.25	--	--
Ce	0.0044	--	--	--
Cr	0.018	0.013	--	--
Cu	0.007	0.0078	--	<0.003
Fe	0.31	0.094	--	--
K	--	0.66	0.099	--
Li	--	--	<0.06	--
Mg	0.08	2.94	--	--
Mn	0.0029	0.0104	--	--
Mo	0.0066	0.018	<0.26	<0.008
Na	0.108	8.84	75.4	--
Ni	0.011	0.0035	--	--
P	0.014	--	--	<0.04
Si	0.69	60.1	1.90	12.4
Sr	0.003	0.0188	--	--
Th	<0.004	<0.008	<0.017	<0.013
Ti	0.013	0.0125	--	--
U	--	--	<0.002	<0.002
Y	0.035	--	--	--
Zn	0.335	0.08	--	<0.005
Zr	--	0.048	--	--
Total	1.80	89.4	<77.9	<12.6

quality was determined by compressive and tensile testing of simulated samples of the vitrified glass, and radon emanation analysis of a portion of the vitrified block. The durability of the vitrified block was determined by leach testing samples of the vitrified block, using MCC and EP Toxicity Leach Test procedures.

Figure 5.6 shows a section of the vitrified block that was broken open. The glass in the block appeared to be of high quality, with just a small amount of crystallinity. However, leach data has shown that the quality of the vitrified product is unaffected by crystallinity in the glass (Buelt et al. 1987).

5.1.5.1 Glass Durability

The dissolution (durability) properties of the vitrified product were analyzed using EP Toxicity procedures and 7-day and 28-day MCC-3 and MCC-1 leach test procedures. To allow for direct comparison of data, the leachate, temperature, and surface area/volume ratio (SA/V) to be used in the MCC-1 and MCC-3 leach tests were the same as those parameters used to test high-level nuclear waste borosilicate glasses. The differences in application (repository conditions such as ground water saturation and temperature) and the nature of the waste form (multi-phased ceramic-glass versus single-phased glass) would otherwise make such comparison difficult. Most high-level nuclear waste glasses are tested at 90°C. By conducting the leach testing of the Weldon Spring waste forms at 90°C, the results can be compared to the large data base of leaching data on the high-level glasses.

To allow the comparison of leach tests results from waste forms with different compositions, the results are given in terms of normalized elemental mass release for the MCC-1 and MCC-3 test. Normalized elemental mass releases were calculated with use of the following equation:

$$NR_i = m_i / (F_i \times SA)$$

where, NR_i = normalized mass release of element i (g/m^2)

m_i = mass of element i in leachate (g)

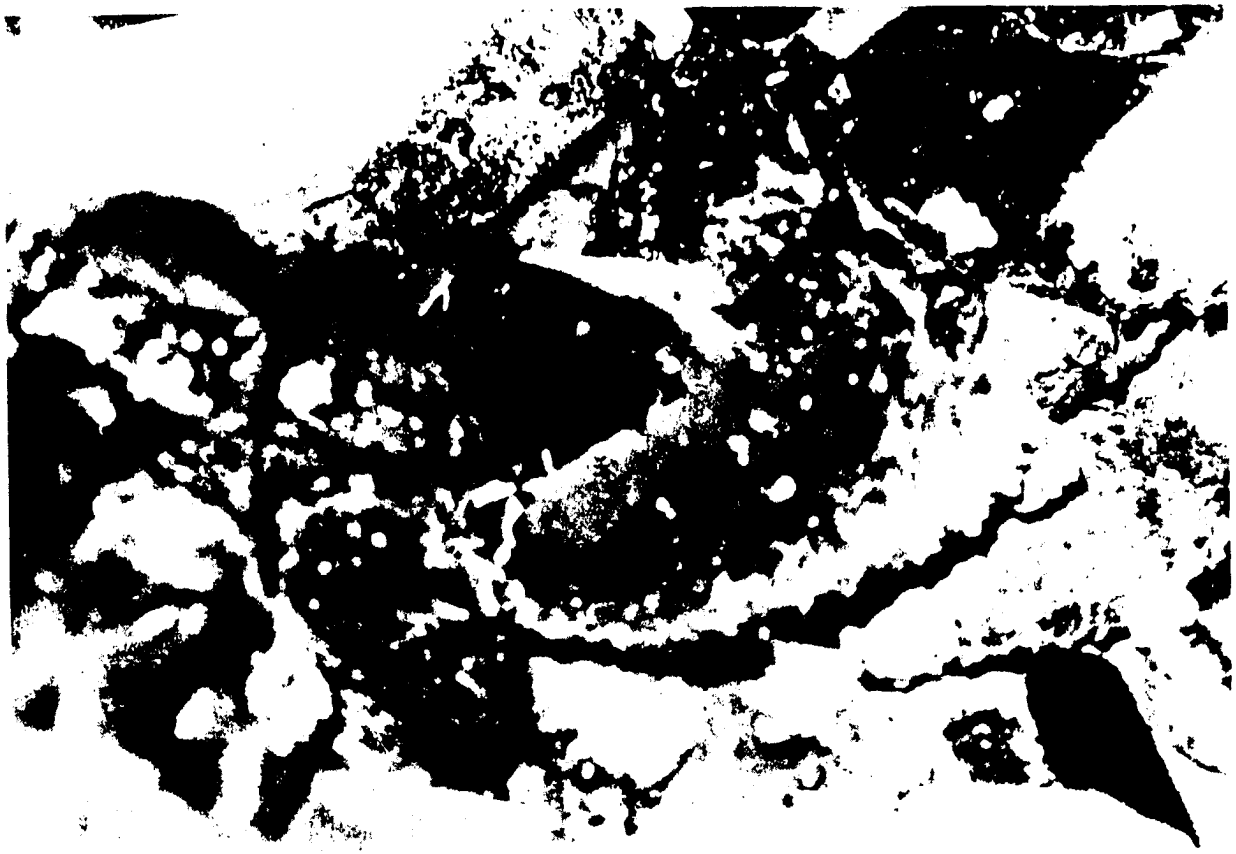

FIGURE 5.6. Cross-Section of the Vitrified Glass Block

F_i = fraction of element i in glass (dimensionless)
SA = surface area of monolith or powder(m^2)

The MCC-1 static leach test measures the elemental mass loss of a monolith sample of glass as a function of time. A glass sample is suspended within a sealed Teflon container by a Teflon support. The SA/V ratio is selected, nominally 10 m^{-1}. The leachant can be a synthetic silicate ground water, a synthetic brine, or reagent water. The sealed container is maintained at 90°C for 3, 7, 14, or 28 days. The results of the test are based on leachate ICP analysis from which the total concentrations of materials removed from the sample are determined. For this evaluation, testing was conducted with an SA/V ratio of 10 m^{-1} in deionized water (DIW) at 90°C for 7 and 28 days.

The MCC-3 agitated powder leach test is very similar to the MCC-1 test procedure with two exceptions; the glass is in a powdered form, and the glass powder and leachant are agitated by rotating the container. This produces an elemental leachate concentration that may be more representative of dissolution under saturated conditions. Leachate saturation is achieved more rapidly in the MCC-3 test because higher SA/V ratios are used than in MCC-1 tests. The powder MCC-3 test is also very useful in cases when multiple phases are present in the waste form. Because the MCC-1 test uses a cut monolith of sample, the test results are affected by the amount of the different phases on the surface of the monolith. The MCC-3 test uses powdered samples (-100+200 mesh for this testing), allowing all phases to contact the leachate. For this evaluation, testing was conducted with an SA/V ratio of 2000 m^{-1} in DIW at 90°C for 7 and 28 days. The MCC-3 leachates are filtered through both a 0.45 μm filter and an 18 Å filter to determine the amount of colloidal material in the leachates. Since no significant differences are observed between the 0.45 μm and 18 Å filtered, only the data from the 0.45 μm filtered leachate are reported.

The average results from duplicate 7-day and 28-day MCC-1 leach tests of the ISV glass are presented in Tables 5.4 and 5.5, respectively. Average results from duplicate 7-day and 28-day leach tests are presented in Tables 5.6 and 5.7, respectively. Included in each table are the results from leach

TABLE 5.4. ISV Glass 7-Day MCC-1 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	0.90	7.40
B	0.00	9.90
Ca	1.50	6.25
Fe	1.29	0.00
K	0.00	--
Na	1.20	9.51
Si	0.80	8.11
V	0.00	--
Final pH	5.08	9.52

TABLE 5.5. ISV Glass 28-Day MCC-1 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	2.77	9.11
B	2.77	14.85
Ca	8.73	7.25
Fe	0.56	0.00
K	3.67	--
Na	3.15	13.54
Si	2.95	11.22
V	0.00	--
Final pH	8.75	9.32

testing of a high-level nuclear waste glass for comparison (Bates, Piepel and Johnston 1989). The MCC-1 and MCC-3 leach test samples from the bench-scale ISV test had Na releases that were approximately 4 to 8 times lower than the HW-39 glass. As a result, the durability of the Weldon Spring glass samples were 4 to 8 times better than the HW-39 high-level waste glass under the same conditions. It is also important to note that these tests were conducted at

TABLE 5.6. ISV Glass 7-Day MCC-3 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	0.01	0.12
B	0.09	0.44
Ca	0.29	0.04
Fe	0.00	0.00
K	0.06	--
Na	0.08	0.4
Si	0.04	0.21
V	0.25	0
Final pH	9.77	10.38

TABLE 5.7. ISV Glass 28-Day MCC-3 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	0.01	0.17
B	0.12	0.53
Ca	0.33	0.07
Fe	0.00	0.00
K	0.08	--
Na	0.11	0.52
Si	0.06	0.25
V	0.45	--
Final pH	9.79	10.55

an elevated temperature of 90°C. After the ISV product has cooled to ambient temperature, it is expected that the dissolution rates will be as much as two orders of magnitude lower.

The EP Toxicity test is a measure of the EP Toxicity metals concentrations in leachate generated from immersing the powdered glass in room temperature DIW for 24 h. Table 5.8 shows the EP Toxicity test results for

TABLE 5.8. EP Toxicity Concentrations for the ISV Glass

Contaminant	EP Toxicity Concentration for Weldon Spring Glass, mg/L	Maximum Allowed EP Toxicity Concentration, mg/L
Arsenic	<1	5.0
Barium	0.04	100.0
Cadmium	0.01	1.0
Chromium	<1	5.0
Lead	<1	5.0
Mercury	<0.03	0.2
Selenium	<0.01	1.9
Silver	<0.1	5.0

the Weldon Spring glass compared with the EP Toxicity Concentration Limits. The results of this test, along with the MCC-3 leach test results, show that the vitrified product would be an excellent waste form and would provide long-term isolation of any hazardous or radioactive component in the raffinate sludge/soil mixture.

