2F

Evaluation of Lead-Iron- Phosphate Glass as a High-Level Waste Form

September 1986

**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 any of their employees, makes any warranty, express 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 or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
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

EVALUATION OF LEAD-IRON-PHOSPHATE
GLASS AS A HIGH-LEVEL WASTE FORM

L. A. Chick
L. R. Bunnell
D. M. Strachan
H. E. Kissinger
F. N. Hodges

September 1986

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

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

The lead-iron-phosphate (Pb-Fe-P) glass developed at Oak Ridge National Laboratory was evaluated for its potential as an improvement over the current reference nuclear waste form, borosilicate (B-Si) glass. The evaluation was conducted as part of the Second Generation HLW Technology Subtask of the Nuclear Waste Treatment Program at Pacific Northwest Laboratory. The purpose of this work was to investigate possible alternatives to B-Si glass as second-generation waste forms. While vitreous Pb-Fe-P glass appears to have substantially better chemical durability than B-Si glass, severe crystallization or devitrification leading to deteriorated chemical durability would result if this glass were poured into large canisters as is the procedure with B-Si glass. Cesium leach rates from this crystallized material are orders of magnitude greater than those from B-Si glass. Therefore, to realize the potential performance advantages of the Pb-Fe-P material in a nuclear waste form, the processing method would have to cool the material rapidly to retain its vitreous structure.

CONTENTS

SUMMARY	iii
INTRODUCTION	1
CONCLUSIONS	3
RESULTS AND DISCUSSION	5
GLASS PREPARATION	5
LEACH TESTING	9
PROCESSING-RELATED PROPERTIES	11
Pb-Fe-P GLASSES AS METAL MATRIX WASTE FORM	13
REFERENCES	15

FIGURES

1	Optical Micrograph of Canister Centerline Heat-Treated (CHT) Pb-Fe-P	7
2	X-Ray Diffraction Pattern of 700°C/24-h Annealed Pb-Fe-P Material	8
3	SEM Micrographs of Central Area in CHT (devitrified) Pb-Fe-P Specimen	12
4	Viscosity and Electrical Conductivity of Pb-Fe-P Glass Melt	13

TABLES

1	Comparison of ARM-1, Pb-Fe-P Quenched, and Pb-Fe-P Heat-Treated Glasses in an MCC-1 Leach Test	9
2	Comparison of ARM-1 Standard Borosilicate Glass with Two Pb-Fe-P Glasses in the Vitreous Form or After Heat Treatments	10

INTRODUCTION

The low melting temperatures of phosphate-based glasses have prompted several cycles of investigation over the last 20 years by nuclear waste glass designers worldwide. For example, a phosphate glass process, originally conceived at Brookhaven National Laboratory,⁽¹⁾ was used to demonstrate high-level waste (HLW) glass solidification at Pacific Northwest Laboratory (PNL) in 1965.⁽²⁾ The process used a platinum-lined melter. Ultimately, this process was considered impractical because of the quantities of valuable platinum that would be irretrievable. Additionally, devitrification and the resulting poor leaching performance were noted.⁽³⁾ More recent German interest in phosphate glass has been reported,⁽⁴⁾ and problems caused by devitrification were dealt with by producing the glass as marbles embedded in a metal matrix (the Pamela process).^(5,6)

The present reference high-level waste form in the United States is borosilicate (B-Si) glass, though compositions vary with the waste stream. The choice of B-Si glass is based on processing ease, durability, and general freedom from devitrification. One objective of the Second Generation HLW Technology Subtask of the Nuclear Waste Treatment Program at PNL, sponsored by the Department of Energy, is to investigate possible alternatives to B-Si glass as second-generation waste forms. In order to be seriously considered, these alternative waste forms would have to offer improved performance or lower processing costs over the B-Si approach.

Sales and Boatner at Oak Ridge National Laboratory (ORNL) have developed a lead-iron-phosphate (Pb-Fe-P) high-level waste glass composition that they claim is a promising new waste form for both commercial and defense HLW because it has "several distinct advantages" over the current reference B-Si HLW glasses.^(7,8) The specific features cited by Sales and Boatner are as follows:

- The Pb-Fe-P glass has an aqueous corrosion rate at 90°C that is about 1000 times less than the rate for B-Si glasses.
- The Pb-Fe-P glass has a low viscosity in the range from 800 to 1000°C and therefore can be processed at a temperature that is 100 to 250°C lower than required for B-Si glasses.

