

INVESTIGATION OF LEAD-IRON-PHOSPHATE GLASS FOR SRP WASTE

by

Carol M. Jantzen

E. I. du Pont de Nemours and Company
Savannah River Laboratory
Aiken, SC 29808

SRL FILE COPY

ABSTRACT

Development of a host solid for immobilizing nuclear waste has focused on various vitreous wasteforms. Recently, lead-iron-phosphate (LIP) glasses have been proposed for solidifying all types of high-level liquid waste (HLLW). Investigation of this glass for vitrifying Savannah River Plant (SRP) waste demonstrated that the phosphate glass is incompatible with current borosilicate glass processing. Although the durability of the LIP glasses in deionized water was comparable to current borosilicate waste glass formulations, many of the defense waste constituents have low solubility in the phosphate melt, producing a nonhomogeneous or nonvitreous product. Although the LIP glass has a low melt-temperature, it is highly corrosive, which prevents the use of current melter materials such as Inconel™ and alumina, and requires more exotic materials of construction such as platinum.

The information contained in this article was developed during the course of work under Contract No. DE-AC09-76SR00001 with the U. S. Department of Energy.

INTRODUCTION

Lead-iron-phosphate (LIP) glasses have recently been proposed as a new, very stable, and easily prepared medium for immobilizing all types of HLLW,¹⁻⁴ including SRP waste. Oak Ridge National Laboratory (ORNL), developer of LIP glasses, demonstrated that the corrosion rate of the lead-iron-phosphate waste glass is at least 10^2 - 10^3 times lower than the corrosion rate of a comparable borosilicate waste glass.¹⁻² In addition, they determined that (1) the lead phosphate glass could be prepared at temperatures of 800°C to 1050°C, (2) the glasses did not devitrify at temperatures up to 550°C, and (3) the glasses were not adversely affected by large doses of gamma radiation.¹⁻²

The developers determined that the improved chemical durability and thermal stability of this phosphate glass over previous formulations is due to the Fe_2O_3 content of the glass²⁻⁴ and the structural role of iron, which strengthens the cross-bonding between the polyphosphate chains.^{4,5} A highly stable wasteform is produced when the iron concentration is adjusted to a content of $Fe_2O_3/PbO \cdot P_2O_5 \sim 9$ wt%. The PbO content of the lead metaphosphate starting material must be between 45 and 66 wt%.² Although waste loadings of only 15 - 20 wt% were achievable in the 5.0 g/cm³ LIP glasses, they were considered comparable to 30 - 40 wt% waste loaded 2.5g/cm³ borosilicate glasses on a waste-per-volume loading.²

In subsequent investigations, ORNL examined the compatibility of the phosphate melt with various containment and canister materials.³⁻⁴ Although the LIP melt can be fabricated in stabilized zirconia, platinum, or alumina crucibles,^{2,3} platinum containment is preferred for defense waste glasses and zirconia for commercial waste glasses.³⁻⁴ ORNL also tested Inconel™, aluminum, and stainless steel to determine their suitability as canister

materials. These results are also applicable to use of these metals as electrodes or other melter components. The LIP melt dissolved Inconel™, and was corrosive to aluminum, but was compatible with stainless steel.

The developers suggested¹⁻⁴ that the lead-iron phosphate glasses could be prepared with minimal modification to the technology developed for processing borosilicate glass for high-level nuclear defense waste. Because some SRP defense high-level wastes have high iron concentrations, no additional iron would need to be added to the lead metaphosphate formulation.² Therefore, the applicability of the LIP formulation to the specific defense wastes stored at SRP and the compatibility of this glass with the Defense Waste Processing Facility (DWPF) design were investigated.

The areas considered in this study were the following:

- o The flexibility of the glass with respect to the range of SRP waste compositions
- o The effect of the reducing conditions in the DWPF melter caused by the requirement to add formic acid to the hydroxide waste sludge during premelt processing
- o The durability of the final glass product as a function of waste composition and solubility of the waste components
- o The compatibility of the phosphate melt with the DWPF melter chrome-alumina refractory and the Inconel™ electrodes

EXPERIMENTAL

Glass Formulation

The chemical composition of the simulated Savannah River Waste (SRW*) glass first fabricated by the ORNL developers represents a 50 mol% PbO + 50 mol% P₂O₅ glass, to which 15 wt% simulated waste as oxides and sulfates¹ was added. The simulated ORNL/SRW composition given¹ for an average SRP waste