5.1.5.2 ISV Product Radon Emanation

The quality of the resultant vitrified block was determined by performing radon emanation analysis on a portion of its surface, in accordance with Health and Safety Laboratory Manual-300, Method No. E-RN-01. In this procedure, the sample is sealed for up to 21 days, after which the vapor space is analyzed for ^{222}Rn. Previous studies have shown that ISV decreases the amount of radon released to the atmosphere by a factor of 3000 (Buelt and Freim 1986) by containing the uranium and decay products in the vitrified product matrix.

The results showed that the radon surface emanation of the Weldon Spring bench-scale glass was less than 1/1000 (0.1%) of the maximum theoretical radon emanation level in the glass. As a result, the vitrified product can be considered safe from an air emissions standpoint.

5.1.5.3 ISV Product Strength

To measure glass compressive and tensile strength, simulated core samples of the vitrified Weldon Spring sludge/soil mixture were prepared, using a 50:50 dry weight mixing ratio. In determining glass strengths, the use of simulated, nonradioactive glass samples will to be more representative of the expected Weldon Spring ISV operation than actual core samples from the bench-scale melt because of the large amount of uncontaminated soil and clay liner material in the bench-scale test, which diluted the 50:50 dry weight mixture by over an order of magnitude (from 50:50 to approximately 1.7:98.3).

The glass samples were prepared by mixing nonradioactive oxide components in the amounts needed to make a 50:50 dry weight soil mixture. The oxide mixture was then melted and pored into a slab of glass that was annealed at 61C°C for 3 h. Annealing the glass block is required to prevent its shattering of the glass during coring. Although the actual ISV glass will not be annealed, it is expected that the chunks in the glass will be of sufficiently low stress that they can be simulated by an annealed glass sample.

Six 1.3-cm (0.5-in.)-diameter core samples were then machined out of the glass block and cut to a length of 1.9 cm (0.75 in.). Three of the core samples were subjected to compressive testing, and the other three samples were subjected to tensile testing. The compressive strength of the glass is determined according to the equation:

$$4\ BF_a\ /\ \pi\ D^2$$

and the tensile strength of the glass sample is determined according to the equation:

$$2\ BF_r\ /\ \pi\ L\ D$$

where BF_a = breaking force of the glass core sample, when placed in the axial orientation (lb).

BF_r = breaking force of the glass core sample, when placed in the radial orientation (lb).

L = the length of the core sample (in.).

D = the diameter of the core sample (in.).

The results showed that the 50:50 (dry weight) sludge/soil mixture had a average tensile strength of 4,410 psi and an average compressive strength of 59,350 psi, with standard deviations of 670 psi and 9,020 psi, respectively. This compares favorably with typical high-level nuclear waste glasses (tensile strengths of 4860 ± 750 psi) and is significantly better than non-reinforced concrete [tensile strengths of 400 to 600 psi, compressive strengths of 3000 to 8000 psi (Buelt et al. 1987)].

The tensile strengths for a 20:10:70 (dry weight) sludge/soil/liner mixture were 4309 ± 324 psi, while the compressive strengths were 43,210 ± 2410 psi. By comparing these numbers with those of the 50:50 (dry weight) sludge/soil mixture, it can be seen that an increase in glass strength is observed as the sludge content is increased. However, this increase is not significant enough to affect processing of the clay liner and contaminated soil material.

5.1.5.4 Post ISV Test Soil Analyses

Composite samples of the soils surrounding the vitrified block were analyzed after completion of the Weldon Spring bench-scale test to determine if any radionuclide (radium, thorium, or uranium) had migrated away from the melt zone during testing. Composite samples of each of the surrounding soil layers (sand, soil, clay liner, and non-Weldon Spring soil) were analyzed for thorium and uranium. The data from these analyses are shown in Table 5.9. All of the radionuclide concentrations in the surrounding soils were typical

TABLE 5.9. Post-Test Radionuclide Concentrations (ppm) in the Soil

Material Layers	Thorium	Uranium
Non-Weldon Spring Sand	2.8 ± 1.0	0.7 ± 0.3
Weldon Spring Soil	11.8 ± 1.2	4.2 ± 0.4
Weldon Spring Clay Liner	10.1 ± 1.6	2.9 ± 0.2
Non-Weldon Spring Soil	6.1 ± 0.4	2.9 ± 0.2

of that expected in ordinary nonradioactive soils. The results verify that there was no migration of radionuclides into the surrounding soils.

5.1.6 Process Performance for Soils and Quarry Waste

The chemical composition and melting behavior of the uncontaminated soil and clay liner material were very similar. Analytical data (U.S. DOE 1987a) indicate that the chemical compositions and physical properties of the actual soils and clay liner are similar to the compositions and properties of the uncontaminated Weldon Spring soil and clay liner material that were used during bench-scale ISV testing. Therefore, ISV process effectiveness with the contaminated soil and clay liner materials should be similar to that with the uncontaminated soil and clay liner materials. The effectiveness of ISV remediation on the quarry refuse waste at Weldon Spring should be similar to that of the raffinate sludge/soil mixture and the contaminated vicinity soils and clay liner materials, provided the quarry fill material is similar in composition to the Weldon Spring soil tested here.

5.2 ISV IMPLEMENTABILITY

5.2.1 ISV of Raffinate Sludge

The implementation of ISV to remediate the Weldon Spring raffinate sludge will require combining the sludge in a 50:50 (dry weight) ratio with Weldon Spring clay liner or site soil to prevent the excessive devitrification that was observed upon melting the raffinate sludge alone. In addition, the high moisture content and large area of each raffinate pit makes it technically infeasible to vitrify the raffinate sludge and contaminated clay liner in place. As a result, both of the alternatives identified for raffinate sludge treatment involve combining the raffinate sludge with soil or clay liner material before or during ISV.

Because of the large moisture content of the resultant soil/sludge mixture, a large volume reduction is anticipated during ISV processing of the raffinate sludge. As the sludge is vitrified and consolidated additional sludge, clay liner, and site soil would be added until the melt is at or near grade level. Therefore, a substantial quantity of the sludge could be processed in one ISV setting. This reduces the number of settings required, as

well as the electrode costs and equipment setup costs. In addition, using the contaminated site soils and clay liner materials at Weldon Spring in the raffinate sludge mixture would result in substantial overall cost savings if these materials are also processed.

Two alternatives for implementing the ISV technology on the raffinate sludge and soil or clay liner mixture are identified below.

Alternative 1 - Combine Sludge with Soil or Clay in 50:50 Dry Weight Mixture at a Staging Area and Apply ISV.

The first alternative involves combining the raffinate sludge (75.6 wt% moisture) with Weldon Spring soil or clay liner material (20.9 wt% moisture) to produce a 50:50 (dry weight) mixture of soil and sludge. The resultant sludge/soil mixture will have a moisture content of 63 wt%. Because of the large volume reduction anticipated during vitrification (over 80%), the sludge/soil mixture can be vitrified in 4 to 5 batches per setting.

Figure 5.7 shows a flow diagram of Alternative 1. To perform this alternative, the sludge would be pumped out of the raffinate into a staging area, where it would be combined with soil or clay liner material from the Weldon Spring site in a 50:50 dry weight ratio. The mixture would be

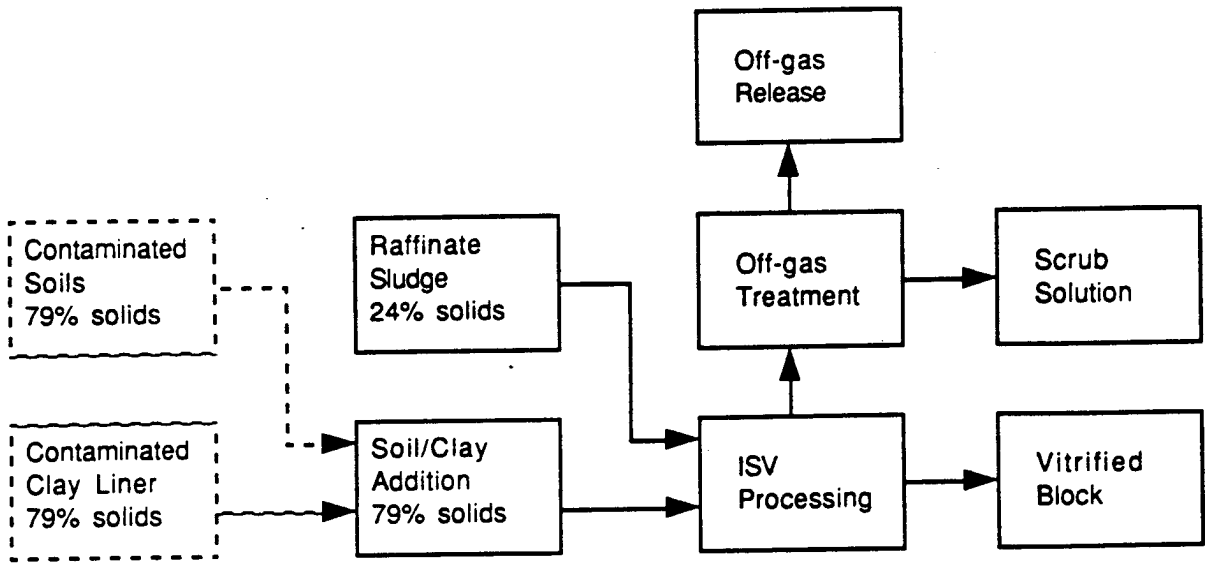

FIGURE 5.7. Flow Diagram for Raffinate Sludge ISV Remediation Alternative 1

processed by ISV into a vitrified mass. It is expected that intimate mixing of the sludge and soil would not be required and that sufficient mixing would take place in the staging pit prior to vitrification as the constituents are added. The vitrification area would be covered by a large hood that would contain any off-gasses released during ISV processing. These off-gases would then be sent to an off-gas system for treatment.

While combining the sludge and soil at the staging area, a substantial effort should be made to increase the soil concentration near the surface of the sludge/soil mixture. This is necessary to improve startup of the ISV melt. The 50:50 overall mixing ratio could still be kept constant by having a higher concentration of sludge in the lower layer of the sludge/soil mixture.

