In Situ Vitrification of Oak Ridge National Laboratory Soil and Limestone

J. G. Carter
S. O. Bates
G. D. Maupin

March 1987

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

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or Battelle Memorial Institute.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

3 3679 00061 4463

IN SITU VITRIFICATION OF OAK RIDGE
NATIONAL LABORATORY SOIL AND LIMESTONE

J. G. Carter
S. O. Bates
G. D. Maupin

March 1987

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

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Process feasibility studies were successfully performed on two different developmental scales to determine the technical application of in situ vitrification (ISV) (Oma et al. 1983) to Oak Ridge National Laboratory (ORNL) intermediate-level waste.^(a) In the laboratory, testing was performed on crucibles containing quantities of 50% ORNL soil and 50% ORNL limestone. In the engineering-scale testing, a 1/12-scaled simulation of ORNL Trench 7 was constructed and vitrified, resulting in waste product soil and limestone concentrations of 68% and 32%, respectively.

Results from the two scales of testing indicate that the ORNL intermediate-level waste sites may be successfully processed by ISV; the waste form will retain significant quantities of the cesium and strontium. Because ^{137}Cs is the major component of the radionuclide inventory in the ORNL seepage pits and trenches, final field process decontamination factors (i.e., off gas at the ground surface relative to the waste inventory) of 10^4 are desired to minimize activity buildup in the off-gas system. These values were realized during the engineering-scale test for both cesium and strontium. The vitrified material effectively contained 99.996% of the cesium and strontium placed in the engineering-scale test. This is equivalent to decontamination factors of greater than 10^4 . Volume reduction for the engineering-scale test was 60%. No migration of the cesium to the uncontaminated surrounding soil was detected. These favorable results indicate that, once verified in a pilot-scale test, an adequately designed ISV system could be produced to treat the ORNL seepage pits and trenches without excessive activity accumulation in the off-gas treatment system.

(a) Work performed under Contract DE-AC06-76RLO 1830 for the U.S. Department of Energy.

ACKNOWLEDGMENTS

Pacific Northwest Laboratory (PNL) gratefully acknowledges Oak Ridge National Laboratory (ORNL) for providing the opportunity to perform this feasibility study. We especially appreciate the enthusiastic support of Brian Spalding, research staff member of ORNL's Environmental Sciences. We would like to thank Jim Buelt and Mike Longaker for their technical assistance in test preparation, test operations, and data collection and evaluation.

Frank Hara and their respective staffs were invaluable in providing high-quality laboratory studies and analytical services to the program.

CONTENTS

SUMMARY	iii
ACKNOWLEDGMENTS	v
1.0 INTRODUCTION	1
2.0 CONCLUSIONS	3
3.0 PROCESS DESCRIPTION	5
4.0 TEST DESCRIPTIONS	7
4.1 LABORATORY TESTS	7
4.1.1 Composition and Physical Properties	7
4.1.2 Melting Properties	8
4.1.3 Estimate of Volume Reduction	12
4.1.4 Devitrification	12
4.1.5 Chemical Durability	16
4.2 ENGINEERING-SCALE TEST DESCRIPTION	20
5.0 ENGINEERING-SCALE TEST RESULTS AND ANALYSIS	27
6.0 REFERENCES	35

FIGURES

1	Operating Sequence of In Situ Vitrification System	5
2	Viscosity Behavior of Oak Ridge National Laboratory Subsoil as a Function of Temperature	9
3	Viscosity Behavior of 50/50 Soil/Limestone as a Function of Temperature	10
4	Electrical Conductivity of Oak Ridge National Laboratory In Situ Vitrification Soil and 50/50 vol% Soil and Dolomite	11
5	Estimated Cool-Down Rate at the Face of an In Situ Vitrification Monolith and Heat Treatment Used on 50/50 Soil/Dolomite	13
6	X-Ray Diffractometry Results for Oak Ridge National Laboratory Dolomite	14
7	X-Ray Diffractometry Results of Devitrified Oak Ridge National Laboratory 50/50 Soil/Dolomite	15
8	Heat-Treated 50/50 Oak Ridge National Laboratory Soil/Dolomite MCC-1 Test Results Compared to PNL76-68 Glass	18
9	Heat-Treated 50/50 Oak Ridge National Laboratory Soil/Dolomite Elemental Concentrations from MCC-3 Tests as a Function of (SA/V) Time	19
10	Engineering-Scale Test Assembly	21
11	A-Phase and B-Phase Volts Versus Run Time	24
12	A-Phase and B-Phase Amps Versus Run Time	25
13	A-Phase and B-Phase Kilowatts Versus Run Time	25
14	Temperature of the 0.15-, 0.25-, 0.41-, and 0.56 in Thermocouple Versus Run Time	26
15	Off-Gas Sample System for Engineering-Scale Oak Ridge National Laboratory Test	28
16	Projected Amount of Cesium and Strontium in the Off-Gas System Based on Off-Gas System Sample Analysis	30
17	Heat-Treated 68/32 Soil/Dolomite MCC-1 Test Results Compared to PNL76-68 Glass	32

18	Comparison of Engineering-Scale Soil/Limestone to Laboratory Soil/Limestone	33
----	--	----

TABLES

1	Scales of Testing Units for Developing Technology	1
2	Chemical Composition of Oak Ridge National Laboratory Materials as Determined by Inductively-Coupled-Plasma Analysis	8
3	Immersion Density of Oak Ridge National Laboratory In Situ Vitrification Materials	12
4	Predicted and Actual Data Obtained from In Situ Vitrification Oak Ridge National Laboratory Engineering-Scale Tests	23
5	Scrub System Sample Analysis	29
6	Normalized Chemical Analysis of a Single Core Sample from Engineering-Scale Test	30

1.0 INTRODUCTION

Pacific Northwest Laboratory (PNL) has successfully performed laboratory and engineering-scale tests of the in situ vitrification (ISV) process on actual Oak Ridge National Laboratory (ORNL) soil and limestone. In situ vitrification is an emerging in-ground thermal treatment technology that fixes radioactive contamination in soil by converting it to glass and crystalline waste form.

PNL began developing ISV technology in 1980 under contract to the U.S. Department of Energy (DOE) (Brouns, Buelt, and Bonner 1983). Since that time, numerous experimental tests using a variety of conditions and waste types have been conducted (Oma et al. 1983; Timmerman and Oma 1984; Timmerman et al. 1983). A large-scale ISV unit was designed, fabricated, and tested (Buelt and Carter 1986). The large-scale unit was designed for processing transuranic-contaminated soil, but the design is adaptable to a variety of waste types (Buelt and Freim 1986), including Oak Ridge contaminated seepage pits and trenches.

