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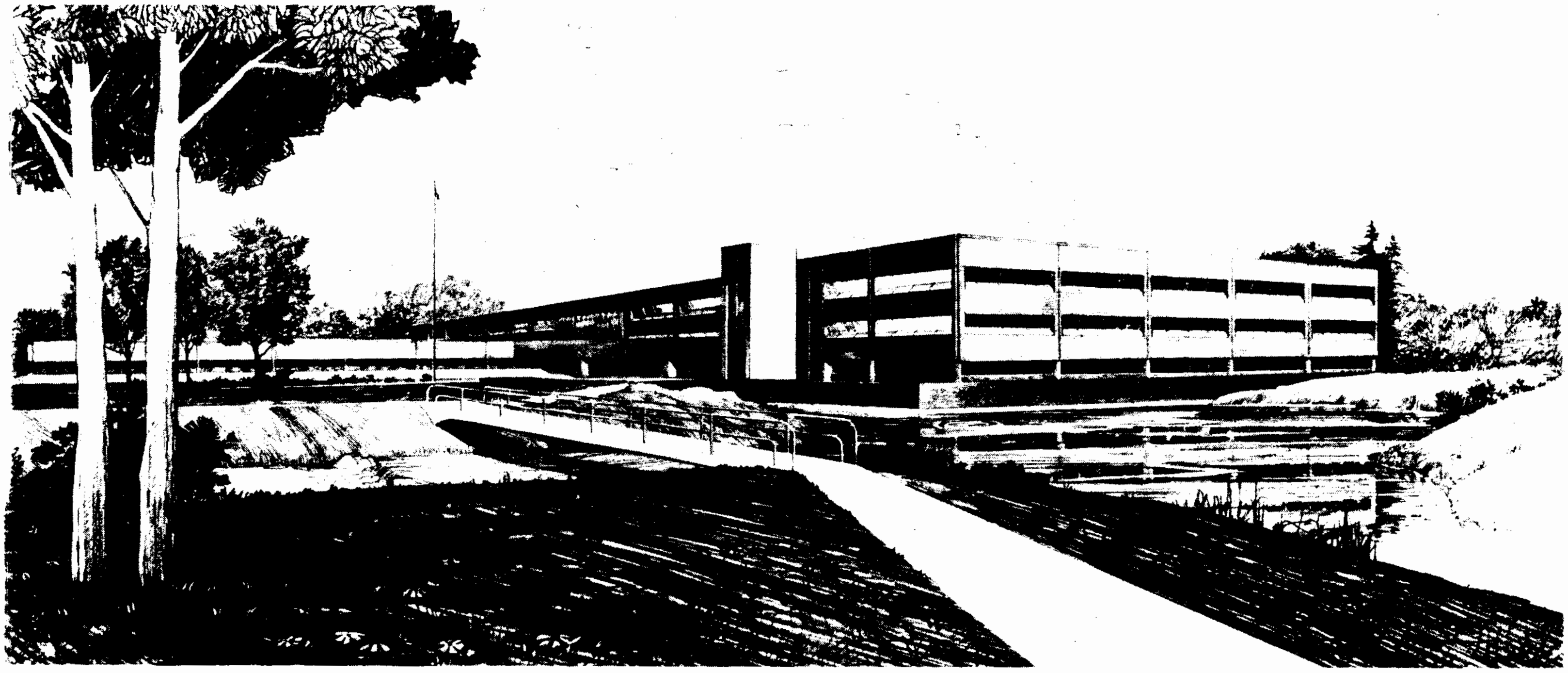
# THE STATUS OF IRON-ENRICHED BASALT AS A MEDIUM FOR NUCLEAR WASTE IMMOBILIZATION: A REPORT BY AN INDEPENDENT PEER REVIEW PANEL

Hayne Palmour III, Chairman
Robert G. Dosch
Pedro B. Macedo
Albert J. Machiels
Dennis E. Owen, Editor

**U.S. Department of Energy**
Idaho Operations Office • Idaho National Engineering Laboratory



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Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under DOE Contract No. DE-AC07-76ID01570

EG&G Idaho

# DISCLAIMER

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# EXECUTIVE SUMMARY[a]

It was the concensus of the Peer Review Panel that the concept, experimental research, and identification of potential applications of the iron-enriched basalt waste form were of high quality.