*Terminology used by ORNL will be used hereafter to designate their SRP waste formulation.

composition, TDS-3A, was attributed to Baxter⁶ and doped with 4.5 wt% U_3O_8 , 1 wt% SrO and 1 wt% Cs_2O . The coal and zeolite components of TDS-3A⁶ were omitted. Comparing the ORNL/SRW, and the TDS-3A SRP waste composition^{6,7} demonstrates that the ORNL/SRW formulation is incorrect. It is alkali enriched and silica deficient.⁸ Using the correct TDS-3A waste composition with zeolite at 14 wt% waste loading gives a $Fe_2O_3/PbO \cdot P_2O_5$ ratio of only 7.8 and additional Fe_2O_3 would have to be added to increase this ratio to about 9.0. By increasing the waste loading to 15.7 wt% and not adding additional Fe_2O_3 , a ratio of 8.5 can be achieved.⁸

The ORNL/SRW and the TDS-3A formulations were fabricated with and without the zeolite component of the waste in alumina and platinum crucibles. High-purity alumina crucibles were used because of their compositional similarity to the alumina-rich refractory lining of the DWPF melter. In some experiments, the U_3O_8 component was omitted as well.

The SRP wastes may vary from alumina-enriched to iron-enriched types.^{6,7} Therefore, LIP glass formulations representing the waste composition extremes, and high iron and high alumina waste were also investigated.⁸

The glasses were fabricated from reagent-grade oxides, carbonates, sulfates, and $(NH_4)_2HPO_4$. Activated carbon was used as the coal component, and Linde AW-500 molecular sieve as the zeolite.⁶ The P_2O_5 was added as $(NH_4)_2HPO_4$ and each of the formulations was melted at 850^o, 950^o, 1050^o, and 1150^oC following procedures specified by the ORNL developers.¹⁻³

The alkaline hydroxide waste sludges at SRP are mixed with formic acid to reduce mercury compounds to the metallic state so that mercury may be

steam-stripped from the waste.⁹⁻¹⁰ The addition of the formic acid also changes the rheology of the sludge to a transportable slurry.¹¹ The formic acid, aromatics that arise during waste sludge processing, and the presence of coal in some of the wastes will control the oxygen fugacity of the DWPF melter at 10^{-6} to 10^{-7} atmospheres.⁹⁻¹⁴

To evaluate whether the LIP glass formulations would be compatible with the reducing conditions of the DPWF melter, all the LIP formulations were melted in open crucibles with no coal, and in closed crucibles with coal. Using coal as the reductant during a closed crucible test imparts only mildly reducing conditions to the melt.¹³

The durability of the LIP glasses was evaluated based on the scoping leach test developed by the Materials Characterization Center (MCC) for evaluation of nuclear wasteforms. The MCC-IP test procedure was followed.¹⁵ The tests were run in duplicate and the solution analyses determined by ICP for Si, P, Pb, Sr, and Na. The Cs was determined by AA, and the U analyses were determined with a Syntrex UA-3 analyzer.

Twelve samples each of Inconel™ 690 (DWPF electrode metal) and Monofrax™ K-3 (DWPF melter sidewall refractory) were submitted to Corning Engineering Laboratory Services. The samples were tested by the ASTM C-621 Static Test for Corrosion Resistance of Refractories to Molten Glass. The tests were conducted at 1150°C for seven days in the SRP high-iron lead-iron-phosphate formulation without zeolite, and in SRL borosilicate waste glass formulations (SRL165 and SRL131).¹⁶

RESULTS

Glass Flexibility

Twenty-four lead-iron-phosphate glass formulations were melted containing 13-16 wt% simulated SRP waste. All but two formulations made with high-iron waste were visually nonhomogeneous or did not melt when the zeolite component of the waste was present. The glasses were fabricated in alumina crucibles (Table I). Although 16 of the glasses melted and poured easily at temperatures as low as 850°C large particulates were visible in all the glasses melted between 850°C and 1150°C. The latter temperature is 100°C above the melt-temperature range determined by the developers.¹⁻⁴ The glasses fabricated at the lowest temperature, 850°C, were the most nonhomogeneous. The high-iron, 13 wt% waste-loaded LIP glass that melted at 1150°C appeared visually homogeneous, but the high-alumina, 15 wt% loaded glasses did not melt at any temperature (Table I).