Table 1 describes the different scales of testing units that PNL used in developing ISV technology. The successful results of 47 bench-, engineering-, pilot-, and larger-scale tests proved the feasibility of the process. Economic studies indicate that tremendous economies of scale are attainable with the ISV process (Oma et al. 1983).

TABLE 1. Scales of Testing Units for Developing Technology

<u>Equipment Size</u>	<u>Electrode Separation</u>	<u>Block Size</u>	<u>Tests Completed(a)</u>
Bench-Scale	4 in.	1 to 20 lb	4
Engineering-Scale	9 to 15 in.	100 lb to 1 ton	25
Pilot-Scale	3 to 4 ft	10 to 50 tons	14
Large-Scale	11 to 18 ft	400 to 800 tons	4

(a) As of July 1986.

The objective of this study is to provide technical support for ISV technology application to ORNL intermediate-level waste. Evaluation areas of ORNL soil/limestone were composition and physical properties, melting properties, volume reduction, crystal structure/devitrification, and chemical durability. Another important objective was determining cesium and strontium retention in the vitrified soil under conditions representative of actual ORNL sites. The evaluation of the test results has indicated the feasibility of the process to vitrify the ORNL wastes.

2.0 CONCLUSIONS

Process feasibility studies were successfully performed on two different processing scales to determine the technical support for ISV technology application to ORNL intermediate-level waste. In addition, analysis of the data from the two test scales provided the following conclusions regarding the performance of the ISV process as applied to ORNL soil and limestone found in the ORNL trenches and seepage pits.

- The evaluation of the ORNL soil, limestone, off-gas scrub system, off-gas high-efficiency particulate air (HEPA) filter and core samples from the vitrified mass confirm that ISV application is technically feasible.
- Soil to off-gas decontamination factors (DFs) as determined by the engineering-scale testing is 2.6×10^4 for cesium and 2.7×10^4 for strontium. These are equivalent to cesium and strontium retention values in the molten soil of 99.996%. Quantities of cesium and strontium tested in the engineering-scale were several orders of magnitude higher than those present in ORNL trenches and seepage pits.
- Volume reduction of greater than 40% may be expected. Volume reduction for the engineering-scale test was 60%, eliminating concern for future subsidence.
- The soil-to-limestone ratio of the vitrified mass for the engineering scale test was 68 wt% soil to 32 wt% limestone. This improves durability significantly over that originally projected in the laboratory tests because of the reduced tendency to devitrify and the higher silica content.
- No migration of cesium was detected to the uncontaminated surrounding soil. The same behavior is expected for strontium although not analytically determined.
- The dissolution rates at 90°C as determined by MCC-1 (1986) testing of the vitrified mass sample is equal to or less than those of

PNL76-68 high-level waste glass. In addition, once the ISV vitrified product has cooled, the anticipated storage temperature would be essentially ambient ground temperature, and dissolution rates could be as much as one or two orders of magnitude lower.

The laboratory and engineering-scale testing indicated the potential for ISV to treat the trenches and seepage pit at the ORNL contaminated waste sites. Based on the results of these feasibility tests, adequate technical bases are available to proceed with a pilot-scale demonstration on a simulated trench at ORNL.

3.0 PROCESS DESCRIPTION

The ISV process as applied to contaminated soil stabilization involves the insertion of electrodes into the soil, typically in a square array. A starter path for electric current is established by using a small amount of a graphite and glass frit mixture placed between the electrodes on the soil surface. Dissipation of power through the starter material creates temperatures high enough to melt a layer of soil, establishing a molten, conductive path. This molten zone continues to grow downward and encompasses the contaminated soil. Rocks (if present), which are less dense, create a floating layer near the molten surface. The rocks are eventually incorporated into the molten mass.

Figure 1 illustrates the process sequence. At the high temperatures (approximately 1600°C) created, organic materials pyrolyze, diffuse to the surface, and combust. This movement of gas through the melt may produce some porosity near the surface of the melt. Any off gases from the process are collected, treated, and monitored to ensure their environmentally safe release. Remaining ash, along with other noncombustible materials, dissolves or becomes encapsulated in the molten soil. Natural convective currents within the molten soil help distribute the stabilized materials uniformly. The molten soil cools to a durable glass and crystalline waste form resembling natural obsidian or basalt.

FIGURE 1. Operating Sequence of In Situ Vitrification System

The principles of the ISV operation are based on extensive joule-heated melter work performed at PNL for various nuclear waste immobilization projects (Buel et al. 1979). The joule-heating principle operates by internal resistance heating of the conducting material as an electric current passes through the molten media. In ISV, the resistance decreases as the molten mass grows. To maintain a power level high enough (according to the formula $P = I^2R$) to continue melting more soil, the current must be increased. To accomplish the variable current during ISV processing, a power transformer with multiple voltage taps is used. At startup, the ISV process requires a high voltage potential and low amperage. As the melt progresses and resistance decreases, the lower voltage taps on the power transformer allow increased amperage to the melt, maintaining a high power level. The process will continue until heat losses from the melt approach the energy delivered to the molten soil via the electrodes or until power is discontinued to the melt.

A hood over the vitrification zone is maintained under a slight negative pressure to contain any hazardous gases or particulates that may be released. The hood also provides support for the electrodes. The negative pressure on the hood is supplied by the off-gas treatment system, which scrubs and filters any potentially hazardous components from the off-gas stream.

4.0 TEST DESCRIPTIONS

This section describes the laboratory and engineering-scale ISV testing of ORNL soil and limestone, the associated off-gas sampling equipment, and the specific test setup and operations used for both tests.

4.1 LABORATORY TESTS

To determine whether ISV could be used on ORNL soil, laboratory testing was conducted to evaluate the physical and melting characteristics of the ORNL soil, limestone, and a 50 vol% soil/50 vol% limestone mixture. Since the trenches are filled with limestone backfill, the 50/50 ratio was selected for product evaluation and characterization and to simulate a worst-case scenario. Because the primary duty of the ISV waste form is the containment of the waste components, a preliminary evaluation was made of the chemical durability of the predicted ISV product. The following characteristics and properties of ORNL subsoil, limestone (dolomite), and 50/50 soil/limestone glass were investigated:

- composition and physical properties
- melting properties
- crystal structure/devitrification
- chemical durability
- estimate of volume reduction.