- The Pb-Fe-P glass can dissolve (in the melt) the elements found in both commercial and defense HLW.
- The Pb-Fe-P glass "can be processed using a technology similar to that developed for borosilicate glass nuclear waste forms."

Because the Pb-Fe-P glass proposed by Sales and Boatner appeared to offer both cost and performance advantages, it was evaluated as part of the PNL program. This report contains the results of tests to determine melting, devitrification, and processing qualities of the proposed Pb-Fe-P glass, and thus to evaluate its suitability as a host for future commercial high-level wastes.

CONCLUSIONS

The results from the experiments on Pb-Fe-P glass have led to the following conclusions:

1. The Pb-Fe-P glass, in the vitreous state, performs better (10 to 100X) than B-Si glass in leach tests, although the margin of improvement does not appear to be as great as that claimed (1000X) by Sales and Boatner at Oak Ridge National Laboratory.
2. Slow cooling of Pb-Fe-P glass, as would occur in filling a typical canister, causes extensive devitrification of the glass.
3. Devitrification is accompanied by a large decrease in leaching performance in regard to cesium and, in a recent composition, strontium. Specifically, these elements leach much more rapidly from Pb-Fe-P waste glass than from typical B-Si waste glass.

RESULTS AND DISCUSSION

The testing of Pb-Fe-P glasses at PNL has included melting, devitrification, and chemical durability studies. In summary the results show that:

- Leach releases at 90°C of vitreous Pb-Fe-P samples that were rapidly quenched from the melt were roughly 100 times less than those of B-Si glass under dilute conditions (MCC-1) and 10 to 100 times less than those of B-Si glass under more saturated conditions (MCC-3).
- Melt viscosity and electrical resistivity were within reasonable ranges for joule-heated electric melting of the Pb-Fe-P glass between 900°C and 1000°C but increased rapidly below 900°C as a result of crystallization.
- At 1000°C, the Pb-Fe-P melts adequately dissolved typical HLW compositions. Lower melting temperatures did not produce totally vitreous samples.
- When the Pb-Fe-P glass was cooled in a manner that mimics the thermal history of glass near the centerline of a large canister, the resulting material was extensively crystallized.
- Leach releases at 90°C for this crystallized material were much greater than for the rapidly cooled vitreous samples. In particular, Cs release from crystallized material was more than 100 times greater than that from B-Si glass.

GLASS PREPARATION

During the first Pb-Fe-P glass testing at PNL, melts prepared at 900°C and 950°C containing 15 wt% of simulated Hanford and West Valley wastes did not result in totally vitreous products. Furthermore, aluminum oxide and transition metal phosphate crystals were detected in quenched samples. In subsequent testing on simulated (nonradioactive) Savannah River HLW glasses melted at 1000°C, the composition and sample preparation procedures described by Sales and Boatner⁽⁸⁾ were closely followed. In the PNL work, however, U oxide was replaced with Ce and Nd oxides (nonradioactive substitutes). The glass was

melted at 1000°C for 2 h, poured into a 5/8 x 5/8-in. steel bar mold, and annealed for 2 h at 475°C. The resulting glass was essentially vitreous; the analyzed composition of the glass is shown below:

<u>Oxide</u>	<u>wt%</u>	<u>Oxide</u>	<u>wt%</u>
PbO	51.5	CaO	0.58
Fe ₂ O ₃	8.9	SrO	0.13
P ₂ O ₅	31.8	CeO ₂	0.19
Al ₂ O ₃	1.5	Nd ₂ O ₃	0.40
MnO ₂	2.1	Na ₂ O	1.2
NiO	0.95	Cs ₂ O	0.09
SiO ₂	0.60	SO ₃	0.2
		Total	100.1

The vitreous glass was subjected to a heat treatment designed to simulate the asymptotic cooling curve for glass near the center of a large-scale canister. The canister centerline heat treatment (CHT) is calculated based on the melting temperature (1000°C) of the Pb-Fe-P glass and an approximation of canister temperatures derived from thermocouples attached to 0.6-m-diameter canisters filled with molten glass.⁽⁹⁾ The thermocouple data were for B-Si glass; thus, actual cooling rates for Pb-Fe-P glass may be slightly different. The heat treatment used on the Pb-Fe-P samples consisted of soaking the samples at 1000°C for 1 h and then cooling at the rates below, which are linear approximations of the actual cooling curve.