TABLE I. LEAD PHOSPHATE GLASSES WITH SRP WASTE
SIMULATIONS (OXIDIZED & REDUCED CONDITIONS)

Waste Type	Waste Loading (wt%)	Melt Temperature (°C)			
		850	950	1050	1150
High Al	15	Did Not Melt	Did Not Melt	Did Not Melt	Did Not Melt
Composite TDS	16	N	N	N	N
High Fe	13	N	N	N	H

N = Visually Nonhomogeneous
H = Visually Homogeneous

High-alumina LIP glasses containing 5 and 10 wt% waste did not melt at temperatures up to 1150°C, although the $\text{Fe}_2\text{O}_3/\text{PbO}\cdot\text{P}_2\text{O}_5$ ratio of the glass was ≥ 9 and the PbO content was in the range specified by the developer.¹⁻⁴

The nonhomogeneous and particulate components of the TDS-3A LIP glass formulation that melted at 850°C and 1050°C were characterized by x-ray diffraction analysis and quantitative electron microprobe. The x-ray diffraction analysis revealed the presence of undissolved AW-500 zeolite and AlPO_4 (JCPDS 11-500) crystallites. No attempt was made to finely crush the zeolite component during these first scouting tests because a waste treatment procedure is unrepresentative of the DWPF process.⁹ The quantitative electron microprobe showed that the lead-iron-phosphate glass forms a reaction zone around the zeolite particles. The microprobe verified the existence of $(\text{Al,Fe})\text{PO}_4$, indicating that the Al_2O_3 component of the waste may combine with the phosphate and possibly some iron to crystallize $(\text{Al,Fe})\text{PO}_4$, as no interaction with the high-purity alumina crucibles was observed.⁸

The ORNL/SRW glass formulation without U_3O_8 and zeolite was melted in alumina crucibles and the product was not vitreous. When the U_3O_8 was left out of the formulation, the resulting glass was still nonhomogeneous.

Twelve of the 24 lead-iron-phosphate glass formulations were melted under reducing conditions. Of the 16 glass formulations that melted, nonhomogeneities and particulates were more abundant in the glasses melted under the reducing conditions.

All of the LIP glass formulations made in alumina crucibles were nonhomogeneous except for the two high-iron waste formulations fabricated at 1150°C. The composite waste formulations (ORNL/SRW and TDS-3A/SRP) made in alumina crucibles were all nonhomogeneous, whether zeolite was present or not.

Fabrication of a homogeneous glass of the ORNL/SRW formulation in platinum crucibles, as recommended by the ORNL developers,³⁻⁴ was attempted. When the zeolite component of waste was included in the ORNL/SRW formulation, the glass was visually nonhomogeneous and undissolved zeolite remained in the platinum crucible. Crushing the zeolite before melting still produced nonhomogeneities, although on a smaller scale. By omitting the zeolite component of the waste and using the ORNL/SRW high-sodium formulation and platinum fabrication crucibles, a homogeneous glass was obtained.⁸

Phase Equilibria

The known phase-diagrams for the bounding binary systems¹⁷ were used to determine the ternary liquidus surface in the P_2O_5 -PbO- Fe_2O_3 system (Figure 1). The P_2O_5 -rich portion of the binary diagrams for the PbO- P_2O_5 and the Fe_2O_3 - P_2O_5 systems was incomplete. The liquidus temperatures for the P_2O_5 -rich portions of these systems were determined in this study to within the nearest 100°C (solid triangles in Figure 1).

An isothermal section of the ternary P_2O_5 -PbO- Fe_2O_3 system at 850°C shows that a low-melting trough parallels the PbO- P_2O_5 binary system (Figure 1). The Fe_2O_3 /PbO· P_2O_5 = 9 wt% ratio, empirically determined by ORNL developers, is shown (converted to mol%) by the large circle lying in the shaded trough. The 1150°C isothermal section widens the trough to include the PbO-rich portion of the ternary diagram and more Fe_2O_3 -rich compositions.

Glass Durability

The ORNL developers compared the durability of the LIP glass formulations with SRL borosilicate glass 131 and found the LIP glasses to be 10^2 - 10^3 times lower in release, in gm/m^2 day (Figure 2A). LIP glass durability published by the ORNL authors was duplicated in the present study, but these results represented the minimum releases observed. These results are superimposed on Figure 2A in bold and represent the last significant digit. The minimum values for the LIP glass could be duplicated, but were not routinely achieved. The glasses made under the more oxidizing conditions were more durable than those made under reducing conditions. Glasses fabricated at higher temperatures were more durable.⁸