One option for remediation of the Weldon Spring raffinate sludge is to use contaminated soils or contaminated clay liner materials in the sludge/soil mixture. This would require emptying one raffinate pit to allow excavation of contaminated liner material for processing the raffinate sludge. Using contaminated soil and clay liner materials in the raffinate sludge remediation process would consume the contaminated soils and reduce the amount of contaminated clay liner to be processed later by approximately 15%.

Alternative 2 - Filter the Raffinate Sludge to 35 wt% Solids, Combine with Soil or Clay in a 50:50 (Dry Weight) Mixture, then Move to a Staging Area and Apply ISV.

Alternative 2 is the same as Alternative 1 except that the sludge would be de-watered before vitrification. Filtration could increase the solids content of the raffinate sludge from 24.4 wt% to 35 wt%. The moisture content of the filtered sludge and soil mixture would be approximately 51 wt%, instead of the 63 wt% for the unfiltered sludge case. It is anticipated that the volume reduction from vitrification of the filtered sludge/soil mixture would be approximately 70%, and that 3 to 4 batches of sludge/soil mixture could be vitrified per setting. Figure 5.8 shows the flow diagram for this alternative.

As with Alternative 1, use of contaminated soils and clay liner materials in the sludge/soil mixture could effectively reduce the volume of

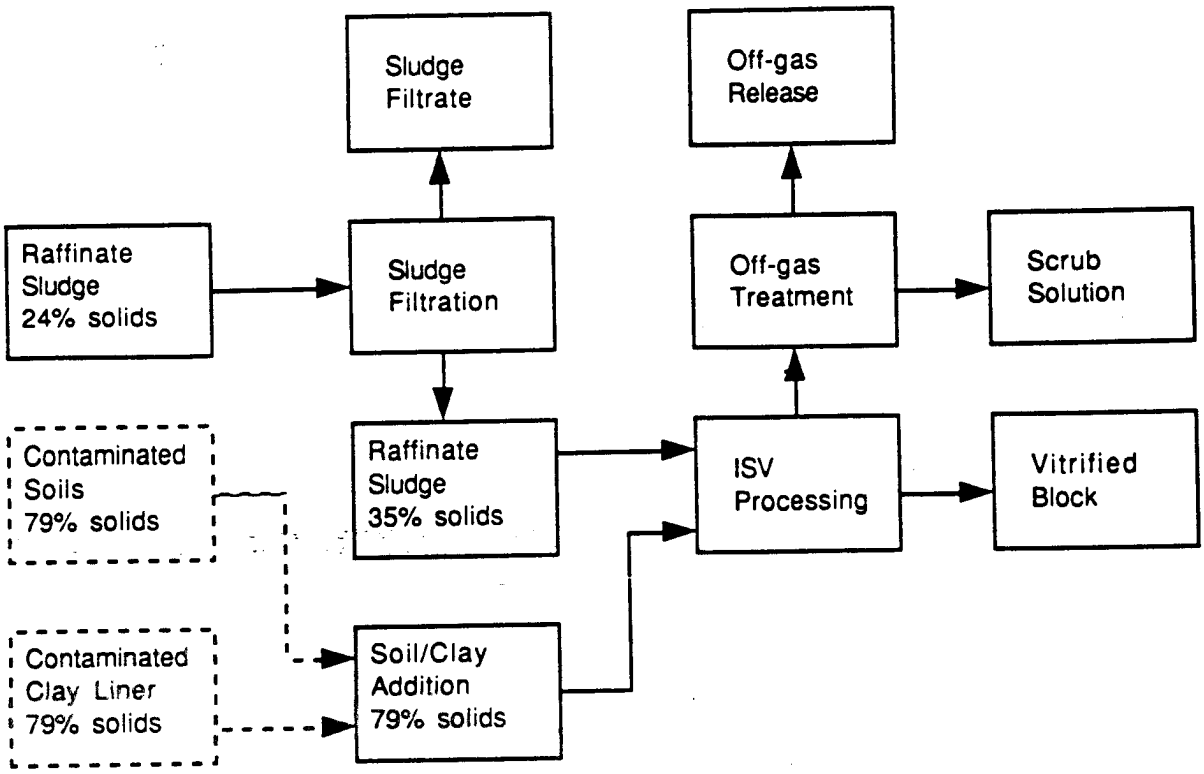

FIGURE 5.8. Flow Diagram for Alternative 2 of the Raffinate Sludge Remediation

contaminated clay liner material that needs to be processed by approximately 15%, and eliminate remediation costs for the Weldon Spring contaminated soils. To do this, the raffinate pits would have to be emptied one at a time to make portions of the contaminated clay liner material available for excavation and mixing.

5.2.2 ISV of Contaminated Soils

Processing of the contaminated vicinity soils and clay liner at Weldon Spring could either be performed in a staging area or treated in place. For economic reasons, the analysis assumes that the vicinity soils and clay liner materials are removed to a staging area before being processed by ISV.

Figure 5.9 shows a simplified flow diagram for processing of the contaminated vicinity soils and clay liner materials at Weldon Spring. Batches of the contaminated material are first transferred to a staging area, where

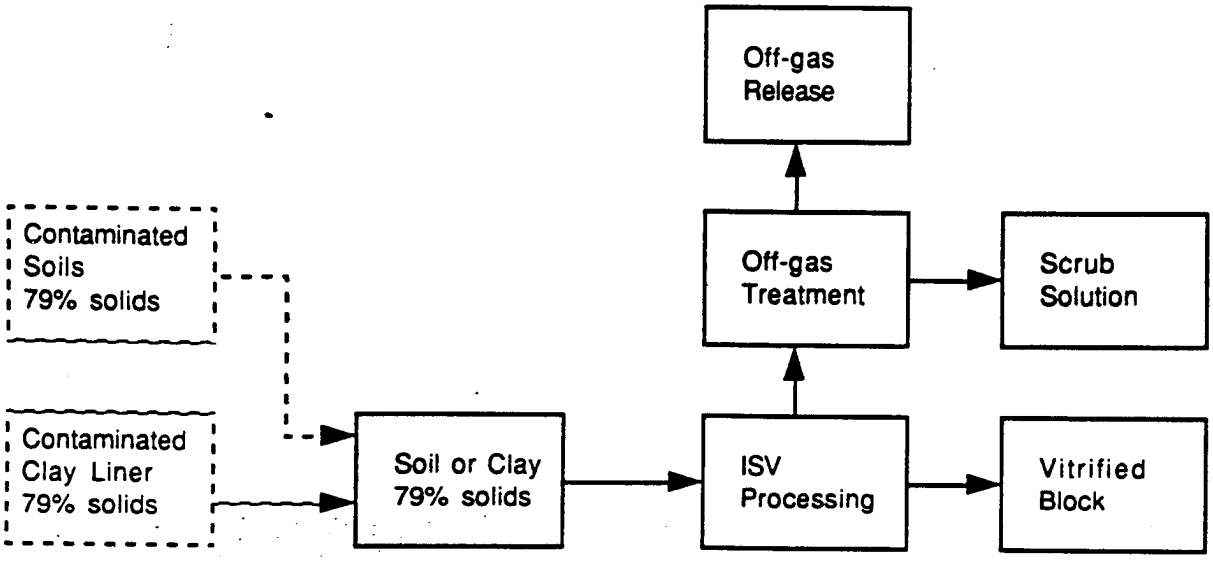

FIGURE 5.9. Flow Diagram for Remediation of the Contaminated Vicinity Soils and Clay Liner Material at Weldon Spring

they are placed into the ground for ISV processing. The contaminated materials are then vitrified into a solid glass block using ISV. During vitrification, any off-gasses or entrained particulate from the block are passed through the ISV containment hood to an off-gas treatment system.

Significant cost reductions could be realized by using the contaminated vicinity soils and a portion of the contaminated clay liner as the mixing soil in the raffinate sludge/soil mixture as described in Section 5.2.1, "ISV of Raffinate Sludge." This option would eliminate the need to vitrify the contaminated vicinity soils, and would reduce the volume of contaminated clay liner that needs to be vitrified by approximately 15%.

5.2.3 ISV of Quarry Refuse

Because of its depth (10 m to 15 m) and the presence of large metal objects in the quarry refuse waste, it is desirable to excavate the quarry wastes rather than vitrify them in place. During excavation, the large metal objects in the waste should be removed and decontaminated to eliminate any possible electrical shorting during ISV remediation.

The flow diagram for this treatment option is similar to that for treatment of the contaminated soil and clay liner wastes (see Figure 5.10). The

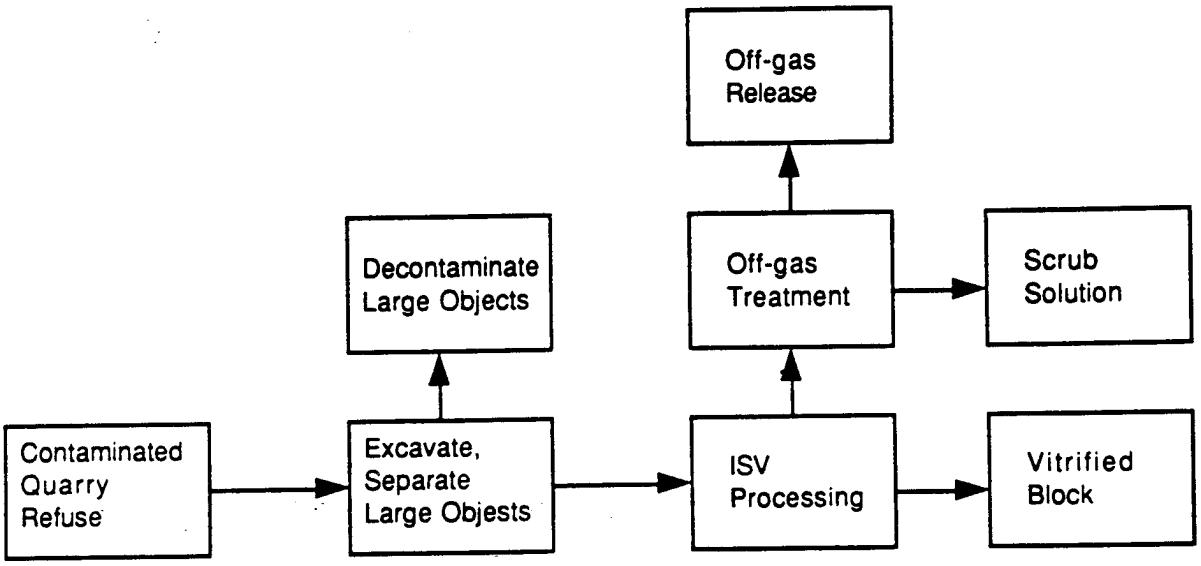

FIGURE 5.10. Flow Diagram for Remediation of the Contaminated Quarry Refuse at Weldon Spring

wastes would first be excavated and transferred to a staging area for ISV processing. The fenced raffinate pit area would provide a logical location for this staging area. The quarry refuse waste would be vitrified into a glass block, while releasing off-gasses (primarily water vapor and entrained particulate) to the ISV off-gas hood and off-gas treatment system. Implementability of ISV on remediation of the quarry refuse is based on the assumption that it has the same ISV processability as the contaminated soils and clay liner materials.