Iron-enriched basalt is a primarily ceramic waste form with a residual glass phase. It has a broad range of composition, permitting the incorporation of a wide variety of nuclear wastes. The product has good mechanical strength and produces very low quantities of respirable particles under impact conditions. Matrix dissolution rates under neutral pH conditions are comparable to or lower than those of borosilicate glass.

In the area of waste form characterization, the Panel recommended additional static and dynamic leaching tests as a function of pH and $CO_2$ in solution, and in brine solutions of varying composition. The panel also recommended that unprocessed transuranic (TRU) wastes be subjected to leach tests in order to determine whether the concentration of actinides in solution is solubility- or dissolution-rate controlled. If the former is true, high-technology waste forms such as IEB may not be needed.

Large-scale iron-enriched basalt castings in which the grain growth was uncontrolled have been observed to be less durable than controlled-grain-growth laboratory-scale castings. Therefore, the Panel also recommended leaching tests as a function of microstructure to determine ranges of acceptable microstructure.

In the area of the IEB production process, the Panel recommended a variety of laboratory-scale and pilot plant-scale research. Laboratory-scale experiments should include measurements of the following: the glass transition temperature, thermal expansion coefficients, liquidus envelope as a function of melt composition, thermal conductivity and viscosity as a function of the iron oxidation states; the laboratory-scale experiments

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[a] Prepared by EG&G Idaho Staff with Panel concurrence.

should also include a heat treatment study to maximize the durability of the residual glass phase. Pilot plant-scale studies should include long-term melting and casting campaigns on the existing 250 kg capacity electromelter. Refractory and electrode lifetimes should be thoroughly evaluated. In addition, measurements on temperature and metal distribution in the melt, microstructural evaluations, and behavior of volatile elements in the melt should be evaluated.

The Panel reviewed all of the proposed applications for iron-enriched basalt. A rating system was used to rank each application. The existing political, regulatory, and economic climates were considered in evaluating the applications. The Panel recommended that research continue for the following waste form applications of iron-enriched basalt:

1. Commercial transuranic waste (e.g., waste generated by commercial fuel reprocessing, mixed oxide fuel fabrication, fast breeder reactor R&D and operation, etc.)

2. Defense transuranic waste (as a back-up waste form in case current attitudes change regarding defense waste acceptance criteria and volume reduction)

3. Special nuclear wastes (wastes from nuclear emergencies or other unusual sources, e.g., TMI core debris, contaminated soil, etc.)

# FOREWORD[a]

The Idaho National Engineering Laboratory (INEL) is the primary storage facility for defense transuranic waste in the United States. This waste, which is a highly heterogeneous mixture of combustible (paper, plastic, cloth, etc.) and noncombustible (metal, glass, chemical sludge, etc.) materials contaminated with transuranics, is presently stored primarily in 208-L steel drums and in wooden boxes coated with fiberglass-reinforced plastic. This waste is scheduled for retrieval, processing, and shipment to the Waste Isolation Pilot Plant (WIPP) in New Mexico near the end of this decade.

For several years EG&G Idaho, Inc., prime contractor at the INEL, has been funded by the Department of Energy to conduct research on a nuclear waste form called iron-enriched basalt and to investigate its potential for defense transuranic waste immobilization. EG&G Idaho has also obtained funding to investigate other nuclear waste immobilization applications of iron-enriched basalt, including defense high-level waste, commercial transuranic waste, and special nuclear wastes, (e.g., Three Mile Island core debris, contaminated soil, and water decontamination zeolites).