4.1.1 Composition and Physical Properties

Samples of ORNL soil and limestone were submitted for chemical analysis by inductively coupled plasma atomic emission spectroscopy (ICP). The ORNL soil and limestone samples were heated to 1000°C for 16 hours to remove water and carbonates prior to analysis. The results are presented in Table 2 as normalized weight percent and mole percent. The soil was comprised primarily of silica and alumina. The relatively low concentrations of alkalis and alkaline earths explain the soil's high temperature melting point and viscosity and low electrical conductivity properties reported later. The ORNL "limestone" contained the equivalent of approximately 37 wt% magnesium oxide. The ICP analysis, along with x-ray diffraction (XRD) data that are presented later,

TABLE 2. Chemical Composition of Oak Ridge National Laboratory Materials as Determined by Inductively-Coupled-Plasma Analysis (all materials fired at >1000°C for 16 hours to remove water and carbonates)

Oxide	ORNL Sub-Soil		ORNL Dolomite		50 vol%/50 vol% Soil Dolomite	
	wt %	mole %	wt %	mole %	wt %	mole %
Al ₂ O ₃	18.79	12.38	1.55	0.76	12.36	7.21
B ₂ O ₃	0.08	0.08	0.08	0.06	0.06	0.05
BaO	0.05	0.02	0.01	0.00	0.13	0.05
CaO	1.57	1.88	49.67	44.07	20.09	21.29
Fe ₂ O ₃	6.48	2.73	0.58	0.18	4.29	1.60
Li ₂ O	0.02	0.05	0.04	0.07	0.00	0.00
MgO	3.01	5.03	37.00	45.73	15.76	23.24
MnO ₂	0.21	0.08	0.01	0.00	0.09	0.03
Na ₂ O	0.61	0.66	0.07	0.06	0.45	0.43
SiO ₂	68.23	76.31	10.87	9.01	46.17	45.67
SrO	0.01	0.01	0.02	0.01	0.01	0.01
TiO ₂	0.88	0.74	0.04	0.03	0.56	0.41
ZrO ₂	0.06	0.03	0.06	0.02	0.03	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00

indicated that the ORNL limestone was magnesium-calcium-carbonate, i.e., dolomite. Examination of the concentrations of SiO₂ and CaO revealed that weight percent concentrations of soil and limestone in the 50/50 mixture are 62% soil and 38% limestone. The weight percentages differ from the volume percentage because of different weight losses upon heating and different bulk densities of the two components.

4.1.2 Melting Properties

A sample of ORNL soil was placed in a Pt crucible and heated to 1650°C in air. The fusing temperature of the pure soil was observed to be between 1200°C and 1400°C. Some tendency toward melt foaming was observed above 1400°C. Soil heated to 1650°C and quenched to room temperature appeared vitreous with no observed devitrification. The viscosity behavior of this resulting glass is represented in Figure 2. The temperature at which the viscosity is 100 poise

Viscosity Data: ORNL ISV Soil
 Sample: ISV Soil 22-Feb-86 GLG Solndle Factor: 9.39

Temperature, °C	1/K x 10 ⁴	Read.	Speed	Poise	Log Viscosity
1648	5.21	60	3.0	188	2.274
1597	5.35	87	3.0	272	2.435
1547	5.49	71	1.5	444	2.648
1497	5.65	48	0.6	751	2.876

FIGURE 2. Viscosity Behavior of Oak Ridge National Laboratory Subsoil as a Function of Temperature

(T100P) is above 1650°C (the maximum temperature of the furnace used in this study) and is extrapolated to be 1720°C. The smooth viscosity curve suggests the pure soil produces a glass with little tendency toward devitrification over the temperature range measured.

To estimate the melting composition and conditions of the ORNL ISV site, a layered mixture of 50 vol% soil and 50 vol% -20/+100 mesh dolomite (soil on top) was placed in a platinum/rhodium crucible and held at 1000°C for 16 hours to release off gas and avoid melt foaming. The sample was then heated to

1600°C at 200°C/hour and held for 0.5 hour. The melt was removed from the furnace and air-quenched to room temperature. Optical microscopy of thin sections of the glass revealed that a predominantly glassy product had been produced with virtually all of the dolomite being incorporated into the glass. The oxide composition of the laboratory-scale glass was determined by ICP and is shown in Table 2.

The viscosity behavior of the laboratory-scale glass as a function of temperature is shown in Figure 3. Observed instabilities in the viscosity at constant temperature indicated that this mixture had a ready tendency toward

Viscosity Data: ORNL ISV Soil I					
Sample: 50/50 28-Feb-86 GLG			Spindle Factor: 9.39		
Temperature, °C	1/K × 10 ⁴	Read.	Speed	Poise	Log Viscosity
1482	5.70	33	60.0	5	0.713
1385	6.03	63	60.0	10	0.994
1333	6.23	75	30.0	23	1.371
1262	6.51	65	6.0	102	2.007

FIGURE 3. Viscosity Behavior of 50/50 Soil/Limestone as a Function of Temperature

devitrification. The T100P of the glass was determined to be 1265°C, significantly lower than pure soil, indicating a lower ISV processing temperature with the mixture. Crystalline material was observed in fibers pulled from the melt at temperatures as high as 1350°C while the bulk of the melt was quite fluid. Devitrification can be avoided, however, by increasing the silica content from higher soil concentrations, as achieved in the subsequent engineering-scale test.

The electrical conductivity behavior of melts of pure solid and the laboratory-scale melt were measured as a function of temperature using a two-probe method (Chick et al. 1984). Figure 4 shows that the laboratory-scale glass was approximately 25 times more conductive than pure soil at 1500°C. However, at the temperatures corresponding to 100 poise melt viscosity (1265°C for 50/50 soil/dolomite, 1720°C for soil), the electrical conductivities were nearly equal at about $0.035 \text{ (ohm}\cdot\text{cm)}^{-1}$.

FIGURE 4. Electrical Conductivity of Oak Ridge National Laboratory In Situ Vitrification Soil and 50/50 Vol% Soil and Dolomite

4.1.3 Estimate of Volume Reduction

Immersion density determinations were performed on the dolomite, vitrified soil, air quenched (vitreous) 50/50 soil/dolomite, and heat-treated (devitrified) 50/50 soil/dolomite. The results are listed in Table 3. Since the pack densities of the dolomite and soil were approximately 1.6 g/cm^3 and the resulting density of 50/50 soil/dolomite glass was approximately 2.9 g/cm^3 , the ISV process could be expected to result in a volume reduction of approximately 45%. Devitrification of the soil/dolomite glass resulted in a 3% volume reduction. The devitrification of glass can produce volume changes that often result in microcracking, shrinkage voids, and a general increase in surface area. Since elemental release from a waste form is a function of the exposed surface area, the chemical durability of the ISV product may be adversely affected.

4.1.4 Devitrification

To obtain some indication of the devitrification characteristics of the 50/50 soil/dolomite glass, a sample was heat treated at 1000°C for 8 hours in air. This resulted in nearly complete devitrification of the glass sample.

Since a large ISV melt requires a long time to cool, the devitrification behavior of the 50/50 glass was investigated under more representative conditions. An air-quenched sample was subjected to a 200-hour heat treatment. The heat treatment, represented in Figure 5, approximates the anticipated cool-down rate at the face of an actual full-scale ISV monolith. The heat-treated sample appeared to be nearly 100% crystalline. Large prismatic crystals were apparent on the surface of the sample and were found to extend throughout the bulk. Other crystalline phases and some void space occupied the areas between the prismatic crystals.