<u>Cool From, °C</u>	<u>Down To, °C</u>	<u>Rate, °C/h</u>
1000	950	31
950	750	20
750	600	13
600	450	7
450	350	4

The resulting product was almost totally crystallized, and it was difficult to locate the residual glass phase in micrographs (Figure 1). Areas that

FIGURE 1. Optical Micrograph of Canister Centerline Heat-Treated (CHT) Pb-Fe-P

crystallized first were composed of densely packed fine grains. The regions that cooled more slowly contained much larger grains (up to 3 mm long) and large voids. Isothermal heat treatments were performed by heating premelted samples at a constant temperature ranging from 550 to 1000°C in 50°C increments for 24 h. Thin sections of these samples were examined optically; extensive crystallization occurred between 600°C and 800°C, producing morphologies similar to that of the CHT material. Less extensive crystallization occurred at 550°C and from 850 to 950°C. Very few crystals were observed in the 1000°C sample.

Scanning electron microscope (SEM) studies using energy-dispersive x-ray analysis (EDX) indicated that the primary phases produced during the heat treatment and in the 600 to 800°C isothermal anneals were lead phosphates with

varying amounts of Fe, Ni, and Mn. The phases produced at 550°C and in the higher range from 850 to 950°C were Al-Fe phosphates. These phases were also present in the CHT material.

X-ray diffraction patterns of the crystallized glasses were essentially identical for those heat treatments that produced extensive devitrification. Weak x-ray peaks in the 550°C and 850°C isothermal annealed samples corresponded to the strong lines of the massively crystallized samples. A portion of the 700°C annealed sample pattern is shown in Figure 2. Manual and computer search methods failed to account for the observed lines. To streamline the analysis, two simplified $\text{PbO-P}_2\text{O}_5$ glass compositions were prepared; one with no additions and one with 15 wt% Fe_2O_3 . These compositions were held for 24 h at 700°C to produce devitrification. The glass with no Fe remained vitreous. This material also remained vitreous through a 10°C/h slow cooling. The apparent resistance of this glass to devitrification disagrees with Sales and Boatner.^(7,8) The glass with 15 wt% Fe_2O_3 crystallized as intended, with a diffraction pattern only slightly different from that obtained previously (Figure 2), suggesting that the pattern was perhaps that of a single phase. Although the x-ray pattern was not indexed, the symmetry appears to be triclinic. The observed lines could be fitted to a cell having $a = 9.415\text{\AA}$, $b = 12.163\text{\AA}$, $c = 14.33\text{\AA}$, $\alpha = 96.57^\circ$, $\beta = 87.53^\circ$, and $\gamma = 101.73^\circ$.

FIGURE 2. X-Ray Diffraction Pattern of 700°C/24-h Annealed Pb-Fe-P Material

LEACH TESTING

The leaching studies used tests developed by the Materials Characterization Center (MCC) at PNL. Leach results from the 28-day MCC-1⁽¹⁰⁾ and MCC-3⁽¹¹⁾ tests are shown in Tables 1 and 2. The MCC-1 test, the most widely used test for comparing waste form leaching performance, utilizes a monolithic sample and has a relatively small sample surface area-to-solution volume ratio (SA/V) of 10 m^{-1} . Thus, the data are more indicative of the maximum waste form matrix dissolution rate than of performance under the near-saturated, low flow rate conditions expected in geologic repositories. MCC-3 utilizes an agitated

TABLE 1. Comparison of ARM-1, Pb-Fe-P Quenched, and Pb-Fe-P Heat-Treated Glasses in an MCC-1 Leach Test^(a,b)

Element	ARM-1 ^(c)	Pb-Fe-P Glass ^(d)		
	B-Si Glass	Vitreous	Small-Grained CHT	Large-Grained CHT
Si	9.5	<0.9	<0.2	<0.2
B	11	NP	NP	NP
Pb	NP ^(e)	0.14	0.093	0.17
P	<4	0.23	9.2	11
Na	11	<0.3	30	39
Li	11	NP	NP	NP
Ca	6.2	<0.7	3.1	5.1
Sr	5.8	<0.3	<1	<2
Al	8.7	<0.5	<0.2	0.64
Fe	NP	2.8	0.12	0.19
Cs	11	<12	2500	3200
Final pH	8.9	5.2	5.1	5.1

(a) All values are in units of normalized mass release (g/m^2).