The ORNL developers compared the LIP glass formulation with borosilicate SRL waste glass. However, the current SRP waste glass formulation is SRL 165, which is far superior to SRL 131.⁷ Using the SRL 165 durability¹⁸⁻²⁰ and plotting the maximum release values for SRL 165 against the maximum release values reported for LIP glass formulations gives the comparative bar-graph shown in Figure 2B. The bar graph readily demonstrates that the LIP glasses are somewhat better in terms of Cs, Na, and Si releases but that Sr and U releases are much greater than in the borosilicate formulation.⁸

The ORNL/SRW formulation was fabricated in platinum crucibles with zeolite, finely crushed zeolite, and with no zeolite. These glasses were tested in quadruplicate. There was little difference between the elemental releases, whether the zeolite component was present or absent, and whether the zeolite component was crushed or uncrushed.⁸

The durability data for the LIP formulations fabricated in platinum are comparable to the data for the TDS-3A formulation fabricated in alumina crucibles. The values for Na, Sr, and Cs releases are comparable to those published by the ORNL developers,¹⁻³ but the P and Pb releases were 10 times higher. Moreover, the U and Sr releases were 100 times higher than the ORNL values.

Melt Corrosiveness

In the DWPF, the electrodes and lid heaters of the melter will be Inconel™ 690. The melter sidewall refractory will be Monofrax™ K-3, a chrome-alumina refractory. Corrosion tests indicated that the borosilicate glasses corrode Inconel™ 690 at a rate of 230-255 mil/year at the melt line, whereas the LIP glass formulation dissolves the Inconel™.¹⁶ The corrosion rate of the Monofrax™ K-3 in contact with the LIP glass melt was not excessive.¹⁶

DISCUSSION AND CONCLUSIONS

The ORNL developers primarily examined the waste glass formulation and parameters affecting the product performance, such as chemical durability, wasteform solubility, thermal stability, and mechanical stability. A systems approach to the development of a new host-solid for immobilizing nuclear waste must optimize these product parameters relative to processing considerations such as melt temperature, waste solubility, melt corrosiveness, and volatility hazardous species.²¹ Although the ORNL developers considered the low-melt temperatures and, hence, the low volatility of hazardous species during of

melting as attributes of the phosphate glasses, the corrosiveness of the melt was not considered. Phosphate melt corrosiveness and lack of thermal stability led to the abandonment of phosphate-based glasses in both the European²² and U.S.²³ communities. Indeed, the delay in developing phosphate glasses for use in waste disposal has been attributed to the lack of industrial use of these glasses because of their corrosiveness; hence, the lack of commercial experience and technology, such as exists for the various silica and borosilicate-based glasses.²⁴

The ORNL developers did not consider the waste solubility in the phosphate melt, nor did they examine the compositional similarities between their phosphate formulation and those tested by the Waste Solidification Engineering Prototypes (WSEP) program.²³ The WSEP program was initiated in 1966 at Pacific Northwest Laboratory (PNL). WSEP was a pilot plant designed for a radioactive demonstration of three solidification processes, two for borosilicate glass, and one for phosphate glass.²³ Eleven canisters of radioactive phosphate waste glass were solidified. The WSEP program demonstrated that phosphate waste glasses were extremely corrosive, required the use of platinum melters, and placed limitations on the melt temperature in metal canisters. Segregation of fission products in the phosphate glass melts was also observed, as well as low solubility of alumina, alkaline earths, and sulfate.

The LIP glass formulation has a somewhat higher PbO content and lower waste loading than the WSEP phosphate glasses. However, the melt corrosiveness, low waste-component solubility, and increased leaching of nonhomogeneous glass observed in the WSEP phosphate glasses were also observed

in LIP glasses examined in this study and at Karlsruhe.²⁵

The ORNL developers suggested that the lead-iron-phosphate glass could be prepared with minimal modification to the technology developed for processing borosilicate glass for high-level nuclear defense waste. However, the results of this study indicate that the LIP glass formulations are incompatible with SRP wastes; in particular, with the compositional ranges and with the alumina and silica components of the waste.