TABLE 3. Immersion Density of Oak Ridge National Laboratory In Situ Vitrification Materials

<u>ISV Materials</u>	<u>Density, g/cm^3</u>
Dolomite	2.82
Subsoil	2.49
50/50 Soil/Dolomite (vitrified)	2.88
50/50 Soil/Dolomite (devitrified)	2.96

FIGURE 5. Estimated Cool-Down Rate at the Face of an In Situ Vitrification Monolith and Heat Treatment Used on 50/50 Soil/Dolomite

Samples of the dolomite and devitrified 50/50 soil/dolomite were submitted for powder XRD analysis. Figures 6 and 7 represent the position and relative intensity of the resulting diffraction peaks. Standard XRD patterns are also represented for comparison. The locations of the main peaks in Figure 6 confirm that the ORNL limestone is actually dolomite $[\text{CaMg}(\text{CO}_3)_2]$ containing some quartz.

The XRD pattern for the devitrified 50/50 soil/dolomite (Figure 7) is more complex. Several crystalline phases are present. Identification of the specific crystalline phases is difficult since there are a whole series of solid solutions permissible in the Ca, Mg, Al, Fe silicate system. The major crystalline phase appears to be very similar in structure to fassaite, which is a diopside mineral ($\text{CaMgSi}_2\text{O}_6$) with some substitution of aluminum for magnesium and silicon. Iron, as well as aluminum, can substitute for some of the calcium, magnesium, and/or silicon in diopside. Some differences between the

FIGURE 6. X-Ray Diffractometry Results for Oak Ridge National Laboratory Dolomite

FIGURE 7. X-Ray Diffractometry Results of Devitrified Oak Ridge National Laboratory 50/50 Soil Dolomite

observed XRD pattern and the reference fassaite pattern can be explained in terms of these substitutions. The "extra" peaks indicate the presence of other minor crystalline phases, possibly enstatite (MgSiO_3).

Scanning electron microscopy with energy-dispersive x-ray (SEM/EDX) analysis of the devitrified 50/50 soil/dolomite glass confirmed the presence of diopside and enstatite and revealed a potassium-alumino-silicate phase. The potassium phase is of special interest because cesium, the main radionuclide of concern, is expected to behave much like potassium.

4.1.5 Chemical Durability

Due to the long cooling time necessary for a large ISV melt, the resulting product may be devitrified as indicated by heat treatments of a laboratory-scale sample. Because the chemical durability of such a devitrified product is less predictable than for a glassy product, chemical durability testing was performed on samples that were heat treated at the same cool-down rates anticipated for an actual ISV monolith. Incongruent dissolution of a multiphased material is much more likely than for a homogeneous glassy material. Consequently, relatively subtle changes in heat treatment or composition could conceivably result in significant changes, crystalline devitrification products, and thus potentially in the release rates of some elements. For this preliminary work, however, MCC-1 (1986), MCC-3 (1986), and a modified MCC-3 powder test were used to evaluate the chemical durability of the heat-treated laboratory-scale soil/dolomite. All leaching tests were conducted at 90°C using deionized water.

To allow for direct comparison of data, the leachate, temperature, and surface area/volume (SA/V) used in testing the ISV laboratory-scale soil product were the same as those parameters used to test high-level waste borosilicate glasses. The differences in application (repository conditions and curie concentrations) and the nature of the waste forms themselves (multiphased, inhomogeneous ceramic versus single-phased glass) make such comparison difficult and perhaps inappropriate. The results presented here should be regarded as preliminary. Further testing for long-term storage conditions are required to fully assess the ISV product as a suitable waste form.

The results are given in terms of normalized elemental mass release which is 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)

F_i = fraction of element i in glass (dimensionless)

SA = surface area of monolith (m^2).

Elemental release values for the devitrified laboratory-scale soil product vary significantly, suggesting incongruent dissolution is occurring. In an inhomogeneous system such as the devitrified laboratory-scale ISV soil product, incongruent dissolution is expected. As reported earlier, XRD and SEM/EDX analyses identified the presence of diopside (Ca, Mg, Al, silicate), enstatite (Mg silicate), and a potassium-alumino-silicate phase in heat-treated laboratory-scale ISV product. The strontium- and cesium-bearing phases were not identified. The different dissolution rates of the individual mineral phases (and exposed surface areas of each of those phases) are reflected in the varying normalized elemental release values in Figure 8. Normalized strontium release from the laboratory-scale ISV soil is 10 to 100 times that of PNL76-68 glass. Potassium release from the laboratory-scale soil/dolomite ISV product is at least a factor of two higher than the cesium release observed for PNL76-68 glass. These release rates need to be evaluated with regulatory criteria to determine whether silica or soil additives are necessary for anticipated 50/50 soil/limestone mixtures.

Solubility of certain elements, particularly Si, has a significant effect on apparent dissolution rates. As the concentration of Si increases, the dissolution rate slows as the leachant becomes saturated with respect to Si. One way to observe the solubility effects in a waste form/dissolution system is to monitor changes in elemental concentrations (in the leachate) as a function of time. However, some solubility effects do not become apparent until after very

FIGURE 8. Heat-Treated 50/50 Oak Ridge National Laboratory Soil/Dolomite MCC-1 (Monolith) Test Results as Compared to PNL-76-68 Glass

long times. The concept that dissolution progress is a function of the SA/V ratio of the sample multiplied by test duration, $(SA/V) \cdot \text{time}$, can be used to observe these solubility effects in a reasonable amount of time.

Figure 9 is a log/log plot of normalized elemental concentration as a function of $(SA \cdot \text{time})/V$ for the laboratory-scale soil ISV product tested under modified MCC-3 conditions.^(a) Note that on a log/log plot, lines having unit slope represent constant rate of change, and lines having zero slope represent no apparent change. The "Y" intercept (at $\log [(SA \cdot \text{time})/V] = 0$) of a line having unit slope and going through any point on a functional curve will represent the average functional rate at that point. Incongruent dissolution is again apparent. The normalized elemental values do not lie near a single line; but the normalized release of Si, Al, and K parallel each other up to the point where Si and Al reach saturation and their elemental concentration levels out.

(a) Modifications included testing at various SA/V ratios with successive sampling and replenishing of the test solution.

FIGURE 9. Heat-Treated 50/50 Oak Ridge National Laboratory Soil/Dolomite Elemental Concentrations from MCC-3 (Powder) Tests as a Function of (SA/V)•Time

Potassium concentrations continue to rise at very high (SA•time)/V values, indicating that dissolution has not stopped but has slowed greatly.