5.3 PRELIMINARY COST ESTIMATES FOR EACH IN SITU VITRIFICATION OPTION

This section presents an economic analysis of each ISV option, based on multiple, large-scale operating systems at the Weldon Spring site. The remediation of the Weldon Spring site is broken down into five options. These options are:

1) Mix the raffinate sludge with uncontaminated or contaminated soil or clay liner material in a 50:50 (dry weight) mixture. Then vitrify the sludge/soil mixture in a staging area, using four to five batches per setting (Alternative 1-Raffinate Sludge Treatment).

2) Filter the raffinate sludge to increase its solids loading from 24 wt% to 35 wt%. Then mix the filtered sludge with uncontaminated or contaminated soil or clay liner material in a 50:50 (dry weight) mixture. Vitrify the sludge/soil mixture in a staging area, using three to four batches per setting (Alternative 2-Raffinate Sludge Treatment).

3) Move the contaminated vicinity soils to a staging area and apply ISV.

4) Move the contaminated clay liner materials to a staging area and apply ISV.

5) Excavate the contaminated quarry refuse waste and separate out the large metal objects in the waste. Then move the quarry wastes (minus the large metal objects) to a staging area and apply ISV.

The soil and sludge volumes, process parameters, and design bases that were used to estimate ISV processing costs for each of the treatment alternatives are presented in Table 5.10. A computer model was used to predict the run time, volume vitrified, and number of ISV settings (one batch per setting) that would be needed for remediation with each alternative. The estimated time to vitrify all of the wastes ranges from 4.8 years to 6.4 years, depending on the raffinate sludge treatment alternative that is used and whether the Weldon Spring contaminated clay liner and vicinity soils are mixed with the raffinate sludge. The total time requirements for treatment of each waste option are based on the assumption that six ISV hoods and transformers would be used for remediation of the entire site. However, the estimates do not include the time for waste excavation and removal or the time and cost required for pre-filtering of the raffinate sludge, as is necessary in Alternative #2. These additional time and cost estimates are to be separately evaluated by the Weldon Spring Project Management Contractor (PMC).

Table 5.11 gives an itemized cost breakdown of the site equipment costs. The equipment listed in the ISV cost estimate includes six electrical transformers and six off-gas hoods, with three off-gas treatment systems and three backup blower systems. Each off-gas system and backup blower system

TABLE 5.10. Cost Estimate Bases for Processing Weldon Spring Wastes Using ISV

Parameter	Type of Waste: Raffinate Sludge (Mixed with Soil) Alt. 1 (Normal)	Raffinate Sludge (Mixed with Soil) Alt. 2 (Pre-filt.)	Contaminated Soil (Staged)	Contaminated Liner (Staged)	Quarry Refuse (Staged)
Sludge Volume, m^3	170,000	110,000	--	--	--
Sludge Wt., MT	204,000	140,000	--	--	--
Sludge Moisture, wt%	24	35	--	--	--
Soil/Clay Volume, m^3	--	--	21,000[a]	98,000[b]	73,000
Soil/Clay Wt., MT	62,000	62,000	31,500[a]	206,000[b]	117,000
Soil/Clay Moisture, wt%	21	21	21	23	30
Mix Wt., MT	266,000	202,000	--	--	--
Mix Volume, m^3	211,000	158,000	--	--	--
Mix Moisture, wt%	63	51	--	--	--
Vitrification Depth, m	6.0	6.0	6.0	6.0	6.0
Electrode Separation, m	5.5	5.5	5.5	5.5	5.5
Time per ISV Setting,[c] h	306	292	254	352	265
Volume per Setting, m^3	454	454	454	477	454
Number of Settings[d]	512	383	51[a]	226[b]	177
Annual Process Rate per ISV Machine,[e] m^3/h	10,400	10,900	12,500	9,500	12,000
Total Vitrification Time,[f] yr	3.4	2.3	0.3[a]	1.7[b]	1.0

(a) May be eliminated if used in reffinate sludge remediation.
(b) May be reduced by 15% if used in raffinate sludge remediation.
(c) Time includes 12 h for a low-powered startup and 16 h for moving and setting up the hood.
(d) The number of ISV settings accounts for a 10% overlap between settings.
(e) The annual processing rate assumes operating at 80% capacity.
(f) Vitrification time assumes that six ISV hoods and transformers are used concurrently.

would treat the off-gas from two ISV operations, thus reducing capital costs. The equipment costs include the costs for engineering and designing the equipment and mobilizing and demobilizing it at the site. The total equipment cost for staged operations is $17.5M. Equipment costs for waste excavation and transport are not included in this itemized list, however. In addition, the equipment costs for filtration of the Weldon Spring sludge have

TABLE 5.11. ISV Equipment Costs

Equipment	Estimated Costs, $1000
Engineering and Design	500
Equipment Mobilization (6 systems)	540
Transformers (6 required)	1,500
Off-Gas Hood and Line (6 required)	3,600
Off-Gas System (3 required)	9,000
Backup Blower System (3 required)	600
Power Lines (6 systems)	120
Electrode Power Cables (6 systems)	240
Portable Generators (3 systems)	300
Equipment Demobilization (6 systems)	780
Electrode Placement Machinery (1 system)	120
Crane (1)	130
Front End Loader (1)	80
Total Equipment Costs	17,500

not been evaluated or costed in this report. The equipment costs for waste excavation, transport, and filtration (where required) will be included in a separate evaluation by the Weldon Spring PMC.

Site operating costs for each waste type and treatment alternative are listed in Table 5.12. These costs represent estimates of the anticipated cost for ISV processing of each option, and should not be considered as a bid.

The electrode costs for each remediation alternative were calculated assuming that four electrodes would be reused for multiple batch setting (3 to 5 batches/setting) of raffinate sludge and used only once in a single setting for the uncontaminated soil, clay liner, and quarry refuse. The use of electrodes over extended operating periods still needs to be evaluated, and confirmed before it is actually implemented on site.

The total costs for remediation of all four waste types (sludge, soil, clay liner and quarry refuse) at Weldon Spring are estimated to be between

TABLE 5.12. ISV Site Operating Costs

Cost Breakdown	Cost for Waste Type and Treatment Alternative, in thousands of dollars				
	Raffinate Sludge Pits (Mixed with 50% Soil)		Contaminated Soils (Staged)[a]	Contaminated Liner (Staged)[b]	Quarry Refuse (Staged)
	Alt. 1 (Normal)	Alt. 2 (Pre-filtered)			
Labor Costs					
Vitrification Crew	4,600	3,300	380	2,300	1,400
Heavy Equipment Crew	400	300	130	590	460
Total Labor	5,000	3,630	510	2,900	1,900
Consumable Costs					
Electrodes	4,900	4,800[c]	1,930	8,500	6,700
Energy (6¢/kWh)	28,900	20,500	2,340	14,800	8,500
Secondary Waste	270	200	27	120	92
Total Consumables	34,100	25,500	4,290	23,500	15,300
Total Oper. Cost	39,100	29,130	4,800	26,400	18,500

(a) May be eliminated if used in raffinate sludge remediation.
(b) May be reduced by 15% if used in raffinate sludge remediation.
(c) Assumes three batches per setting.

$86.2M and $105M (unit volume cost of approximately $274/m^3 and $260/m^3). The actual cost is dependant on whether or not the sludge was filtered before soil mixing, and whether uncontaminated or contaminated soils and clay liner materials were used in the raffinate sludge remediation alternatives.

Significant reductions in ISV processing time and cost can be realized by using contaminated soils and clay liner materials in the Weldon Spring raffinate sludge/soil mixture. This option would eliminate remediation of the contaminated vicinity soils at Weldon Spring and reduce the costs and time required for remediation of the Weldon Spring clay liner by 15%. The total reduction in operating cost is estimated to be $8.8M.

Pre-filtering the raffinate sludge to 35 wt% solids would also reduce the operational cost and vitrification time for complete ISV processing of the sludge by $10M and 1.1 years, respectively.

Pre-filtering the raffinate sludge to 35 wt% solids would also reduce the operational cost and vitrification time for complete ISV processing of the sludge by $10M and 1.1 years, respectively.

6.0 EVALUATION OF JOULE-HEATED CERAMIC MELTER

The evaluation conducted during the first phase of the Weldon Spring project concluded that waste materials currently identified for treatment could be successfully processed in a JHCM (Koegler, Oma, and Perez 1988). During the second phase of the project, compositional analyses of actual raffinate pit wastes, laboratory crucible tests, and glass product characterizations were conducted and used to further define alternative process flowsheets and estimated costs for vitrification of Weldon Spring materials. A description of processing quarry wastes was provided in the first phase of the Weldon Spring evaluation. Additional information concerning this waste stream was not provided and an update on treatment requirements has not been included. The discussion presented in this section applies to materials associated with the raffinate pits and contaminated site soils.

6.1 PROCESS EFFECTIVENESS

The flexibility of the JHCM process to incorporate a wide range and variety of chemical components has been demonstrated during the development of the technology for the immobilization of high-level nuclear wastes. The compositions of the Weldon Spring wastes present no significant technical concerns to the vitrification process. However, the addition of glass fluxing chemicals will be required to adjust the physical properties of the glass to meet constraints associated with the operation of the system. This section describes the methods and results of the laboratory crucible tests that were used to formulate an acceptable glass composition. The testing effort included multiple crucible melt tests, viscosity, electrical conductivity, leaching, and tensile and compressive strength analyses.