The LIP formulations lack of flexibility with SRP waste compositional extremes is in agreement with previous experience at the Savannah River Laboratory with Pb glasses, where a single composition could not be made compatible with both high-iron and high-aluminum wastes.²⁶ The lack of phosphate glass flexibility toward waste variation was also noted in the WSEP at PNL.²⁴

The incompatibility of the lead phosphate glass with SRL waste components arises from the following:

- o Incomplete dissolution of Al_2O_3 , which crystallizes as $(Al,Fe)PO_4$
- o Unreacted SiO_2 as a melt insoluble
- o Unreacted or partially reacted zeolite as a melt insoluble
- o Interactions of Al_2O_3 U_3O_8 , which forms a nonvitreous product

The ternary liquidus surfaces for the $PbO-P_2O_5-Fe_2O_3$ system between 850-1050°C were determined in this study. The low-melting trough is optimized along an isoplethal section of about 10 mol% Fe_2O_3 . This is the composition empirically determined at ORNL as the optimal LIP glass formulation.

The phase relations for the quaternary system $\text{PbO-SiO}_2\text{-P}_2\text{O}_5\text{-Fe}_2\text{O}_3$ are not known, but the phase relations of an isoplethal section at 10 mol% Fe_2O_3 should be very similar to the $\text{PbO-SiO}_2\text{-P}_2\text{O}_5$ ternary phase relations. A large region of liquid-liquid phase separation exists between $\text{PbO-P}_2\text{O}_5$ compositions and as little as 1 mol% SiO_2 . Raman spectroscopy²⁷ demonstrated that the immiscibility of silicate in phosphate melts is due to the competing structural role of $(\text{PO}_4)^{-3}$ and $(\text{SiO}_4)^{-4}$ and the tendency of the tetrahedrally coordinated phosphorous to form AlPO_4 clusters. The formation of AlPO_4 clusters is supportive of the AlPO_4 and silicate nonhomogeneities found in the LIP glass formulations.

Fabrication of a homogeneous LIP glass was achieved in this study when the ORNL high-sodium, low-silicon composition without zeolite was melted in a platinum crucible. Adding the zeolite component in this formulation produced nonhomogeneous glass, and undissolved zeolite remained in the platinum crucible. Crushing the zeolite before melting produced nonhomogeneities, although on a smaller scale. It may be that the high Na content of this waste composition fluxes the reactivity with the silicate components, as was found during the WSEP program when sodium hydroxide and ferric nitrate were added to phosphate melts to adjust the melt temperature and viscosity.²⁴

The low leachabilities reported by ORNL were duplicated in this work but were not routinely achievable, particularly with the nonhomogeneous glasses and the glasses produced under reducing conditions. The poor performance of the glasses made under reducing conditions is not surprising, because the ORNL developers suggest that it is the Fe_2O_3 component of the LIP formulation which strengthens the cross-bonding in the phosphate glass.²⁴ However, the

reducing conditions are representative of the oxygen fugacity in the DWPF process.⁹⁻¹⁴

When the maximum releases of SRP borosilicate glasses were compared with the maximum releases from LIP glasses fabricated in alumina crucibles, there was very little difference between the LIP glass and SRL 165 waste glass durability. The Cs release of the LIP glasses was lower than that of the borosilicate. The releases of Si and Na were lower than that of borosilicate glass, but the Sr and U release were up to 100X greater than borosilicate glass. The Pb and P releases determined in this study varied ten-fold from those reported by ORNL.

The durability of the LIP formulation (ORNL/SRW) fabricated in platinum crucibles was higher than that reported by the developers. There was little difference between the elemental releases of this glass formulation, whether the zeolite was present or absent and whether the zeolite was crushed or uncrushed. The data for all the melts fabricated in platinum crucibles, whether homogeneous or nonhomogeneous, were higher than those reported by the developers.

In the the DWPF, the electrodes and lid heaters of the melter will be Inconel™ 690 and the melter sidewall refractory will be Monofrax™ K-3, a chrome-alumina refractory. The results of the corrosion tests demonstrated that the Inconel™ 690 dissolves in the LIP glass formulation. The Monofrax™ K-3 corrosion is minimal. However, the contact between the Al₂O₃-rich refractory and the phosphate melt is expected to make nonhomogeneous glass, as evidenced during laboratory-scale melting in Al₂O₃ crucibles.