Since the ISV product will be near the surface (not in a deep geological repository), flow rates will probably be relatively high. In this case, the initial (forward) release rate will be most important. The forward rate for potassium from the soil ISV product is seen to be about 10 normalized g/m². The forward rate for strontium is between 10 and 100 g/m². The concentration of strontium in the leachate (due to the low level in the waste form) is near the detection limit for strontium using ICP, resulting in increased uncertainty in the data. As a point of reference, the 76-68 glass forward matrix dissolution rate is about 1 g/m². Again, comparison to regulatory criteria is necessary to determine whether an ISV waste form without durability additives is appropriate for this application.

In addition to the MCC-3 data, the MCC-1 data from Figure 8 are also represented in Figure 9. The (SA/V) ratio, based on geometric measurements of the bulk monolith, is specified to be 10 m^{-1} for an MCC-1 test. At 28 days, this corresponds to an (SA·time)/V of $280 \text{ d}(\text{m}^{-1})$ (see the shaded data to the left on Figure 9). The monolith data do not "fit" well. A much better fit is observed if the data are moved to the right corresponding to about a factor of 100 increase in SA/V. Although porosity measurements have not been performed, macroscopic observation reveals large shrinkage voids in the monoliths of the devitrified ISV product that was tested. Coupled with the high density of micropores (approximately $0.5 \text{ }\mu\text{m}$ in diameter) observed by SEM, the resulting increase in the monolith surface area may actually account for an effective increase of approximately 100 times in true surface area as compared to the geometric surface area. Under forward rate conditions, elemental release is proportional to exposed surface area. This would equate to a 100-fold increase in elemental release above what might be calculated, based on geometric surface area. This effective increase in exposed surface area may explain the 10- to 100-fold increase in releases of cesium and strontium.

It is important to note that these tests were conducted at 90°C . Once the ISV product has cooled, the anticipated storage temperature would be essentially ambient ground temperature. Dissolution rates could be as much as two orders of magnitude lower making the ISV waste form equivalent to the PNL76-68 high-level waste form. The leach data presented here apply only to 50/50 soil/limestone waste forms. Higher soil concentrations improve leach resistance of cesium and strontium. Based on this analysis and the lack of firm regulatory criteria on which to evaluate the ISV waste form, no apparent reason was identified for the use of durability additives for the engineering-scale test.

4.2 ENGINEERING-SCALE TEST DESCRIPTION

The engineering-scale ISV test was performed on a 1/12-scale simulation of the ORNL Trench No. 7 without durability additives. The trench simulation contained actual ORNL soil and limestone supplied to PNL by ORNL. The limestone was crushed to $-1/4 \text{ in.}$, scaled to actual trench material. The vitrification test took place within a 2.4-m high by 1.8-m (8 ft by 6 ft) diameter aluminum

corrugated container. The engineering-scale power supply system consisted of a 30-kW Scott-Tee-connected transformer. The transformer has 16 voltage taps and is wired for secondary control with saturable reactors (Oma et al. 1983).

The engineering-scale test trench was constructed as shown in Figure 10. To avoid influence with the Hanford soil filler material, the ORNL soil was placed inside a metal ring 0.91-m in diameter and 0.74-m deep (36 in. by 29 in.). Thermocouples were placed at various increments to a depth of 0.56 m. Hanford soil was placed below and around the metal retaining ring. ORNL soil was placed inside of the metal ring to a depth of 0.45 m (17-3/4 in.). At the 0.45-m depth, a blended mixture of 1220 g Cs_2CO_3 and 2780 g $\text{Sr}(\text{OH})_2$ was placed in a 0.30-m (12 in.) square by 0.04-m (1-3/4 in.) deep. These amounts, which were much higher in mass concentration than would be expected at the actual

FIGURE 10. Engineering-Scale Test Assembly

ORNL Trench No. 7, were based on detectability of cesium and strontium in the scrub solution and waste form. Wooden forms were then assembled to form a trench 0.43 m (17 in.) long (Figure 10). The area outside the forms was filled with ORNL soil. The crushed limestone was placed inside the form to a depth of 0.25 m (10 in.). The surface above the limestone was covered with ORNL soil. The wooden forms and the metal retaining ring were then removed.

Four electrodes were placed at a 0.23 m (9 in.) spacing in a square pattern. The electrodes were 1.9 cm diameter by 0.91-m long (3/4 in. by 36 in.) molybdenum with 5.1-cm diameter by 0.36-m long (2 in. by 14 in.) graphite sleeves placed over the molybdenum electrodes. The annulus between the graphite and the molybdenum was filled with molybdenum powder for electrical continuity. A graphite and frit starter material was placed between the electrodes at a depth of 0.10 m (4 in.). The surface above the starter material was covered with ORNL soil. After completion of the simulated trench, the entire test surface was covered with two 2.5-cm (1-in.) layers of insulation material (kaowool). The test assembly was sealed and prepared for electrical power application. The off-gas line used to sample gaseous effluents contained a 0.30-m by 0.30-m by 0.29-m (12 by 12 by 11 5/8 in.) HEPA filter and a 3 LPM sample scrubber/filter assembly.

Initial startup resulted in a false start caused by insufficient molten soil formation before encountering the limestone layer. The melt zone had reached the limestone layer without sufficient glass formation, and several gas formation bubbles and a vent port had formed under the insulation blanket, disrupting the electrical continuity. The gas formations were broken up, the melt zone was refilled with ORNL soil, and a new surface starter path was formed. The test was restarted and continued to completion with two normal interruptions. Power was turned off for 10 minutes to change the transformer-voltage tap-setting range from 400 to 200 volts control and to change wiring in a saturable core reactor from series to parallel to accommodate higher current near the end of the test. The thermocouple at the 0.56-m (22-in.) depth indicated a fusion temperature of 1000°C when the test was completed. The actual run time for the test was 8 hours.

Table 4 shows predicted and actual data obtained from ISV/ORNL engineering-scale tests. Predicted data is based on a mathematical model developed for ISV (Oma et al. 1983). In reviewing the data, note the close comparison of the actual test results to the model predictions. This close comparison provides a reasonable degree of confidence for prediction of the pilot-scale test. Note the difference under the "Actual" column between the mass of material treated versus the ISV mass produced. The difference in mass is due to the loss of volatile components (i.e., moisture, carbonates, etc.) during processing. Laboratory tests showed 23% moisture weight loss of the ORNL soil heated to 1000°C for 16 hours. Weight loss of the ORNL limestone heated to 1000°C for 16 hours was 42%.

A description of the vitrified block after removal from the test assembly is given below:

- Subsidence from the surface was 0.30 m (12 in.), giving a volume reduction of 60%.
- The surface of the melt zone was very smooth with no porous cold cap observed. This feature maximizes volume reduction and eliminates concern for future subsidence.