Iron-enriched basalt (IEB) is a rock-like waste form analogous to natural basalt. It is formed by dissolving nuclear waste in a high temperature molten bath. A brief overview of IEB and its properties is contained in Appendix I.

IEB is a very versatile waste form with a broad range of potential applications. To assess the validity of these applications and to provide an overall review of the IEB research and development effort, an independent Peer Review Panel was convened at EG&G Idaho in August 1981. This panel consisted of four nuclear waste form experts selected from a list of candidates approved by DOE. The Panel members included the following persons:

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[a] Prepared by EG&G Idaho staff with Panel concurrence.

Dr. Robert G. Dosch, Sandia National Laboratories

Dr. Pedro B. Macedo, Professor of Physics, The Catholic University of America

Dr. Albert J. Machiels, Nuclear Engineering Program, University of Illinois

Dr. Hayne Palmour III (Chairman), Professor of Ceramic Engineering, North Carolina State University.

At DOE's request, an observer was also in attendance:

Mr. Peter L. Gray, Research Staff Engineer, Savannah River Laboratory.

This report states the findings of the IEB Peer Review Panel.

## CONTENTS

# THE STATUS OF IRON-ENRICHED BASALT AS A MEDIUM FOR NUCLEAR WASTE IMMOBILIZATION: A REPORT BY AN INDEPENDENT PEER REVIEW PANEL

## 1. INTRODUCTION

At the invitation of EG&G Idaho, Inc., a panel comprised of Dr. Hayne Palmour III, North Carolina State University; Dr. Pedro B. Macedo, The Catholic University of America; Dr. Albert J. Machiels, University of Illinois; and Dr. Robert G. Dosch, Sandia National Laboratories, was formed and met on August 17-19, 1981, at Idaho Falls, Idaho, to provide a technical peer review of the Iron-Enriched Basalt Waste Form Program being conducted by EG&G Idaho. Dr. Palmour served as chairman of the panel. Mr. Peter L. Gray, Waste Management Planning, Savannah River Laboratory, attended the meetings as an observer. Complete addresses and phone numbers of panel members and the observer are given in Appendix II.

## 2. SCOPE OF WORK

The purpose of the Peer Review Panel was to provide an independent review by experts in nuclear waste processing and materials on the adequacy of the existing data base for the iron-enriched basalt waste form developed by EG&G Idaho, and to evaluate the broad range of proposed applications for this waste form. It was not the purpose of this review to specifically rank iron-enriched basalt against other nuclear waste forms, although technical comparisons with other waste forms could be addressed.

The Peer Review Panel members performed the following tasks:

1. Reviewed a data package on the iron-enriched basalt (IEB) waste form in order to become familiar with the research performed to date and the results obtained. The data package was supplied by EG&G Idaho, Inc.

2. Participated in a three-day review of the IEB waste form development program. The review was held in Idaho Falls, Idaho. This review consisted of:

    a. Presentations by EG&G Idaho personnel on IEB properties, fabrication processes, and nuclear waste applications;

    b. Discussions among peer reviewers of their observations;

    c. The preparation (under the direction of the Peer Review Panel Chairman) of a written critique of the IEB waste form development program. This critique was to address at least the following subjects:

        - Independent view of basalt waste form concept

        - Adequacy of the existing data base in supporting the proposed IEB nuclear waste applications

- Practicality of the IEB production process for use in large-scale applications

- Recommendations for additional research.

d. The letter report was prepared in draft form while the Peer Review Panel was in Idaho Falls.

## 3. DISCUSSIONS WITH EG&G IDAHO PERSONNEL

Having already had the benefit of reviewing several reports and documents describing the iron-enriched basalt (IEB) waste form, the Panel met with the EG&G staff members involved for a total of ten working hours on August 17 and 18, 1981.