References

1. B. C. Sales and L. A. Boatner, "Lead-Phosphate Glass as a Stable Medium for the Immobilization and Disposal of High-Level Nuclear Waste", Materials Letters, 2 [4B], 301-304 (1984).
2. B. C. Sales and L. A. Boatner, "Lead-Iron-Phosphate Glass: A Stable Storage Medium for High-Level Nuclear Waste" Science, 26, 45-48 (October 5, 1984).
3. B. C. Sales and L. A. Boatner, "Physical and Chemical Characteristics of Lead-Iron-Phosphate Nuclear Waste Glasses", ORNL-6168, Martin Marietta Energy Systems, Inc., Oak Ridge, TN (May, 1985).
4. B. C. Sales and L. A. Boatner, "Physical and Chemical Characteristics of Lead-Iron Phosphate Nuclear Waste Glasses" J. Non-Crystalline Solids 79, 83-116 (1986).
5. B. C. Sales and L. A. Boatner "Structural Properties of Lead-Iron-Phosphate Glasses", J. Non-Crystalline Solids 71, 103-112 (1985)
6. R. G. Baxter, "Description of Defense Waste Processing Facility Reference Wasteform and Canister", U.S. DOE Report DP-1606-Rev. 1, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, SC 29808 (August, 1983).
7. P. D. Soper, D. D. Walker, M. J. Plodinec, G. J. Roberts and Leo F. Lightner, "Optimization of Glass Composition for the Vitrification of Nuclear Waste at the Savannah River Plant". Am. Ceram. Soc. Bull. 62 [9]1013-1018 (1983).
8. C. M. Jantzen, "Investigation of Lead-Iron-Phosphate Glass for SRP Waste", DP-XXX/CJ, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, (June, 1985)
9. R. G. Baxter, R. Maher, J. B. Mellen, L. F. Shafranek, W. R. Stevens, III, "The Defense Waste Processing Facility" Waste Management 84, 1, 275-278 (1984).
10. F. H. Brown, C. T. Randall, M. B. Cospers and J. P. Moseley, "Savannah River Laboratory's Operating Experience with Glass Melters" The Treatment and Handling of Radioactive Wastes, Springer-Verlag, New York, 191-196 (1983).
11. M. J. Plodinec, P. D. Soper, N. E. Bibler and J. L. Kessler, "SRP Radioactive Waste Glass Studies: Small-Scale Process Development and Product Performance" The Treatment and Handling of Radioactive Wastes, Springer-Verlag, New York, 431-434 (1983).

12. M. J. Plodinec, "Factors Affecting the Iron Oxidation State and Foaming in SRP Waste Glass", Proceedings of the Symposium on High Temperature Materials Chemistry. The Electrochemical Society, Pennington, N. J. 201-209 (1982).
13. D. F. Bickford, R. B. Diemer, Jr. and D. C. Iverson, "Redox Control of Electric Melters with Complex Feed Compositions, Part II. Preliminary Limits for Radioactive Waste Melters" J. Non-Crystalline Solids E. I. du Pont, etc. (1986)
14. D. F. Bickford and R. B. Diemer, Jr., "Redox Control of Electric Melters with Complex Feed Compositions, Part I. Analytical Methods and Models, J. Non-Crystalline Solids E. I. du Pont, de Nemours & Co., Aiken, SC. (1986).
15. Nuclear Waste Materials Handbook--Waste Form Test Methods, MCC-1P Static Test, Prepared by Materials Characterization Center, J. E. Mendel, Manager, U.S. DOE Report DOE/TIC-11400, Pacific Northwest Laboratory, Richland, WA (1981).
16. Corning Engineering Laboratory Services Report MKT3, Corning, NY (January, 1986).
17. E. M. Levin, C. R. Robbins and H. F. McMurdie, "Phase Diagrams for Ceramists, Vol I" The American Ceramic Society, Columbus, OH (1964).
18. S. Williams and G. G. Wicks, "MCC-1 Leachability Study of SRP Black Frit Waste Glass--Part II", U. S. DOE Report DPST-84-209, E. I. du Pont, de Nemours & Co., Aiken, SC. (1984).
19. J. E. Mendel, "Final Report of the Defense High-Level Waste Leaching Mechanisms Program" PNL-5157, Pacific Northwest Laboratory, Richland, WA 99352 (1984).
20. N. E. Bibler, "Leaching Radioactive and Nonradioactive Elements from Actual Savannah River Plant Nuclear Waste Glass" American 86th Annual Ceramic Society, Pittsburgh (1984) April DP-MS-83-133 (1984).
21. C. M. Jantzen, "Systems Approach to Nuclear Waste Glass Development" J. Non-Crystalline Solids (1986).
22. J. L. McElroy, W. J. Bjorklund and W. F. Bonner, "Waste Vitrification: A Historical Perspective: The Treatment and Handling of Radioactive Wastes, Springer Verlag, New York 171-177 (1982).
23. J. L. McElroy, J. J. Schneider, J. N. Hartley, J. E. Mendel, G. L. Richardson, R. W. McKee and A. G. Blasewitz, "Waste Solidification Program Summary Report, Vol 11, Evaluation of WSEP High Level Waste Solidification Processes", BNWL-1667 (1972).
24. J. E. Mendel, "The Storage and Disposal of Radioactive Waste as Glass in Canister", PNL 3946, Battelle Pacific Northwest Laboratories, Richland, WA 99352 (1978).