(b) Conditions: MCC-1; 90°C; 28 d; deionized water; SA/V = 10 m^{-1} .

(c) ARM-1 borosilicate glass is an Approved Reference Material and is intended mainly to assess test procedures. Its leaching performance is not as good as present borosilicate waste glasses.

(d) Values preceded by < were less than the ICP detection limit.

(e) Not present in glass.

TABLE 2. Comparison of ARM-1 Standard Borosilicate Glass with Two Pb-Fe-P Glasses in the Vitreous Form or After Heat Treatments^(a,b)

Element	ARM-1 B-Si Glass	Vitreous Pb-Fe-P Glass ^(c)	Pb-Fe-P Glass Cooled to Simulate 0.6-m Canister	Pb-Fe-P Glass Cooled at 1°C/min ^(d)
Si	0.39	NP	NP	NP
B	0.79	NP	NP	NP
Pb	NP ^(e)	0.004	0.003	0.17
P	0.52	0.06	0.43	11.83
Na	0.82	0.12	1.3	NP
Li	1.2	NP	NP	NP
Ca	0.01	0.11	0.28	NP
Sr	0.01	0.07	0.07	4.31
Al	0.18	NP	NP	NP
Fe	NP	0.01	0.01	0.21
Cs	0.10	0.14	61	50.13
Final pH	11	4.0	3.8	2.2

(a) All values are in units of normalized mass release (g/m^2).

(b) Conditions: MCC-3; 90°C; 28 d unless otherwise stated; -100/+200 mesh powder in 40-mL deionized water; $\text{SA/V} = 1120 \text{ m}^{-1}$.

(c) Prepared according to Reference 7.

(d) Prepared according to Reference 22.

(e) Not present in glass.

powder sample ($\text{SA/V} = 1120 \text{ m}^{-1}$) and more closely approaches the expected repository environment. For comparison, the tables also include leach data for ARM-1 B-Si glass,⁽¹²⁾ an approved MCC reference material.

For MCC-1, the CHT material was partitioned into predominantly fine-grained and coarse-grained portions. Most of the release data for the vitreous Pb-Fe-P sample were below detection limits in MCC-1. If P release is taken to represent the glass matrix behavior (as B release is for B-Si glass), then the vitreous Pb-Fe-P matrix leaches about 50 times more slowly than the ARM-1 matrix. However, both fractions of the CHT material show greatly increased leaching of P, Na, Ca, Al, and especially Cs. MCC-3 data exhibit similar

patterns, except that the ratio between the ARM-1 boron and the vitreous Pb-Fe-P phosphorous releases under these more saturated conditions is smaller, about 15 rather than 50.

It is evident that P, Na, Ca, Al, and particularly Cs were partitioned into highly leachable phases during the heat treatment. SEM examination of $\sim 1 \text{ cm}^2$ of oil-polished CHT material identified three regions containing the Cs-rich phase (Figure 3). In all three instances, Cs silicate (probably a residual glass) was found on the surfaces of aluminum-iron-phosphate (Al-Fe- PO_4) crystals located in shrinkage voids. Although most of the Al-Fe- PO_4 crystals in the sample were surrounded by the major lead-phosphate phase, no Cs silicate was present on the surfaces of these crystals, which would explain the greatly enhanced leachability of Cs in the CHT material. The Cs partitioned into a relatively soluble composition and was located in voids readily invaded by water. The isothermal anneal studies indicate that as the CHT material cools the Al-Fe- PO_4 crystals form first in the 950 to 850°C range. It can be postulated that as the sample cools to the range where the major lead phosphate crystals begin forming, the Cs silicate is rejected from the melt and is left clinging to the Al-Fe- PO_4 crystals as the melt withdraws from the voids.

PROCESSING-RELATED PROPERTIES

Figure 4 shows viscosity and electrical conductivity data for the Pb-Fe-P glass melt. The effects of crystallization on these properties are indicated by rapid changes at temperatures below about 900°C. As the melt cools and begins to crystallize, the viscosity increases and the electrical conductivity decreases rapidly. B-Si glass does not have this temperature dependence because it is less prone to devitrification. Although the melt properties are probably acceptable for joule-heated melting from 900 to 1000°C, these data suggest that such electric melting may not be advisable for Pb-Fe-P glass. For example, if electrode power were lost for a long enough period that the melt cooled to 800°C, the resulting crystalline mass would probably not be conductive enough to allow restarting the melter using joule heating. External resistance heating^(5,6) may be a more appropriate means of producing Pb-Fe-P glass.