The time was devoted to informal but very thorough presentations, via viewgraphs and slides, of the IEB concept (including processing, phase characterization, durability, and potential applications) by the Technical Manager (John Flinn) and others. The materials presented were made available to the Panel members in the form of convenient briefing books.

The remainder of the time was devoted to wide-ranging, often very detailed, technical discussions involving Panel members and the EG&G Idaho technical program managers and staff members present. The EG&G managers and staff members are identified in Appendix III.

After the Panel had completed its initial deliberations, another meeting was held on August 18, 1981 with EG&G Idaho personnel to brief them on the Panel's main findings and recommendations. Again, the free exchange of opinions and information between all the parties was very helpful to the Panel in preparing for its final deliberations and the drafting of this report.

It was the consensus of the Panel that the IEB work, including concept development, identification of potential applications, and initial experimental demonstrations, were of high quality. The multi-disciplinary make-up of the participating EG&G Idaho staff was evidenced by the thoroughness of the program, and the cooperation and communication between individual investigators were apparent.

Although the quantity of IEB information presented to the Panel was extensive, typical time and funding constraints were evident in some areas of the work. The Panel believes that additional information in specific areas would be of great value both in identifying and communicating the positive aspects of IEB and in facilitating direct comparisons of IEB with waste forms under development in other laboratories. Two general areas, waste form characterization and process definition, were judged to be of particular importance in this regard and are discussed in the following section.

# 4. GENERAL TECHNICAL RECOMMENDATIONS

## 4.1 Product Characterization

The product of the IEB process is a glass-ceramic having a wide range of composition, permitting the incorporation of a wide variety of nuclear waste ranging from contaminated soils to TRU sludges and metal parts. The product has adequate mechanical strength and when impacted produces very low quantities of respirable fines. It does not burn and is thermally stable to temperatures in excess of 873 K. Matrix dissolution rates under neutral pH are comparable to or lower than those of borosilicate glass.

A key question pertaining to the chemical durability of IEB is whether the actinide retention capability of the IEB waste form is superior to that of lower technology waste forms such as compacted wastes, calcines, cements, etc. In fact, it is generally postulated that under reducing conditions (rusted metal drums) and high pH, the concentration of actinides in solution is controlled by solubilities rather than dissolution rates. If this were true, high technology processing of TRU wastes would not be necessary. Therefore, a comparative leach study concentrating on the behavior of TRU elements should receive highest priority in order to either prove or disprove the above postulate.

Other areas where the IEB data base must be increased include these:

1. Leaching results as a function of leachant chemistry (specifically pH, $CO_2$ in solution, and brine solution composition, both for static and dynamic leach test conditions);

2. Leaching results as a function of microstructure.

## 4.2 Process Characterization

The IEB production process consists of preparing a melt at a nominal temperature of 1773 K, to which inert and radioactive constituents, primarily metal oxides, are added. After complete dissolution of the additives, the melt is cast into a metallic container. The container undergoes an appropriate heat treatment which promotes nucleation and growth of a number of crystalline phases bonded together by a residual glassy structure.

Scoping studies have resulted in the accumulation of a substantial data base: viscosity, thermal conductivity, and temperature ranges for nucleation and growth of the principal crystalline phases. The following additional information should be obtainable without difficulty:

1. Determination of liquidus envelope as a function of melt composition

2. Glass transition temperature

3. Thermal expansion coefficients

4. Thermal conductivity and viscosity as a function of the states of oxidation of iron in the melt

5. Optimum heat treatment resulting in a partially devitrified structure with a durable residual glass phase.

Since the IEB concept involves the use of high temperatures, it is imperative to generate, as soon as possible, long-term operational data using the existing INEL 250-kg capacity electromelter, with special emphasis on refractory and electrode lifetimes. Temperature and metal distributions in the melt should also be thoroughly characterized.

The current assessment of the homogeneity, microstructure, and chemical durability of waste forms obtained from large castings and their comparison with those obtained by laboratory-scale castings should be continued.