TABLE 4. Predicted and Actual Data Obtained from In Situ Vitrification/Oak Ridge National Laboratory Engineering-Scale Tests

	<u>Predicted</u>	<u>Actual</u>
Run Time, h	9.1	8.0
Melt Depth, m	0.54	0.51
Melt Width, m	0.53	0.51 to 0.60
Mass of Material Treated, kg	160	173
ISV Mass, kg	--	86
Heat Loss, kW	9.0	--
Average Power, kW	17	17
Energy, kWh	155	139
E/Mass, kWh/kg	0.95	0.80

- The walls of the subsided area were vertical with a thickness of 1.3 cm (1/2 in.) on the north and south surfaces. The east and west faces, which contained the ends of the limestone trench, had no structural strength and crumbled during excavation. This indicates that during larger-scale applications sloughing may occur down the trench and the off-gas hood will have to be designed to accommodate such sloughing.
- The soil around the entire vitrified block, approximately 6.4 cm by 7.6 cm thick (2-1/2 in. by 3 in.), had changed to a red rusty color. This indicated a ferrous-to-ferric ratio change due to temperature but has no implications on processing behaviors.

The electrical data obtained from the engineering-scale test are shown in Figure 11, which gives A-phase and B-phase volts versus run time, and Figure 12, which gives A-phase and B-phase amps versus run time. Figure 13 shows A-phase and B-phase kilowatts versus run time. Figure 14 shows the temperature of the 0.15-, 0.25-, 0.41-, and 0.56-m (6, 10, 16, and 22 in.) thermocouple versus run

FIGURE 11. A-Phase and B-Phase Volts Versus Run Time

FIGURE 12. A-Phase and B-Phase Amps Versus Run Time

FIGURE 13. A-Phase and B-Phase Kilowatts Versus Run Time

FIGURE 14. Temperature of the 0.15-, 0.25-, 0.41- and 0.56 m (6, 10, 16, and 22 inch) Thermocouple Versus Run Time

time. We can conclude that ISV is very applicable to ORNL intermediate-level waste sites. Chemical pretreatment of the soil/limestone is not required to enhance electrical conductivity.

The data presented in the figures show that the soil and limestone can be processed with the existing electrical designs of ISV units. The ranges of voltage and currents match those of previous runs with Hanford soil, supporting the conclusion that molten soil properties do not vary enough to affect ISV processing of ORNL soil (Oma et al. 1983). Soil moisture, low alkali concentrations, or the presence of limestone did not impede the downward-melting progress. ISV of ORNL soil and limestone can be performed with up to 60% volume reduction. No chemical pretreatment of the soil/limestone is required to enhance electrical conductivity.

5.0 ENGINEERING-SCALE TEST RESULTS AND ANALYSIS

Sampling was used to compile a material balance for the cesium and strontium retention. Samples were taken from HEPA filter media, each of the two water scrubbers, millipore sampler filters, samples of the surrounding soil of the vitrified mass, and core samples of the vitrified mass.

Off-gas stream sampling (Figure 15) provided an quantitative analysis of the amount of cesium and strontium released during processing. The off gas was sampled at a rate of 2.73 to 3.03 L/min through the sample train to match off-gas velocity at the isokinetic sampling port. During the processing period, seven liquid samples were taken from each of the liquid scrubbers and six millipore filter samples. The gas line to the sample train was flushed with water between each sequence of samples to detect line accumulation. Table 5 provides analytical results for the water scrubbers and the millipore filter. The second-stage water scrubber served as a final check of the first-stage scrubber efficiency. The millipore filter serves as a final check prior to atmosphere releases. Sample periods ranged from 1.08 to 3.58 hours.

The data from Table 5 were corrected for off-gas flow, sample time, and sampler system flow for conversion to grams released from the soil. The converted gram quantities collected in the off-gas system were divided into the amount of cesium and strontium placed in the soil prior to testing. This gives a mass to off-gas decontamination factor (DF) for cesium of 2.6×10^4 and a strontium DF of 2.7×10^4 . With the data from Table 5, the calculated amount of cesium and strontium released to the off-gas system was plotted as shown in Figure 16. These data are confirmed by analysis of off-gas line HEPA filter samples.

Table 6 gives the chemical analysis of a single core sample taken from the engineering-scale test.

In reviewing the data in Table 6, note that the strontium converts to a larger quantity than that placed in the test site prior to vitrification. It appears that the core sample was taken in an area where convection in the melt

FIGURE 15. Off-Gas Sample System for Engineering-Scale Oak Ridge National Laboratory Test

TABLE 5. Scrub System Sample Analyses ($\mu\text{g}/\text{sample period}$)

Samples	Cesium	Strontium
Scrubber 1	<1.275	21.5
Scrubber 2	<1.275	21.68
Flush	<0.225	4.37
Millipore	<0.16	0.25
Scrubber 1	<1.275	28.05
Scrubber 2	<1.275	21.93
Flush	<0.33	6.73
Millipore	<0.16	0.25
Scrubber 1	<1.275	24.23
Scrubber 2	<1.275	21.68
Flush	0.560	6.37
Millipore	<0.16	0.25
Scrubber 1	4.77	25.71
Scrubber 2	<1.30	21.25
Flush	1.54	6.37
Millipore	<0.16	0.29
Scrubber 1	2.12	24.91
Scrubber 2	<1.30	22.10
Flush	1.54	3.70
Millipore	0.40	0.15
Scrubber 1	3.24	22.14
Scrubber 2	<1.30	22.10
Flush	0.585	3.15
Millipore	NR (a)	NR
Scrubber 1	67.5	21.50
Scrubber 2	12.2	21.68
Flush	30.5	4.60
Millipore	28.0	0.18

(a) Filter was not removed during this sample period.

zone created a higher concentration of strontium than that distributed throughout the remaining block. Previous convection data from ISV testing shows distribution of radionuclides to be within a factor of three from the norm (Timmerman and Oma 1984). Core sample examination also reveals the final soil and limestone concentrations in the vitrified product are 68 wt% soil and

FIGURE 16. Projected Amount of Cesium and Strontium in Off-Gas System Based on Off-Gas System Sample Analysis

TABLE 6. Normalized Chemical Analysis of a Single Core Sample from Engineering-Scale Test

Element	wt%
Al ₂ O ₃	14.68
B ₂ O ₃	0.14
BaO	0.10
CaO	14.99
Fe ₂ O ₃	4.14
K ₂ O	2.28
Li ₂ O	0.07
MgO	10.88
MnO ₂	0.14
MoO ₃	0.05
Na ₂ O	0.93
SiO ₂	45.41
SrO	4.17
TiO ₂	0.64
ZrO ₂	0.03
Cs ₂ O	1.35
Total	100.00

32 wt% limestone. This is slightly higher in soil concentration than the laboratory-scale sample, which resulted in a 62 wt% soil and 38% limestone concentration.