6.1.1 Waste Sample Compositions

Elemental analyses were conducted on the three test material samples received from the Weldon Spring site: raffinate sludge, clay liner, and vicinity soil. The results of the waste analysis are reported in Section 5.1.1. The relatively high concentration of sulfur (9.8 wt%) and low amount of fluorine (0.1 wt%) in the sludge sample were unexpected based on previous

information. The low fluorine concentration benefits the process. The high concentration of sulfur, however, could result in SO_3 being discharged from the melter in the off-gas stream because of the limited solubility of sulfur in glass.

A separations test was run to determine whether the sulfur was present in a soluble form that could be separated from the raffinate sludge solids. A second sample of the raffinate sludge was centrifuged to reduce the water content and both the solids fraction and the liquid fraction were analyzed using ICP and IC. These results showed that only a limited amount of the sulfur in the sludge sample was present in a water-soluble form and that a mechanical dewatering of the sludge will not significantly affect the overall composition of the material.

6.1.2 Melting Behavior Evaluation and Glass Development

Laboratory testing was used to further define JHCM process options proposed in the Phase I evaluation. A series of glass oxide compositions were developed based on laboratory melts using a simulation of the nominal waste composition. The major purpose of the glass development effort was to determine what glass forming components (i.e., SiO_2, alkali oxides, B_2O_3, and alkaline earth oxides) needed to be added to the wastes and at what levels to produce a melt composition that can be processed within a JHCM and have acceptable chemical durability.

The development of an acceptable glass composition was based on blending waste--raffinate sludge, clay liner, and vicinity soil (in proportions consistent with the estimated quantities of each material)--with chemical additives. Chemicals were added to the waste blend to adjust the glass melt properties to within the ranges required for melter processing. The amounts and types of additives were adjusted to provide the required processing properties while optimizing the economic implications of these additions. The three major processing properties are melt viscosity, electrical conductivity, and phase behavior.

Based on glass industry standards and experience at PNL, melting of glasses at economical rates ordinarily proceeds at the temperature at which the glass has a viscosity of 100 poise (T100P) or less. For melter operation

and product quality, the temperature at which the glass has a viscosity of 100 poise (T100P) should be between 1070°C and 1250°C. If the T100P is outside this range, processing problems may be encountered in the melter. If the viscosity of the glass is too low, glass penetration into the melter bricks and increased corrosion of melter tank components, due to high convection currents, may occur. The characteristic leach rate of low melting glasses is also generally poor. If the viscosity is too high, the interaction between the glass melt and the feed pile will be reduced, thus slowing the processing rate. The glass viscosity should also remain stable with time to allow stable melter operation.

In joule-heated ceramic melters, the electrical conductivity of the glass melt could be 0.18 to 0.5 $ohm^{-1}cm^{-1}$ at the nominal melter operating temperature (T100P). If the electrical conductivity of the glass is too high, the current required to heat the glass will exceed the recommended maximum current density for the melter electrodes. If the electrical conductivity of the glass is too low, the resulting high voltage potential of the melt could cause conduction to occur within the melter refractories. Low electrical conductivity melts also necessitate undesirably large electrical power systems.

No excessive crystallization or phase separation should be present in the glass. Large amounts of crystallinity may cause the formation of sludge within the melter, possibly reducing the lifetime of the melter, clogging areas within the melter, and/or shorting the melter electrodes. Significant liquid-liquid phase separation should not be present in the glass either. Liquid-liquid phase separation may result in the segregation of waste components into a less durable phase and interrupt or interfere with processing (e.g., possible excess volatility of the phase or excessive corrosion).

Because of the "extremes" between the sludge and liner/soil, the mixing of the two wastes would dilute out the extremes and allow for higher total waste loadings with smaller amounts of additives required. Glass compositions are expressed as the sum of the oxide components. Using the results of total moisture from the ICP analyses, the relative oxide proportion of the three wastes were calculated. Because the compositions of the soil and clay

liner were essentially equivalent, the total volume and oxide amounts have been combined. The relative wt% oxides is 82 wt% for the soil/liner and 18 wt% oxides for the sludge. This mixture of soil/liner and sludge was established as the "standard" composition for melter glass development. The composition of the waste is presented in Table 6.1.

6.1.3 Crucible Melt Test Results

Using the oxide proportions from Table 6.1 to define a waste blend, a series of glass compositions have been generated and tested. The compositions of these glasses (WSM-1 through WSM-5) are summarized in Table 6.2. Because of the low alkali content of the waste blend, sodium was added to reduce the viscosity and increase the electrical conductivity. Other additives (boron and lithium) were added to adjust both the viscosity and electrical conductivity properties. These additives could be added to the waste in their carbonate, oxide, or hydroxide forms depending on cost and availability.

The first test melt (WSM-1) contained the addition of 10 wt% Na_2O and was visually observed to have a viscosity of greater than 3000 poise at 1450°C. To lower the viscosity, the sodium concentration was increased in the second composition (WSM-2) to 20 wt% added Na_2O and was visually observed to have a viscosity of ≈150 to 200 poise at 1300°C. Based on earlier experience, the viscosities of these compositions were determined to be outside the acceptable range and the characterization was discontinued.

The WSM-3 composition contained 25 wt% Na_2O. The viscosity of WSM-3 was measured using a rotating spindle viscometer. The viscosity versus temperature curve for WSM-3 is presented in Figure 6.1. The T100P for this glass was 1206°C, indicating that the viscosity of this glass would be acceptable for melter processing. The electrical conductivity of the WSM-3 glass was measured using a Wheatstone Bridge apparatus. The electrical conductivity curve for WSM-3 is presented in Figure 6.2. At the T100P, the electrical conductivity of the WSM-3 was 0.56 $(ohm\text{-}cm)^{-1}$. This is just outside the range for acceptable processing.

TABLE 6.1. Composite Waste Composition Used For JHCM Laboratory Tests

Oxide	Waste and Substituted Compositions, wt% Oxide			
	Sludge	Liner	Soil	Sub. Waste
Al_2O_3	5.6	15.3	13.1	11.8
As_2O_2	0.3			0.0
BaO	0.1	0.0	0.5	0.4
CaO	36.2	0.7	0.9	7.2
CuO	0.2			0.0
F	0.1			0.0
Fe_2O_3	8.1	4.6	4.9	5.5
K_2O	0.5	1.6	1.7	1.5
MgO	11.6	0.9	1.0	2.9
MnO_2	0.6	0.0	0.1	0.2
MoO_3	0.7			0.1
Na_2O	2.1	0.9	1.2	1.4
Nd_2O_3	0.5			0.1
NiO	0.1	0.1	0.0	0.0
P_2O_5	4.2			0.8
SiO_2	15.0	75.0	75.6	64.7
SO_3	9.9			1.8
ThO_2	sub. Zr	sub. Zr	sub. Zr	sub. Zr
TiO_2	0.4	0.7	0.8	0.7
U_3O_8	sub. Nd	sub. Nd	sub. Nd	sub. Nd
V_2O_3	3.0	0.0	0.0	0.5
Y_2O_3	0.1			0.0
ZrO_2	0.8	0.0	0.1	0.2
	100.0	100.0	100.0	100.0

TABLE 6.2. JHCM Test Glass Compositions Used In Crucible Experiments

	WSM-1		WSM-2		WSM-3		WSM-4		WSM-5	
Oxide	10 wt% Additive	Glass	20 wt% Additive	Glass	25 wt% Additive	Glass	18 wt% Additive	Glass	25 wt% Additive	Glass
Al_2O_3		10.59		9.41		8.83		9.65		8.83
As_2O_2		0.04		0.04		0.04		0.04		0.04
B_2O_3							35.00	6.30	10.00	2.50
BaO		0.35		0.31		0.29		0.32		0.29
CaO		6.52		5.79		5.43		5.94		5.43
CuO		0.02		0.02		0.02		0.02		0.02
F		0.02		0.01		0.01		0.02		0.01
Fe_2O_3		4.95		4.40		4.13		4.51		4.13
K_2O		1.36		1.21		1.14		1.24		1.14
Li_2O							15.00	2.70		
MgO		2.63		2.34		2.19		2.40		2.19
MnO_2		0.17		0.15		0.14		0.16		0.14
MoO_3		0.11		0.10		0.09		0.10		0.09
Na_2O	100.00	11.25	100.00	21.11	100.00	26.04	50.00	10.14	90.00	23.54
Nd_2O_3		0.08		0.07		0.07		0.07		0.07
NiO		0.04		0.04		0.04		0.04		0.04
P_2O_5		0.68		0.61		0.57		0.62		0.57
SiO_2		58.22		51.75		48.52		53.05		48.52
SO_3		1.61		1.43		1.34		1.46		1.34
SrO		0.02		0.02		0.01		0.02		0.01
ThO_2		del		del		del		del		del
TiO_2		0.64		0.57		0.53		0.58		0.53
U_3O_8		del		del		del		del		del
V_2O_3		0.49		0.44		0.41		0.45		0.41
Y_2O_3		0.01		0.01		0.01		0.01		0.01
ZrO_2		0.18		0.16		0.15		0.17		0.15
TOTALS	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