Additional information is required about the behavior of elements expected to be volatile at 1773 K. Preliminary data show exceptional cesium retention; the responsible mechanism should be identified (for example, mass transport control vs. chemical control could be investigated by bubbling an inert gas, such as argon, through the melt). Airborne particulate size distributions may have to be determined for various feed stocks and for volatile species.

# 5. DETAILED PROGRAMMATIC EVALUATION OF IEB

## 5.1 Method of Peer Review Panel Evaluation

The Panel was asked to consider ten different potential applications for the IEB process and to comment on the feasibility and marketability of each such potential waste form, its need for additional research and technology development, and its potential for full-scale operation. In carrying out this phase of its responsibility, the Panel met alone for more than four hours on August 18 and held extended discussions. It voted individually and point-by-point on factors pertinent to each waste form application. The individual rankings were averaged and pooled (without weighting factors) to arrive at relative figures-of-merit. Panel members expressed generally close agreements in the numerical values assigned to factors of interest for a given waste form. Since the numerical scale employed was an arbitrary one and would be of little value for any purpose other than establishing relative rankings, the actual values arrived at are not reported here. Using the composite figures-of-merit, the applications were ranked with the most favorable being first.

The consensus of the Panel was based upon several considerations, including existing and attainable IEB data bases, known processing and performance of IEB relative to a variety of other first- and second-generation waste forms, existing and proposed requirements for meeting safety and regulatory standards, as well as inescapable politico-economic and techno-economic factors and trends as presently perceived.

These opinions, together with a number of specific technical suggestions and the relative rankings of potential applications, were communicated to the EG&G staff in a briefing session by the Panel later in the day on August 18. All points of interest were discussed thoroughly by those present.

Because of similarities in the character of the wastes and the means required to treat them, two applications on the original list of potential applications were regrouped to form a single category. Potential non-nuclear applications were not considered in the formal sense, since they were not within the work scope of the panel, nor were they within the areas of expertise represented.

Two potential applications were viewed by the panel as being natural outgrowths of the present defense TRU studies and have been recommended for further research and development.

A new application, potentially involving strong gamma as well as TRU activities, has been identified for which IEB is possibly unique. This application involves the immobilization of wastes from nuclear emergencies or other special nuclear applications. Though many details need to be established to qualify the IEB process for such an operation, the Panel has also recommended that this option be considered for future development.

In the prevailing regulatory and fiscal climate, the other options were not considered to have good prospects for success and at this time they are not being recommended for extensive future work.

Subsection 5.2 below summarizes this panel's recommendations. Subsection 5.3 discusses the potential applications recommended for future development and briefly reviews those not recommended.

## 5.2 Summary of Peer Review Panel Recommendations

The following are the recommended applications for IEB:

1. Commercial transuranic waste

2. Defense transuranic waste

3. Reactor core debris and other special nuclear wastes (hereafter identified as "special nuclear waste")

The following are the IEB applications which are not recommended:

1. Defense and commercial high level waste (HLW)
2. Zeolites, resins (e.g., from TMI water cleanup). See qualification discussed in Section 5.3.2.2.
3. Commercial spent fuel

The following IEB applications were not considered:

1. Non-nuclear applications

## 5.3 Evaluation of Potential Applications

### 5.3.1 Applications Recommended by the Panel for Future Development

5.3.1.1 Commercial TRU Waste. Potential applications in this area depend in part upon resumption of commercial spent fuel reprocessing operations in the near future. The IEB concept could, in principle, accommodate cladding hulls as well as a number of waste streams and contaminated equipment derived from reprocessing operations. Other commercial TRU waste applications include mixed-oxide fuel fabrication wastes and wastes from the operation of the Fast Flux Test Facility and the future operation of the Clinch River Breeder Reactor.