Samples of the soil surrounding the vitrified mass were taken at the top on two sides, midway down the vitrified mass on two sides, and under the vitrified mass in two locations. The bottom samples were collected after the mass was removed from the test assembly. All soil sample analyses showed a water leach analysis for cesium of <0.001%, indicating no outward migration of cesium during processing.

The concentration of cesium and strontium placed in the soil prior to vitrification testing were several orders of magnitude greater than that found in ORNL Trench 7. This increased concentration was used to provide detectable levels of cesium and strontium in the off-gas sampling system and detectable quantities for MCC-1 evaluation of the vitrified mass.

MCC-1 tests were performed on the engineering-scale vitrified mass. The tests were performed to determine product durability for the 68/32 engineering-scale soil and limestone and to verify the findings of the laboratory soil and limestone tests. One of two samples of the engineering-scale vitrified glass was heat-treated at the same cooling rate as the face of a full scale ISV monolith (Figure 5). Both samples taken directly from the engineering-scale vitrified mass were subject to a 28-day, MCC-1 leaching test at 90°C in deionized water.

A summary of the results from these tests is presented in Figure 17. The leaching releases were similar for both the engineering-scale samples and the laboratory tests discussed earlier in this report, except that the releases for cesium, potassium and strontium were significantly lower for the engineering-scale heat-treated and non-heat-treated glasses. The strontium releases reported for the engineering-scale test results are probably more accurate than those reported in the laboratory test results section. The concentration of strontium in the engineering-scale glasses was approximately 400 times greater than in the laboratory-scale glasses (4 to 0.01 wt%).

FIGURE 17. Heat-Treated 68/32 Soil/Dolomite MCC-1 (Monolith) Test Results as Compared to PNL 76-68 Glass

Because 0.01 wt% of strontium in the laboratory test is near the detection limits of ICP analysis, the analytical numbers at 4 wt% are well above the detection limits to improve the confidence level.

The most probable reason for the increased durability of the engineering-scale samples is the higher soil to limestone ratio. Since this ratio is more representative of the actual test condition, the engineering-scale data should be used to predict waste form durability of ISV applied to ORNL low level waste sites. Another possibility is that the engineering-scale sample was held at processing temperature for a longer time period resulting in more homogeneous vitrification and an approved waste form.

Comparison of the heat-treated 68/32 engineering-scale soil to the PNL 76-68 for 28-day leach test are shown in Figure 18. Normalized strontium release from the 68/32 soil/limestone ISV product is the same as or less than the 76-68 glass. The normalized cesium release, for instance, is a factor of 3 lower than that of the 76-68 glass.

FIGURE 18. Comparison of Engineering-Scale Soil/Limestone to Laboratory-Scale Soil/Limestone

With leach testing for the laboratory-scale and engineering-scale performed at 90°C, the engineering-scale 68/32 soil presents a very durable product, comparable to a specially developed high-level waste form (i.e., PNL 76-68). It is anticipated that if the vitrified mass leach tests are performed at the lesser temperature of 20°C, to simulate ambient temperature, the leach rates would be one to two orders of magnitude lower.

6.0 REFERENCES

- Brouns, R. A., J. L. Buelt, and W. F. Bonner. 1983. "In Situ Vitrification of Soil." U.S. Patent 4,376,498, March 1983.
- Buelt, J. L., and J. G. Carter. 1986. Description and Capabilities of the Large-Scale In Situ Vitrification Process. PNL-5738, Pacific Northwest Laboratory, Richland, Washington.
- Buelt, J. L., and S. T. Freim. 1986. Demonstration of In Situ Vitrification for Volume Reduction of Zirconia/Lime Sludges. Pacific Northwest Laboratory, Richland, Washington.
- Buelt, J. L., C. C. Chapman, S. M. Barnes, and R. D. Dierks. 1979. "A Review of Continuous Ceramic-Lined Melter and Associated Experience at PNL," pp. 107-113. In Ceramics and Nuclear Waste Management. CONF-790420. Technical Information Center, Springfield, Virginia.
- Chick, L. A., et al. 1984. West Valley High-Level Nuclear Waste Glass Development: A Statistically Designed Mixture Study. PNL-4992, Pacific Northwest Laboratory, Richland, Washington.
- Materials Characterization Center, Rev. 7, 1986, "MCC-1P Static Leach Test Method." In Nuclear Waste Materials Handbook. Test Methods. DOE/TIC-11400. Pacific Northwest Laboratory, Richland, Washington.
- Materials Characterization Center, Rev. 7, 1986, "MCC-3S Agitated Powder Leach Test Method." In Test Methods Submitted for Nuclear Waste Materials Handbook. PNL-3990, Pacific Northwest Laboratory, Richland, Washington.
- Oma, K. H., D. R. Brown, J. L. Buelt, V. F. FitzPatrick, K. A. Hawley, G. B. Mellinger, B. A. Napier, D. J. Solvoera, S. L. Stein, and C. L. Timmerman. 1983. In Situ Vitrification of Transuranic Wastes: Systems Evaluation and Applications Assessment. PNL-4800, Pacific Northwest Laboratory, Richland, Washington.
- Timmerman, C. L., and K. H. Oma. 1984. An In Situ Vitrification Pilot-Scale Radioactive Test. PNL-5240, Pacific Northwest Laboratory, Richland, Washington.
- Timmerman, C. L., R. A. Brouns, J. L. Buelt, and K. H. Oma. 1983. "In Situ Vitrification: Pilot-Scale Development." Nuclear and Chemical Waste Management. Vol. 4, No. 3, pp. 267-276. Pergamon Press Inc., Elmsford, New York.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

30 DOE Technical Information
Center

J. W. Bennett, RW-20
DOE Office of Civilian
Radioactive Waste Management
Forrestal Building
Washington, DC 20585

C. R. Cooley, RW-4
DOE Office of Civilian
Radioactive Waste Management
Forrestal Building
Washington, DC 20585

M. W. Frei
Geologic Repository Division
DOE Office of Civilian
Radioactive Waste Management
Forrestal Building
Washington, DC 20585

R. Stein, RW-23
DOE Office of Civilian
Radioactive Waste Management
Forrestal Building
Washington, DC 20585

D. B. LeClaire, DP-12
DOE Office of Defense Waste &
Byproducts Management
GTN
Washington, D.C. 20545

R. B. Walton, Jr., DP-123
DOE Office of Defense Waste &
Byproducts Management
GTN
Washington, D.C. 20545

J. Jicha DP-123
DOE Office of Defense Waste &
Byproducts Management
GTN
Washington, D.C. 20545

J. E. Baublitz, NE-24
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

J. A. Coleman, NE-25
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

D. J. McGoff, NE-23
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

J. A. Turi, NE-25
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

W. R. Voigt, NE-20
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

H. F. Walter, NE-25
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

No. of
Copies

J. B. Zorn, NE-25
DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545

M. J. Bell
Division of Nuclear Materials
Safety & Safeguards
Mail Station 881-SS
Nuclear Regulatory Commission
Washington, DC 20555