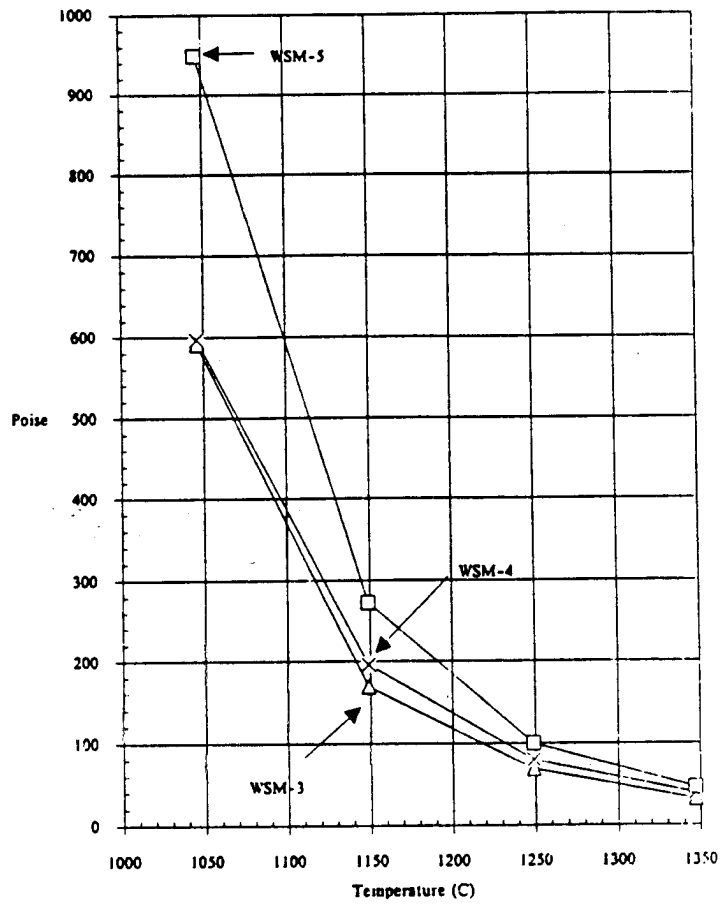

FIGURE 6.1. Viscosity Curves of JHCM Test Glasses

The WSM-4 composition was developed to increase the waste loading of the glass (decrease the amount of required additives) and lower the electrical conductivity while maintaining the viscosity of the glass at the same level as WSM-3. Lithium was added to take advantage of the mixed alkali effect where two alkalies together have a greater effect on viscosity and electrical conductivity than a similar amount of a single alkali. This allows for a decrease in the required amount of additives. Boron (a non-charge carrier) was also substituted for a portion of the sodium to reduce the electrical conductivity of the melt. The viscosity and electrical conductivity curves for WSM-4 are shown in Figure 6.1 and 6.2, respectively. The T100P of 1216°C was judged acceptable; the electrical conductivity at 1216°C was just below the required range at 0.16 $(ohm\text{-}cm)^{-1}$. No phase separation, such as a

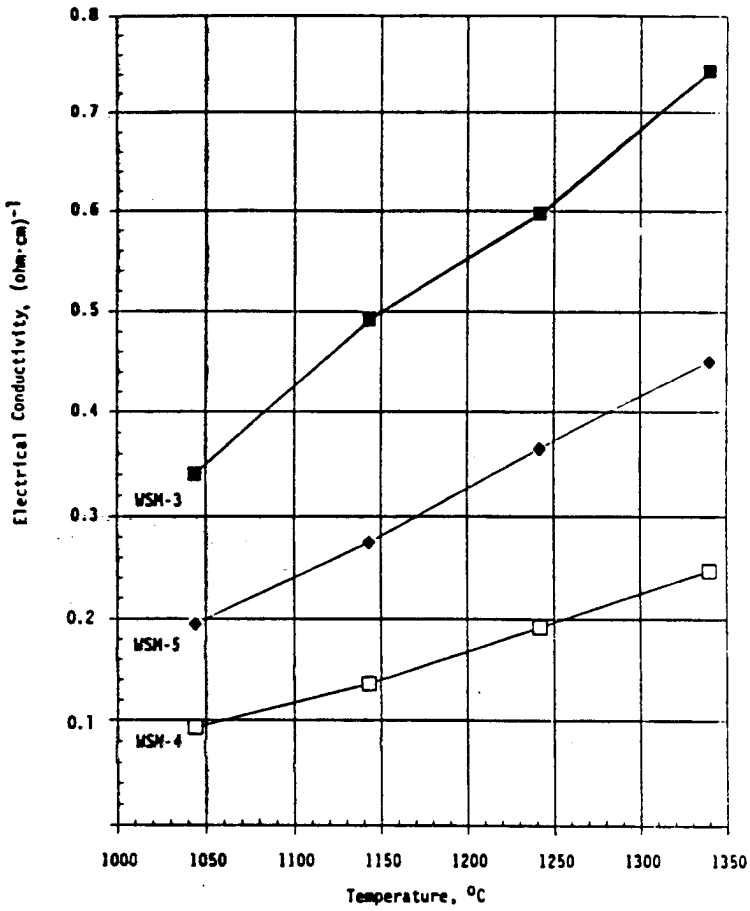

FIGURE 6.2. Electrical Conductivity Curves of JHCM Test Glasses

sulfate phase, was observed on the surface of the melt. It was expected that this sulfate phase would be observed because of the high SO_3 levels in the waste. A sulfate analysis of the WSM-3 glass found only 0.011 wt% SO_3 instead of the 1.43 wt% added to the glass. In the absence of a yellow salt phase on the surface of the melt, it is assumed that the sulfur in the glass volatilized.

An assessment of the cost of bulk quantities of the borax ($Na_2B_4O_7$) and the carbonate forms of sodium and lithium found that lithium was prohibitively expensive (see subsection 6.3). This assessment also found that the use of boron should be minimized to reduce cost. A WSM-5 glass composition was developed in consideration of minimizing costs for chemical additions. The WSM-5 glass contained 25 wt% additives where the additives consisted of

90 wt% Na_2O and 10 wt% B_2O_3. The viscosity and electrical conductivity curves for WSM-5 are shown in Figure 6.1 and 6.2 respectively. The T100P for WSM-5 was 1194°C and the electrical conductivity at this temperature 0.37(ohm-cm)$^{-1}$. This glass should be very acceptable for processing in a JHCM. No phase separation was observed in the melt.

To confirm the properties of the WSM-5 glass composition observed for the simulated waste glass, the WSM-5 composition was batched and melted using a mixture of actual soil, clay liner, and sludge. These waste components were dried, combined together, and then mixed with borax and sodium carbonate to produce the WSM-5 composition. This combination of actual waste and additives was melted in a 1200°C furnace. Active degassing was observed during calcination and melting but excessive glass foaming did not occur. A surface layer was observed on the surface of the melt, which contained yet undissolved particles of clay. This material was easily stirred into the melt. The melt was very smooth, and fibers pulled from the melt had very few crystals in them. The viscosity of the melt was approximately 80 poise at 1200°C which agrees well with the laboratory simulation of this composition. The surface layer reappeared after the melt was allowed to sit for 45 min. This surface layer is thought to be a sulfate phase.

6.1.4 JHCM Product Quality

Samples of the glass prepared using actual raffinate pit materials were subjected to analyses to determine the quality of the final product. The durability of the glass was determined using MCC and EP toxicity leach test procedures. Compressive and tensile testing was conducted to establish the relative strength of the glass. Descriptions of the procedures used in these analyses are presented in Section 5.0. Results obtained for the JHCM glass are presented in this section.

6.1.4.1 Glass Durability

The dissolution (durability) properties of the JHCM glass were analyzed using 7-day and 28-day MCC-1 and MCC-3 leach test procedures. The results of these tests in terms of normalized elemental mass release, are presented in Table 6.3 through 6.6. Results from similar testing conducted using a simulated high-level nuclear waste glass are included in these tables for

TABLE 6.3. JHCM Glass 7-Day MCC-1 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	7.24	7.40
B	11.32	9.90
Ca	8.19	6.25
Fe	0.48	0.00
K	8.50	--
Mo	10.12	9.31
Na	11.33	9.51
P	6.51	--
Si	8.47	8.11
V	12.52	--
Final pH	10.03	9.52

TABLE 6.4. JHCM Glass 28-Day MCC-1 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	8.49	9.11
B	13.78	14.85
Ca	9.70	7.25
Fe	0.66	0.00
K	13.11	--
Mo	14.15	13.95
Na	14.12	13.54
P	10.54	--
Si	10.17	11.22
V	15.58	--
Final pH	9.94	9.32

TABLE 6.5. JHCM Glass 7-Day MCC-3 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	0.19	0.12
B	0.26	0.44
Ca	0.01	0.04
Fe	0.01	0.00
K	0.28	--
Mo	0.85	0.43
Na	0.89	0.4
P	0.10	--
Si	0.24	0.21
V	0.29	--
Final pH	11.71	10.38

TABLE 6.6. JHCM Glass 28-Day MCC-3 Leach Test Results Comparison

Element	Normalized Elemental Release, g/m^2	
	Weldon Spring	HW-39
Al	0.29	0.17
B	0.30	0.53
Ca	0.01	0.07
Fe	0.01	0.00
K	0.39	--
Mo	0.82	0.53
Na	1.36	0.52
P	0.16	--
Si	0.37	0.25
V	0.32	--
Final pH	11.96	10.55

comparison. Based on these data, the durability of the Weldon Spring glass produced using JHCM vitrification is similar to that of the high-level nuclear waste glass.

Results of EP toxicity test conducted using the JHCM glass are presented in Table 6.7. They show that the durability of the product greatly exceeds established requirements. In general, the EP toxicity test (or a similar test) is used to determine the regulatory requirements for final disposal of a waste form. These results, combined with the MCC leach data, show that the JHCM process will yield a glass that provides long-term isolation of hazardous and/or radioactive components and should allow for low-cost disposal of the final product.

6.1.4.2 Tensile and Compressive Strength of JHCM Glass

A simulation of the Weldon Spring glass, having the same composition as WSM-5 and the glass generated from actual raffinate pit materials, was prepared and then annealed at 525°C for 6 h. Core samples of this glass (cylinders have dimensions of approximately 1.3 cm in diameter and 2.5 cm in length) were submitted for splitting tensile and compressive strength measurements. Results of these tests showed that the glass had an average compressive strength of 43,210 psi (range 40,800 to 45,600 psi) and an

TABLE 6.7. EP Toxicity Concentrations for the JHCM Glass

Compound	JHCM, mg/L	Maximum Allowable, mg/L
Arsenic	<1	5.0
Barium	0.04	100.0
Cadmium	<0.01	1.0
Chromium	<1	5.0
Lead	<1	5.0
Mercury	<0.03	0.2
Selenium	<0.01	1.9
Silver	<0.1	5.0

average splitting tensile strength of 4,300 psi (range 3,925 to 4,645 psi). A comparison of these values with those presented in Section 5.1.5.3 for the ISV-generated glass show that although chemical additives were included in the composition, the JHCM glass had approximately the same mechanical properties. The tensile and compressive strengths of these glasses are higher than those typically reported for cement. Based on these results, direct disposal of the glass into a land fill should be acceptable from a structural integrity point-of-view.

6.2 IMPLEMENTABILITY

This section of the report describes possible alternatives for the treatment of Weldon Spring waste streams using JHCM technology. The waste streams evaluated in this phase of the project were associated with the raffinate pits and included the sludge (following removal of standing water), clay liner, and vicinity soils. Total quantities and physical properties used to estimate processing requirements and project durations are presented in Table 6.8. A description of treating quarry wastes was provided in the first phase of the Weldon Spring evaluation. Additional information concerning this waste stream was not provided, and an update on processing requirements has not been included in this phase of the evaluation.