Efficient disposal of cladding hulls would require high zirconium loadings. The potential for improvement over the reported 15 weight percent zirconia loading in IEB should be investigated, along with simultaneous microstructure, chemical durability, and mechanical properties assessments. Radiation damage effects should be addressed even though they are not likely to be limiting for this application.

Process technology, including the potential for zirconium fires and the generation of volatiles and respirables, will require thorough documentation. Maintenance and equipment failures can probably be accommodated by a contact handling philosophy.

Marketability of the concept appears good; however, the near-future market appears very limited. For the concept to be viable, it is imperative that the concerns discussed in Section 4.1, with special emphasis on chemical durability based on the behavior of actinides, be thoroughly documented.

5.3.1.2 Defense TRU Wastes. The science and technology goals of the TRU waste form research and development effort have been effectively attained by the EG&G Idaho staff. The marketability of continued work in this area may be low, primarily because WIPP does not currently require the durability or volume reduction provided by this high-technology TRU waste form. A change in these attitudes may be to IEB's advantage, provided that comparative leach data on TRU isotopes from IEB and competing low-technology waste forms show clear superiority.

In this regard, leach data are needed as a function of groundwater/brine composition, pH, and $CO_2$ content. In WIPP, unusually low pH leachants may be encountered and no such data are yet available for IEB.

In the area of volume reduction, the most important consideration may be the amount by which IEB can improve upon simple waste compacting.

In the area of processing, long-term operational data on the durability of melter components (refractories and electrodes) and on potential metal accumulations in the melter are urgently needed.

5.3.1.3 Special Nuclear Wastes. The IEB process may be unique in its ability to digest and immobilize diverse wastes, making it a prime candidate to immobilize wastes from unexpected national nuclear emergencies or other special nuclear wastes. These wastes could include materials as diverse as reactor core debris, contaminated soil, and exotic R&D materials. This application would require the ability to remotely process highly radioactive waste, an ability not yet demonstrated for IEB. The Panel recommends that research and development on IEB be carried out in order to more conclusively demonstrate its capability in this area. This could be done by establishing a special nuclear waste facility that can successfully treat these unusual waste problems.

Since this facility would be likely to encounter high gamma as well as TRU activities, it would require appropriate shielding and remote operation and maintenance capabilities. No demonstrated capability for remote operation of the IEB process exists (as is the case for most other high-temperature processes), though reasonably close parallels in glass and metallurgical operations suggest some prospects for success. Long-term operational data on refractories, electrodes, metal accumulations, etc., are urgently needed.

Because volatility of cesium may be enhanced under air bubbling conditions, off-gases and generation of respirables should be well documented. A great deal of background research will be needed to qualify the IEB process for hot operation, including detailed microstructural characterization, radiation damage effects, actinide retention and complete leaching studies.

In preparation for IEB operation, the large INEL hot cells may require upgrading to current safety standards.

### 5.3.2 Applications Not Recommended by the Panel for Future Development

In establishing relative rankings, the Panel considered many factors, among them:

- The current state of knowlege about the IEB process and the properties of its fused-cast glass-ceramic waste form.
- The kinds of additional data which would be required to qualify IEB for processing various wastes requiring shielding, remote operation, and maintenance, etc. These applications lie well beyond the contact-handled processes typical of present TRU operations.

- The relative status of development of other, better-established high-level waste forms, both first and second generation.

- Current politico-economic and techno-economic positions and trends.

For some of the potential IEB waste form applications considered, the Panel's consensus indicated that, taken as a whole, only low probabilities of success were likely to exist in the prevailing environment. These waste applications, therefore, are not being recommended for future development at this time. They are identified and discussed below.

5.3.2.1 Defense and Commercial High-Level Waste. The Panel concluded that:

- No near-term marketability exists.

- Even though the IEB leach rate data appear to be superior to borosilicate glass, they seem inferior to other second-generation defense (or commercial) waste forms, especially for actinide retention.

- Much research will be needed prior to serious consideration as a HLW waste form, including detailed microstructural characterization, radiation damage effects, actinide retention, and much stronger data bases for all leach rates of interest.