FIGURE 3. SEM Micrographs of Central Area in CHT (devitrified) Pb-Fe-P Specimen. Area A, the major phase, a lead-transition metal phosphate; Area B, a resin-filled shrinkage void; Area C, enlarged in the bottom micrograph, Al-Fe-PO₄ phase (gray) with Cs silicate phase (white).

FIGURE 4. Viscosity and Electrical Conductivity of Pb-Fe-P Glass Melt

Pb-Fe-P GLASSES AS METAL MATRIX WASTE FORM

Pb-Fe-P glass might represent an improved waste form if produced as rapidly cooled marbles packed in a metal matrix. This method has been considered in several comparative waste form studies.⁽¹³⁻²⁰⁾ In general, the metal matrix waste form is considered to be less desirable than B-Si glass poured into steel canisters on the basis of an overall "figure-of-merit" rating that takes into account product performance (leaching), process complexity, and cost. Most of the cost disadvantages of marbles in a metal matrix stem from the necessity to produce about 40% more canisters because the spherical marbles limit packing efficiency.

The process complexity and cost rankings of the metal matrix waste form appear to be technically valid in these studies,⁽¹³⁻²⁰⁾ at least on a

qualitative basis. However, evaluations of leaching performance for this waste form may have been biased low, partly due to insufficient data. The studies assumed that B-Si glass marbles would be used, which could be expected to leach 10 to 100 times faster than Pb-Fe-P marbles. In addition, because U release data on B-Si glass marbles in a lead matrix were unavailable, one study substituted U data from bare glass even though releases of other elements from the metal matrix form were 10 to 50 times less than from the bare glass.⁽²⁰⁾ A fair evaluation of the leaching performance of this waste form demands that Pb-Fe-P glass marbles be used. In addition, attempts to produce marble/metal matrix waste forms have resulted in marble-to-marble contact throughout. In leach tests, a phenomenon known as wicking occurs in which leachant has a continuous path along all marble/matrix interfaces.^(15,21)

Sales and Boatner addressed the devitrification problem and, by decreasing the Fe in the glass, claimed that cooling rates as low as 1°C/min would not degrade the leaching performance.⁽²²⁾ PNL data generally indicate that cooling rates for reasonably sized canisters (0.6 m or larger) will be lower than 1°C/min, especially with the high-heat-producing glasses of major interest as second-generation nuclear waste forms. Such forms will receive relatively fresh wastes, which produce substantial heat. The lower cooling rates will make devitrification more likely. Nevertheless, a glass was prepared according to the procedures described in Reference 22, cooled at 1°C/min, and then leach tested. Although the numerous crystals resulting from devitrification were small, they were responsible for a substantial increase in Cs release (Table 2). Additionally, the Sr release increased substantially over that of previous Pb-Fe-P materials.