25. L. Kahl and W. Bernotat, "Investigation of a Lead-Iron-Phosphate Glass as a Waste Form for Commercial High-Level Liquid Wastes (HLLW) compared with the GP 98/12 Borosilicate Glass Product, this volume.
26. M. J. Plodinec, "Development of Glass Compositions for Immobilization of SRP Waste", U. S. DOE Report, E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, SC, DP-1517 (1979).
27. B. O. Mysen, D. Virgo and F. A. Seifert, "The Structure of Silicate Melts: Implications for Chemical and Physical Properties of Natural Magma", Rev. of Geophys. and Space Phys. 20 [3], 353-383 (1982)

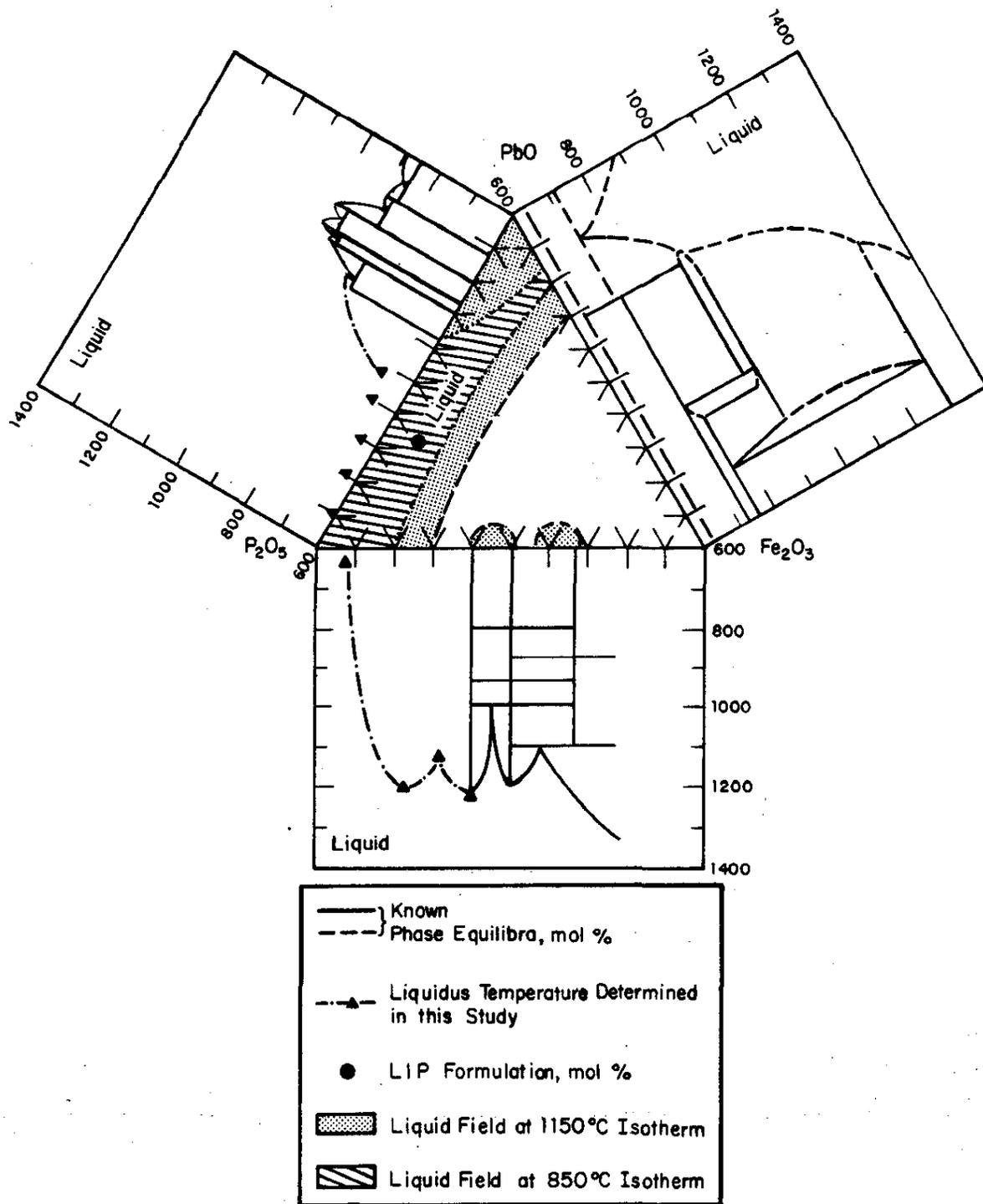


Figure 1. Ternary liquidss for the P_2O_5 - PbO - Fe_2O_3 system between 850 and 1150°C.