TABLE 6.8. Estimated Quantities of Weldon Spring Materials

	Volume, m^3	Volume %	Density, kg/L	Wet Wt, mt	Wt% H_2O	Dry Wt, mt	Dry Wt%
Sludge[a]	170,000	58.8	1.2	204,000	76	49,000	21.1
Liner	98,000	33.9	2.1	205,800	23	158,500	68.2
Soil	21,000	7.3	1.5	31,500	21	24,900	10.7
Totals	289,000	100.0		441,300		232,400	100.0

(a) Quantities and properties of raffinate sludge assume standing water has been removed.

The results of the crucible melt tests and the characterization of the glass product discussed in the previous section confirm the effectiveness of JHCM vitrification as a treatment technology for the raffinate pit materials. Technical concerns associated with the processing of these wastes are limited to the selection of bulk materials handling equipment, off-gas scrubbing methods, and the size of the JHCM for the required production rate. A more detailed characterization of materials properties and process effluents will be required to adequately select and size this equipment. In addition, it is recommended that engineering-scale testing be conducted with actual raffinate pit materials to verify crucible melt test results and establish processing rates, energy consumption requirements, off-gas effluents, and glass properties. Experience at PNL has shown that processing data is required to accurately size the JHCM for a desired production rate, and adequately characterize the glass product and process effluents. In this evaluation, it is assumed that each of the waste streams discussed exhibits similar processing characteristics (i.e. the target production rate of 225 MT/d can be met with a JHCM of approximately the same size for each of the processing flowsheets presented). It is also assumed that the large quantities of materials to be treated can be effectively transferred from current locations to a centralized vitrification facility or temporary storage sites and that excavation activities can be scheduled to accommodate these processing scenarios.

6.2.1 Process Flowsheet Alternatives

Flowsheet alternatives for processing Weldon Spring materials were prepared based on the results of the crucible melt tests and the subsequent characterization of the physical properties of the resulting glass. Each of these alternatives is expected to be equally feasible from a vitrification standpoint. The decision to select one alternative over the other will, therefore, have to be based on overall cost, scheduling of site activities, regulatory restrictions, or a combination of these factors.

6.2.1.1 Waste Stream Blending Process Alternative

The compositions of the raffinate pit wastes are compatible with a processing scenario in which each of three waste streams are blended

together. Both the clay liner and the vicinity soils have high concentrations of silica while the raffinate sludge contains alkaline earths. By blending these materials, the total amounts of glass additives required for processing would be reduced in comparison with processing each stream separately, as discussed in the next subsection. An additional advantage of waste blending would be that the composition of the feed stream to the vitrification facility and the glass additive requirements would be consistent throughout the project and the operation of the facility could be optimized for increased efficiency. This option requires, however, increased coordination and complexity of the excavation activity and the material handling requirements. It would require that both raffinate sludge and clay liner/vicinity soil (the composition of these materials are similar and are assumed to be interchangeable) be available for processing at the same time. Standing water in the raffinate pits would be transferred to a storage site, secondary treatment facility, or directly discharged depending on the concentrations of hazardous/radioactive components. Raffinate sludge would then have to be removed from the pits and temporarily stored so that the liner/soil could be excavated (see Figure 6.3). Once removed, the liner/soil would be crushed/delumped, blended with appropriate quantities of sludge and glass additives, and the resulting feed stream would be processed in the JHCM. Based on the glass composition presented in Table 6.2 and current bulk chemical prices, the total cost of glass additives would be approximately $22 million. Processing the total inventories of the raffinate pit wastes shown in Table 6.8, along with the required glass additives, would produce 276,000 MT of glass and would take approximately 4.2 years based on a 225 MT/day melter (250 t/d) and 292 operating days/year.

6.2.1.2 Separate Waste Stream Process Alternative

This alternative was included in the evaluation to accommodate possible scheduling conflicts during site activities. In this scenario, processing would be split into separate campaigns corresponding to the excavation of each of the raffinate pit materials. The processing sequence would be similar to that presented in the previous subsection with the exception of the blending operation. In the first campaign, following the removal of

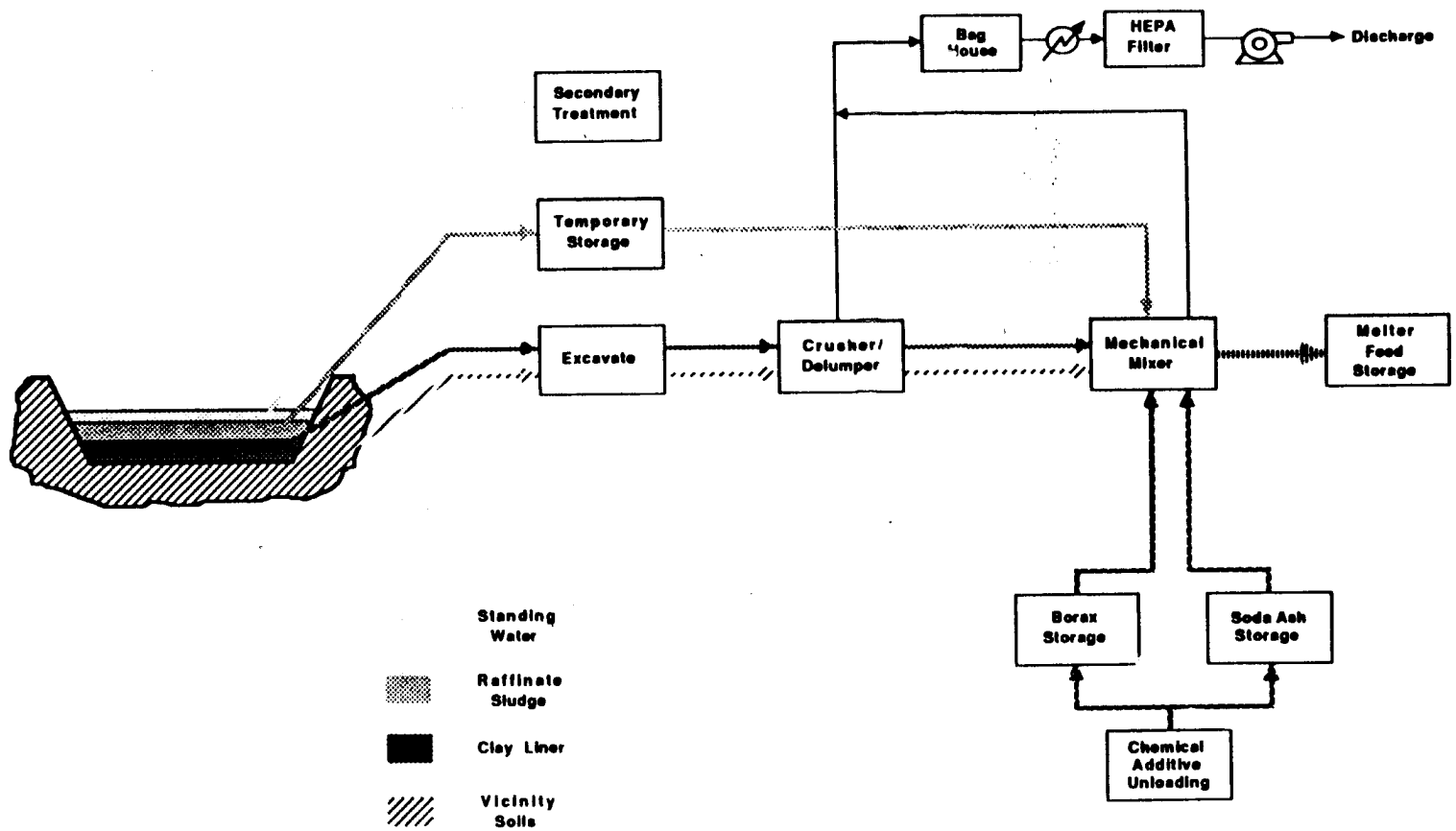

FIGURE 6.3. Process Flowsheet for JHCM Vitrification

standing water in the raffinate pits, the sludge component would be transferred to the vitrification facility, blended with glass additives (SiO_2, Na_2O, and B_2O_3) and processed. Approximately $12.2 million in glass additives would be required; 120,000 MT of glass would be produced over 1.8 years. Clay liner from the raffinate pits would be processed during the second campaign. Following excavation, the liner material would be crush/delumped, blended with glass additives, and processed. The cost of chemicals for this campaign would be $15.5 million, and 195,000 MT of glass would be produced over 2.9 years of operation. Finally, the vicinity soils would be excavated and processed in a manner similar to the clay liner. Cost of glass additives for this campaign would be $2.5 million, and approximately 0.5 years would be required to produce 31,000 MT of glass. Total costs of chemicals for this processing scenario would be on the order of $30.2 million, and 346,000 MT of glass would be produced over a 5.2 years, assuming time required to adapt operations between campaigns is short.

6.2.1.3 Secondary Process Considerations

The secondary process options discussed in this subsection could be applied to either of the flowsheet alternatives presented. Based on information obtained to date, these options should have limited or no impact on the ability to process the Weldon Spring materials or on the quality of the glass product. The emphasis is, therefore, on reducing the overall cost of using JHCM by reducing either capital expenditures or operating costs.

Based on the high moisture content of the raffinate sludge, the large quantities of the material, and the inefficiencies associated with using the JHCM as an evaporator, it is possible that a dewatering step prior to processing could be economically feasible. The basic concept would be to transfer the sludge from the raffinate pits to a dewatering station and reduce the moisture content of the material from 76% to somewhere in the range of 25 to 35%. This operation would removed approximately 34 to 37 million gallons of water from the raffinate sludge without changing the basic composition of the material (see subsection 7.1.1). The incentives for a mechanical dewatering of the sludge would include lower energy requirements during production and a reduction in the amount of liquid in the off-gas

stream that would probably require secondary treatment. Reduced JHCM electrical costs alone would account for about $10 million in savings. The decision on whether to include dewatering as a pretreatment step during operation will be made based on the detailed economic evaluation that is part of the third phase of the project.