REFERENCES

1. Dragner, R. F., et al. 1966. Brookhaven National Laboratory Process for the Conversion of High-Level Radioactive Wastes to Phosphate Glass. CONF-66028, U.S. Atomic Energy Commission.
2. Barton, G. B. 1965. Solidification of High-Level Wastes - Part IV: Phosphate Melts for Fixation of Radioactive Residues from Purex Type Wastes - 3 to 50 Percent Fission Product Oxides. BNWL-80, Pacific Northwest Laboratory, Richland, Washington.
3. Mendel, J. E., and J. L. McElroy. 1972. Waste Solidification Program, Vol. 10; Evaluation of Solidified Waste Products. BNWL-1666, Pacific Northwest Laboratory, Richland, Washington.
4. Van Geel, J., et al. 1976. Solidification of High Level Liquid Wastes to Phosphate Glass-Metal Matrix Blocks. SM-207/83, Vol. 1, pp. 341-359, International Atomic Energy Agency, Vienna, Austria.
5. Heimerl, W. 1979. "Solidification of HLW Solution with the PAMELA Process." In Ceramics in Nuclear Waste Management, Proc. Int. Symp., American Ceramics Soc., April 30-May 2, 1979, CONF-790420.
6. Harmon, K. A., and L. T. Lakey. 1982. International Source Book: Nuclear Fuel Cycle Research and Development. PNL-2478, Rev. 2, Pacific Northwest Laboratory, Richland, Washington.
7. Sales, B. C., and L. A. Boatner. 1984. "Lead Phosphate Glass as a Stable Medium for the Immobilization and Disposal of High-Level Nuclear Waste." Materials Letters 2(4B):301-304.
8. Sales, B. C., and L. A. Boatner. 1984. "Lead-Iron Phosphate Glass: A Stable Storage Medium for High-Level Nuclear Waste." Science 226:45-48.
9. 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.
10. Materials Characterization Center. 1981. Nuclear Waste Materials Handbook Waste Form Test Methods. DOE/TIC-11400, Pacific Northwest Laboratory, Richland, Washington.
11. Materials Characterization Center. 1982. Materials Characterization Center Test Methods Submitted for the Nuclear Waste Materials Handbook. PNL-3990, Pacific Northwest Laboratory, Richland, Washington.
12. Mellinger, G. B., and J. L. Daniel. 1984. Approved Reference and Testing Materials for Use in Nuclear Waste Management Research and Development Programs. PNL-4955-2, Pacific Northwest Laboratory, Richland, Washington.

13. Alternative Waste Form Peer Review Panel. 1979. The Evaluation and Review of Alternative Waste Forms for Immobilization of High-Level Radioactive Wastes. DOE/TIC-10228, U.S. Department of Energy, Aiken, South Carolina.
14. Alternative Waste Form Peer Review Panel. 1980. The Evaluation and Review of Alternative Waste Forms for Immobilization of High-Level Radioactive Wastes, Report No. 2. DOE/TIC-11219, U.S. Department of Energy, Aiken, South Carolina.
15. Alternative Waste Form Peer Review Panel. 1981. The Evaluation and Review of Alternative Waste Forms for Immobilization of High-Level Radioactive Wastes, Report No. 3. DOE/TIC-11472, U.S. Department of Energy, Aiken, South Carolina.
16. Schulz, W. W., et al. 1980. Preliminary Evaluation of Alternative Forms for Immobilization of Hanford High-Level Defense Wastes. RHO-ST-32, Rockwell Hanford Company, Richland, Washington.
17. Wald, J. W., et al. 1980. Comparative Waste Forms Study. PNL-3516, Pacific Northwest Laboratory, Richland, Washington.
18. Treat, R. L., et al. 1980. Preliminary Evaluation of Alternative Waste Form Solidification Processes, Volume 1: Identification of the Processes. PNL-3244, Pacific Northwest Laboratory, Richland, Washington.
19. Johnson, E. R., Associates, Inc. 1980. Preliminary Evaluation of Alternative Waste Form Solidification Processes, Volume 11: Evaluations of the Processes. PNL-3477, JAI-160, Pacific Northwest Laboratory, Richland, Washington.
20. Bernadzikowski, T. A., et al. 1983. "High Level Nuclear Waste Form Performance Evaluation." Ceramic Bulletin 62(12):1364-1390.
21. Jardine, L. F., and M. J. Steindler. 1978. A Review of Metal-Matrix Encapsulation of Solidified Radioactive High-Level Waste. ANL-78-19, Argonne National Laboratory, Argonne, Illinois.
22. Sales, B. C., and L. A. Boatner. 1985. Physical and Chemical Characteristics of Lead-Iron Phosphate Nuclear Waste Glasses. ORNL-6168, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

30 DOE Technical Information Center

6 Geologic Repository Division
DOE Office of Civilian
Radioactive Waste Management
Forrestal Building
Washington, DC 20585
ATTN: C. R. Cooley, RW-4
J. R. Hilley
W. J. Purcell, RW-20
B. C. Rusche, RW-1
D. E. Shelor
R. Stein, RW-23

3 DOE Office of Defense Waste &
Byproducts Management
GTN
Washington, DC 20545
ATTN: R. K. Heusser
J. E. Lytle, DP-12
R. D. Walton, Jr., DP-123

5 DOE Office of Terminal Waste
Disposal & Remedial Action
GTN
Washington, DC 20545
ATTN: J. A. Coleman, NE-25
T. W. McIntosh, NE-25
H. E. Stelling, NE-25
W. R. Voigt, NE-20
H. F. Walter, NE-25