A. T. Clark
Division of Fuel Material
Safety
Nuclear Regulatory Commission
Washington, DC 20555

W. J. Dircks
Office of the Executive
Director for Operations
Mail Station 6209
Nuclear Regulatory Commission
Washington, DC 20555

D. Egan
Environmental Protection Agency
Office of Radiation Programs
401 M Street, S.W.
Washington, DC 20460

G. L. Sjoblom
Environmental Protection Agency
Office of Radiation Programs
401 M Street, S.W.
Washington, DC 20460

M. McFadden
DOE Albuquerque Operations
Office
P.O. Box 5400
Albuquerque, NM 87185

No. of
Copies

J. McGough
DOE Albuquerque Operations
Office
P.O. Box 5400
Albuquerque, NM 87185

W. H. Hannum
DOE West Valley Operations
Office
P.O. Box 191
West Valley, NY 14171

J. P. Hamric
DOE Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

J. B. Whitsett
DOE Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401

L. Lanni
DOE San Francisco Operations
1333 Broadway
San Francisco, CA 94612

W. E. Pasko
DOE Oak Ridge Operations Office
P.O. Box E
Oak Ridge, TN 37830

S. A. Mann
DOE Chicago Operations Office
9800 South Cass Avenue
Argonne, IL 60439

J. O. Neff
DOE National Waste Program
Office
505 King Avenue
Columbus, OH 43201

No. of
Copies

G. K. Dertel
DOE Savannah River Operations
Office
P.O. Box A
Aiken, SC 29801

D. L. Vieth
DOE Nevada Operations Office
P.O. Box 14100
Las Vegas, NV 89114

C. S. Abrams/J. H. Kittel
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

M. J. Steindler/L. E. Trevorrow
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

W. J. Madia
Battelle Memorial Institute
Office of Crystalline
Repository Development
9800 South Cass Avenue
Argonne, IL 60439

W. A. Carbeiner/S. H. Rasham
Battelle Memorial Institute
Project Management Division
505 King Avenue
Columbus, OH 43201

J. F. Kircher
Battelle Memorial Institute
Project Management Division
505 King Avenue
Columbus, OH 43201

Technical Library
Battelle Memorial Institute
Project Management Division
505 King Avenue
Columbus, OH 43201

No. of
Copies

L. D. Ranspott
Lawrence Livermore National
Laboratory L/240
University of California
P.O. Box 808
Livermore, CA 94550

D. T. Oakley, MS 671
Los Alamos Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87544

T. H. Row
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830

J. O. Blomeke
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

W. D. Burch
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

N. J. Cutshall
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

L. A. Dole
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

10 R. P. Spalding
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

D. R. Anderson
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185

No. of
Copies

J. F. Ney
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185

R. W. Lynch
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185

W. Weart
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Technical Library
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185

B. R. Wheeler
Westinghouse Idaho Nuclear
Co., Inc.
P.O. Box 4000
Idaho Falls, ID 83401

M. D. Boersma
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

J. L. Crandall
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

E. J. Hennelly
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

No. of
Copies

L. L. Kilpatrick/L. M. Lee
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

S. Mirshak
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

R. M. Wallace
E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801

E. A. Jennrich
EG&G Idaho
P.O. Box 1625
Idaho Falls, ID 83415

K. V. Gilbert/P. G. Hagan
Rockwell International
Rocky Flats Plant
P.O. Box 464
Golden, CO 80401

G. W. Meyers
Atomics International Division
Rockwell International
8900 DeSoto Avenue
Canoga Park, CA 91304

T. H. Pigford
Department of Nuclear
Engineering
University of California
Berkeley, CA 94720

M. E. Spaeth
Science Applications, Inc.
2769 South Highland
Las Vegas, NV 89109

No. of
Copies

J. F. Strahl
Weston
2301 Research Boulevard
Third Floor
Rockville, MD 20850

R. Williams
Electric Power Research
Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304

C. C. Chapman
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

J. C. Cwynar
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

L. R. Eisenstatt
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

J. L. Knabenschuh
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

J. E. Krauss
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

J. M. Pope
West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171

No. of
Copies

J. W. Bartlett
The Analytic Sciences
Corporation
6 Jacob Way
Reading, MA 01867

W. A. Freeby/J. L. Jardine
Bechtel National, Inc.
P.O. Box 3965
San Francisco, CA 94119

Librarian
Westinghouse Electric
Corporation
Technical Library
P.O. Box 40039
Albuquerque, NM 87196

L. L. Hench
Department of Materials Science
& Engineering
University of Florida
Gainesville, FL 32611

J. L. Larocca, Chairman
Energy Research & Development
Authority
Empire State Plaza
Albany, NY 12223

R. G. Post
College of Engineering
University of Arizona
Tucson, AZ 85721

K. McKinley
Joint Integration Office
Rockwell Hanford Operations
Box 3150
Albuquerque, NM 87190

M. Neal
Joint Integration Office
Rockwell Hanford Operations
Box 3150
Albuquerque, NM 87190

3 3679 00D61 4463

ONSITE8 DOE Richland Operations Office

J. H. Anttonen
E. A. Bracken
P. A. Craig
M. T. Karagianos
J. L. Rhoades
M. W. Shupe
J. J. Sutey
J. D. White

14 Rockwell Hanford Operations

B. N. Anderson
L. Fitch
K. A. Gasper
R. N. Gurley
N. W. Kirch
H. E. McGuire
D. E. McKinney
J. W. Patterson
R. D. Prosser
J. H. Roecker
T. B. Venziano
D. D. Wodrich
R. J. Wojtasak
File Copy

7 UNC United Nuclear Industries

T. E. Dabrowski/W. J. Kyriazis

2 Westinghouse Hanford Company

R. E. Lerch
J. D. Watrous

No. of
Copies45 Pacific Northwest Laboratory

S. O. Bates
W. F. Bonner
J. L. Buelt
H. C. Burkholder
J. R. Carrell
J. G. Carter (10)
D. B. Cearlock/R. P. Marshall/
W. R. Wiley
T. D. Chikalla
V. F. FitzPatrick
D. L. Futch
J. E. Hansen
M. S. Hanson
J. H. Jarrett
D. E. Knowlton
L. T. Lakey/K. M. Harmon
J. M. Latkovich
R. C. Liikala
G. D. Maupin
J. L. McElroy
J. E. Minor
I. C. Nelson/J. G. Stephan
K. H. Oma
A. M. Platt/R. E. Nightingale
J. M. Rusin
J. A. Shaw
D. J. Silveira
S. L. Stein
C. L. Timmerman
Technical Report Files (5)
Publishing Coordination (2)