The results of the crucible melt tests indicate that a blend of raffinate pit wastes, without chemical additives, can be converted to a glass at a temperature of approximately 1450°C. In order to process this waste stream within the constraints of the JHCM process, the operating temperature of the melter would have to be increased to somewhere in the range of 1500°C to 1800°C. Processing at these temperatures would require limited modifications to the JHCM design. Metal components in contact with the molten glass would have to fabricated from materials such as molybdenum instead of Inconel. In addition, the current refractory materials and the cooling requirements would have to be evaluated. Again, this option would not have a significant impact on the vitrification process other than to possibly increase volatility losses of certain waste components in the melter effluent. It could, however, reduce the costs associated with JHCM processing and produce a more durable glass product. The economic impact of using a high-temperature melter for the treatment of Weldon Spring wastes will be evaluated in the third phase of this project. Cost savings associated with the elimination of chemical additives from the processing flowsheet and the reduction in the total amount of glass produced during the remediation will be compared with the increased capital and operating costs of a high-temperature melter. Potential cost savings associated with high-temperature processing are estimated to be between $10M and $20M

6.3 COST ESTIMATES FOR JHCM OPTION

Cost estimates for vitrifying Weldon Spring materials using the JHCM have been prepared based on the analyses of the raffinate pit materials and the results of the crucible melt tests. The JHCM system and operating costs are estimated for the two options described in Section 6.1: 1) blending of the raffinate sludge, clay liners, and vicinity soils and 2) processing the wastes separately.

6.3.1 Comparative Costs for Chemical Additives

In Phase II, crucible melt tests were performed to establish the quantities and species of chemical additives required to adjust the physical properties of the glass to within JHCM processing constraints. As described in Section 6.1, the crucible tests showed that additions of Na_2O and B_2O_3 were required to lower the melting temperature of the waste while maintaining an acceptable electrical conductivity. These tests also showed that the use of Li_2O lowered the amount of Na_2O required because of the mixed alkali effect. Based on the total quantities of raffinate materials, the use of Li_2O would reduce the total amount of glass produced by almost 10% and would shorten the time required for processing by approximately half a year. However, a comparison of bulk chemical costs revealed that the use of Li_2O would increase chemical additive costs by over 350%. This comparison also showed that the use of B_2O_3 should be minimized because of the higher cost of borax compared to soda ash. Therefore, based on minimizing overall costs soda ash and borax will be specified at a weight ratio of about 7:1.

6.3.2 Equipment Required for JHCM Processing

The processing alternatives presented in Section 6.2 will require essentially the same equipment. The equipment list provided in Table 6.9 is complete for preparing and vitrifying the wastes. Included in the list are equipment needed for size reduction and blending, the vitrification system, glass product handling, and off-gas treatment. Not included are equipment associated with excavation of raffinate pit materials. Total equipment costs are estimated to be $5.5M. This list is also complete for the possible processing of the quarry refuse assuming that large metal materials will be removed at the quarry. A crusher has been included in the equipment list to size-reduce the concrete debris present in the quarry refuse. An assessment will need to be made on the amount of iron rebar present and whether it can be removed from the concrete or sheared and fed to the melter. If shearing is selected, a slight increase in equipment costs will result.

Changes in equipment requirements from the Phase I study include elimination of the option for pouring glass into canisters and additional off-gas

TABLE 6.9. Equipment Required for JHCM Processing

Equipment	Quantity	Unit Cost, $1000	Total Cost, $1000
Bulk Materials Handling			
Raffinate Sludge Transfer Pump	2	15	30
Crush/Delump Unit	1	50	50
Clay Liner/Vicinity Soil Transfer System	1	25	25
Chemical Additive Unloading Station	1	50	50
Chemical Additive Transfer System	3	25	75
Mechanical Mixer	1	50	50
Melter Feed Transfer System	1	25	25
Melter Feed Storage Silo	1	25	20
Melter Feed Transfer System	1	25	25
Dust Abatement System	1	150	150
Melter Feed System			
Melter Feed Storage Hopper	1	25	25
Rotary Valve	1	15	25
Joule-Heated Ceramic Melter			
Melter	1	4500[a]	4500[a]
Off-Gas Treatment System			
Quench Scrubber	1	50	50
Scrub Solution Recycle System	1	35	35
Roughing Filter	1	25	25
Heat Exchanger	1	25	25
HEPA Filter	1	15	15
Concentrator	1	50	50
Blower	1	150	150
Glass Handling System			
Glass Quencher	1	50	50
Heat Exchanger	1	25	25
Fritted Glass Transfer System	1	25	25
TOTAL EQUIPMENT COST:			$5,500

(a) Value is total cost of JHCM system including transformers.

equipment to handle a higher sulfur content in the raffinate pit wastes.(a) Elimination of the option for pouring glass into canisters is based on the high physical (compressive and tensile) strength of the glass and plans to dispose of the glass on site, disposing of the glass product as cullet is preferred. Significant costs savings will be realized, and the disposal of the glass will be comparable to other treatment technologies being considered. In addition, because of the high quality of the glass product, the increase in glass surface area should not lead to an increase in release rate sufficient to result in a disposal concern.

The sulfur content in the raffinate sludge wastes sent to PNL for testing was significantly higher than previous documentation (Bechtel National, Inc. 1987). To account for the potential volatilization of sulfur from the JHCM, a wet scrubber has been included to the off-gas treatment train. If the sulfur concentration is found to be high, the result will likely be the generation of an amount of secondary chemical waste. Recommended small-scale JHCM tests and Phase III flowsheet studies will further define the potential impact of a high sulfur content.

Costs associated with each piece of equipment are based on information obtained from equipment suppliers and engineering experience. Expansion of the equipment list, including size requirements and price ranges, is planned to be provided in the third phase of the project. The JHCM size has been decreased from a 360 MT/d unit to a 225 MT/d unit as a result of the Phase II test results and additional engineering analysis. This change will reduce capital equipment costs while still maintaining the same duration to process the Weldon Spring wastes.

6.3.3 JHCM Capital Costs

Capital costs for the JHCM option were prepared using standard estimating practices and are provided in Table 6.10. A total systems cost of

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(a) The true sulfur content of the raffinate pit sludge wastes is felt to be undecided. As a result, the actual off-gas treatment requirements will require additional refinement following later characterization of the raffinate pit sludge.

TABLE 6.10. Capital Cost Summary for JHCM

Capital Equipment Costs	Costs ($1000)
Bulk Materials Handling Equipment	500
Melter Feed System	50
Joule-Heated Ceramic Melter	4500
Off-Gas Treatment System	350
Glass Handling System	100
TOTAL PURCHASED EQUIPMENT COSTS (PE)	$5,500
Purchased-equipment Installation (33% of PE)	1,800
Instrumentation & Control (15% of PE)	850
Process Piping (12% of PE)	650
Electrical (20% of PE)	1,100
Auxiliaries (20% of PE)	1,100
Building & Facilities (40% of PE)	2,200
Site Preparation (10% of PE)	550
Contingency (20% of PE)	1,100
Fees and Engineering Contingency (25% of PE)	1,400
TOTAL CAPITAL COSTS	$16,250

of low-level radioactive materials. The auxiliaries and facility cost additive factors of 20 and 40%, respectively, assume the facility can be built using standard practices for chemical plant structures with additional requirements for ventilation, filtration, and monitoring equipment.

6.3.4 JHCM Operating Costs

Projected operating costs for the JHCM flowsheets discussed in Section 6.2 are presented in Table 6.11. Costs associated with the operation of the vitrification facility include the cost of bulk chemicals (borax and soda ash), utilities, and labor. The labor costs include operating personnel for three shifts per day, a plant manager, maintenance personnel, clerical staff, and overheads. It was assumed for this evaluation that the vitrification facility would operate seven days per week, 365 days per year, with an

TABLE 6.11. Operating Cost Summary for JHCM

	Wastes Processed Separately[f]				
	Raffinate Sludge	Clay Liner	Vicinity Soil	Total If Processed Separately	Total If Blended
Material Dry Weight, MT	49,000	158,000	25,000	232,000	232,000
Chemical Additives Required, MT	103,000	82,000	13,000	198,000	115,000
Glass Produced, MT	120,000	195,000	31,000	346,000	276,000
Cost of Chemical Additives, $\$10^6$[a]	12.2	15.5	2.5	30.2	21.7
Processing Duration, yr[b]	1.8	2.9	0.5	5.2	4.2
Utilities Cost, $\$10^6$[c]	20.4	15.7	2.5	38.6	34.4
Labor Cost, $\$10^6$[d]	1.8	2.9	0.5	5.2	4.2
Total Operating Cost, $\$10^6$[e]	34.4	34.1	5.5	74.0	60.3

(a) Chemical additive costs based on bulk prices as reported in "ChemicalMarketing Reporter," Vol No. 11, March 13, 1989.
(b) Processing duration based on 225 MT/day and 80% operating efficiency.
(c) Utilities costs based on electricity charges of 6¢/kWh.
(d) Labor costs have been rounded to $1M/yr.
(e) Total operating costs = chemical additive cost + utilities cost + labor cost.
(f) Projected costs for processing wastes separately are based on adjusting each waste to a compo similar to that reported in Table 6.1.

on-line efficiency of 80%. Costs associated with the start-up of the facility were not included but are assumed to be insignificant. Electrical costs included as part of the utilities costs are based on an electricity rate of 6¢/kWh. The optimum alternative is to process a blended waste stream to the JHCM. Treatment would be completed in about four years at an operating cost of $60M. If it is necessary to treat the wastes separately, operations will last about five years at a cost of $74M.

Details on operating costs to treat the quarry refuse are also given in Table 6.11. Without additional details on the makeup of the quarry refuse, we have assumed that the material will be compositionally similar to the Weldon Spring soil. This is a good assumption given that a majority of the quarry refuse will be fill dirt. Treating the quarry refuse will take about 2 years at a cost of approximately $19M.

6.3.5 JHCM Cost Summary

Based on the results of the Phase II study, the use of the JHCM process to treat the raffinate pit sludge, clay liners, and vicinity soils will cost

a minimum of $76M if the wastes are blended and $90M if the wastes are processed separately. Including the estimated cost for treatment of quarry refuse ($19M), the remediation the Weldon Spring site using JHCM will cost between $95M and $109M (unit volume cost of $263/m^3 to $301/m^3). There will be some additional costs incurred to demolish and dispose of the treatment facility and equipment. Also not included in the estimate is a significant cost reduction expected to be realized (estimated to be $10M) by the dewatering of the raffinate sludge. Other cost reduction options, such as using a high-temperature melter, will be evaluated during Phase III.

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