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

V. Stello
Office of the Executive
Director for Operations
Mail Station 6209
Nuclear Regulatory Commission
Washington, DC 20555

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

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

P. G. Hagan
Joint Integration Office
Bldg. 3, 2nd Floor
2201 San Pedro N.E.
Albuquerque, NM 87110

E. Maestas
DOE West Valley Operations
Office
P.O. Box 191
West Valley, NY 14171

2 DOE Idaho Operations Office
550 Second Street
Idaho Falls, ID 83401
ATTN: M. J. Barainca
J. P. Hamric

F. T. Fong
DOE San Francisco Operations
1333 Broadway
Oakland, CA 94612

M. R. Jugan
DOE Oak Ridge Operations Office
P.O. Box E
Oak Ridge, TN 37830

W. J. Brumley
DOE Savannah River Operations
Office
P.O. Box A
Aiken, SC 29801

No. of
Copies

- M. J. Steindler
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
- C. S. Abrams
Argonne National Laboratory
P.O. Box 2528
Idaho Falls, ID 83401
- B. D. Shipp
Battelle Memorial Institute
Office of Crystalline Repository
Development
9800 South Cass Avenue
Argonne, IL 60439
- 3 Battelle Memorial Institute
Project Management Division
505 King Avenue
Columbus, OH 43201
ATTN: W. A. Carbeiner
W. S. Madia
B. Rawles
- F. Holzer
Lawrence Livermore National
Laboratory
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
- 4 Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830
ATTN: J. O. Blomeke
W. D. Burch
R. T. Jubin
L. J. Mezga

No. of
Copies

- 2 Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185
ATTN: R. W. Lynch
Technical Library
- J. R. Berreth
Westinghouse Idaho Nuclear
Co., Inc.
P.O. Box 4000
Idaho Falls, ID 83401
- 6 E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801
ATTN: M. D. Boersma
J. G. Glasscock
E. J. Hennelly
J. R. Knight
M. J. Plodinec
C. T. Randall
- E. A. Jennrich
EG&G Idaho
P.O. Box 1625
Idaho Falls, ID 83415
- R. Williams
Electric Power Research
Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304
- 5 West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171
ATTN: C. C. Chapman
J. C. Cwynar
J. E. Krauss
S. J. Marchette
J. M. Pope

No. of
Copies

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

ONSITE

9 DOE Richland Operations Office

J. H. Anttonen
E. A. Bracken
G. J. Bracken
C. R. DeLaunoy
R. D. Izatt
N. T. Karagianes
J. L. Rhoades
M. W. Shupe
J. D. White

10 Rockwell Hanford Operations

R. N. Gurley
J. M. Henderson
H. E. McGuire
R. D. Prosser
I. E. Reep
J. C. Scott
T. B. Veneziano
D. D. Wodrich
R. D. Wojtasek
File Copy

UNC United Nuclear Industries

T. E. Dabrowski/W. J. Kyriazis

2 Westinghouse Hanford Company

R. E. Lerch
J. D. Watrous

Pacific Northwest Laboratory

85 R. P. Allen
W. J. Bjorklund, Jr.

No. of
Copies

H. T. Blair
W. F. Bonner
D. J. Bradley
R. A. Brouns
G. H. Bryan
L. R. Bunnell (10)
L. L. Burger/L. A. Bray/
R. D. Scheele
H. C. Burkholder (10)
J. R. Carrell
D. B. Cearlock
L. A. Chick (20)
R. D. Dierks
D. S. Goldman
R. W. Goles
H. A. Haerer
M. S. Hanson
L. K. Holton
J. H. Jarrett
D. E. Knowlton
S. S. Koegler
M. R. Kreiter
W. W. Laity
L. T. Lakey/K. M. Harmon
J. M. Latkovich
J. L. McElroy
G. L. McVay
J. E. Mendel/M. D. Merz
G. B. Mellinger
J. E. Minor
D. R. Montgomery
L. G. Morgan
T. R. Myers
R. D. Peters
A. M. Platt/R. E. Nightingale
J. A. Powell
W. A. Ross
K. J. Schneider
P. A. Scott
D. H. Siemens
G. L. Tingey/G. A. Jensen
Publishing Coordination (2)
Technical Information (5)