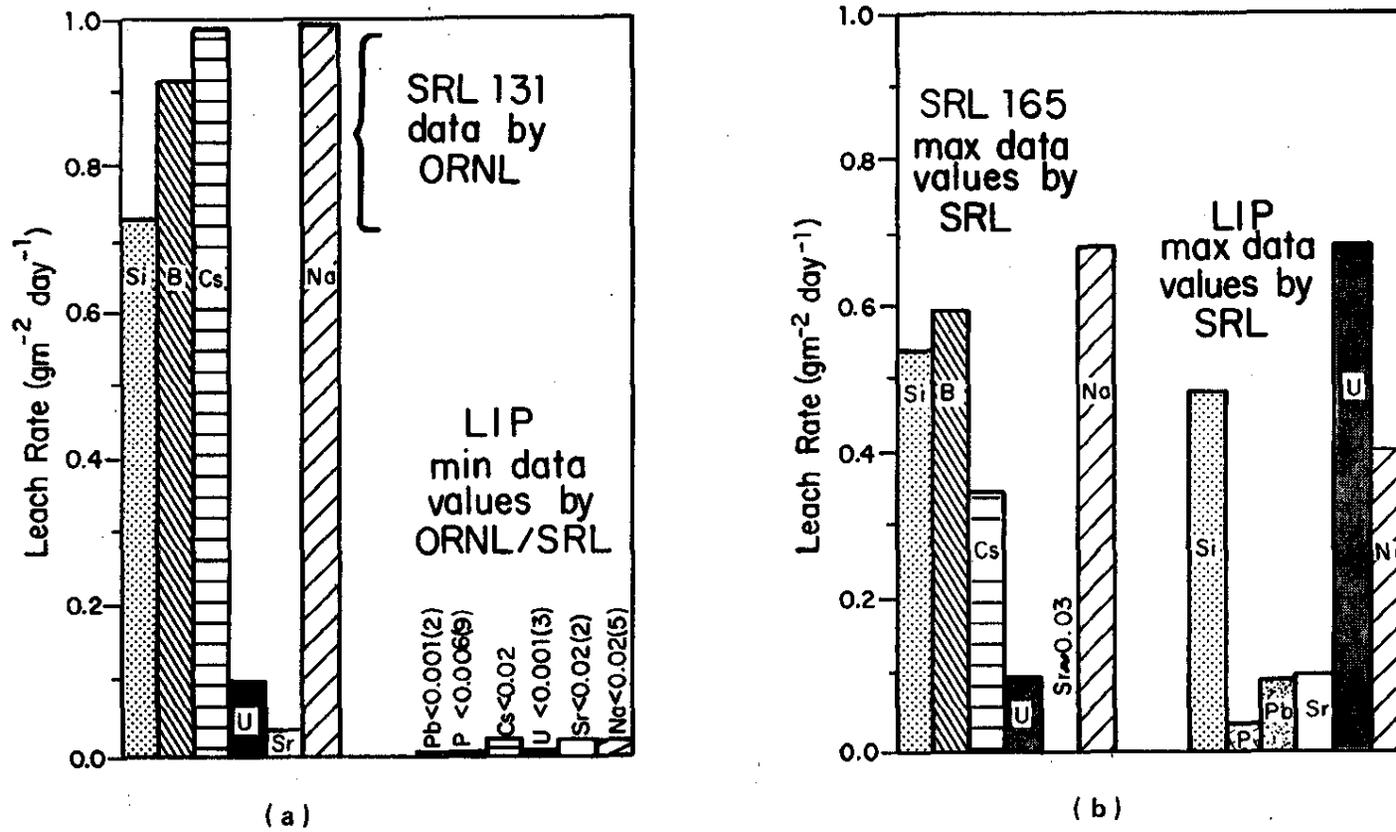


Figure 2.

Comparative durability data for lead-iron-phosphate (LIP) glasses and borosilicate glasses SRL 131 and SRL 165.