- Confirmation is needed, e.g., by radiotracer techniques, of retention of cesium and other volatiles.

- Future prospects will also depend upon the successes or failures of the present first-generation waste form choices for the ongoing HLW program.

5.3.2.2 Zeolites and Resins, (such as those used for radionuclide decontamination of water). Because the quantities of zeolites and resins are small, the Panel did not recommend development of IEB specifically for disposal of these materials. However, this application of IEB could be justified if it could be performed in an existing IEB processing facility, such as a special facility as discussed under Special Nuclear Waste.

The Panel concluded that:

- o These are well characterized wastes. They do not require the broad spectrum capabilities of the IEB process.
- o Pacific Northwest Laboratories has already handled "hot" HLW resins in borosilicate glass.
- o Rockwell Hanford has already stripped large quantities of cesium from zeolites, converted it to CsCl, and packaged it in double-wall stainless steel vessels considered acceptable for storage.
- o Marketability, therefore, is considered to be very low.
- o Many technical problems would have to be considered for the IEB process before working "hot," even for such a well characterized waste input as zeolite.

5.3.2.3 Commercial Spent Fuel (Interim storage of spent fuel in IEB man-made ore). The Panel concluded that:

- o The IEB technology is not yet ready to relieve near-future shortages of spent fuel storage--e.g., no "hot" experience, etc.
- o The present political climate appears to favor reprocessing, and thus industry and government may not be ready for such a semi-permanent interim solution.
- o If reprocessing is abandoned, direct packaging and burial of spent fuel may represent the most acceptable option.

- The front end of the process does not circumvent cutting, shearing, or shredding of spent fuel, a recognized industry-wide problem.

- Process technology to recover $UO_2$ or $PuO_2$ from "hot" man-made ore is not yet developed and would likely be complex.

- Comminution of such "hot" ore would present a difficult contamination-control problem.

- Cleanup and disposal of tailings from such an ore would represent an additional burden on process technology and unit costs.

# 6. REFERENCES REVIEWED BY THE PEER REVIEW PANEL

1. J. E. Flinn et al., Annual Report on the TRU Waste Form Studies with Special Reference to Iron-Enriched Basalt: 1980. EG&G-FM-5366, June 1981.

2. D. E. Owen and J. E. Flinn, Iron Enriched Basalt and Its Application to Three Mile Island Radioactive Waste Disposal: A Brief Review, RE-M-81-004, April 1981.

3. R. M. Horton and J. M. Welch, Preliminary Assessment of Cesium Volatility from Iron-Enriched Basalt Melts, RE-M-81-003, April 1981.

4. D. E. Owen, Application of the Iron Enriched Basalt Waste Form for Immobilizing Commercial Transuranic Waste, EG&G-WM-5484, August 1981.

5. D. E. Owen, J. E. Flinn, P. V. Kelsey, Jr. and R. L. Miller, The Conversion of LWR Fuel to Man Made Ore: An Alternative to Pool Storage, July 1981.

6. Iron-Enriched Basalt Peer Review Briefing Book, EG&G Idaho, Inc., August 1981.

7. Exxon Nuclear Idaho Company, Inc., Independent Evaluation of Candidate Alternative ICPP High Level Waste Forms, ENICO-1088, June 1981.

8. Savannah River Operations Office, Strategy Document: Long Term High Level Waste Technology Program, DOE/SR-WM-79-3, May 1981.

9. Alternative Waste Form Peer Review Panel, The Evaluation and Review of Alternative Waste Forms for Immobilization of High Level Radioactive Wastes, (Report Number 3), DOE/TIC-11472, July 1981.

# APPENDIX I

# AN INTRODUCTION TO THE IRON-ENRICHED BASALT WASTE FORM

(Prepared by EG&G Idaho Staff)

# APPENDIX I

## 1. AN INTRODUCTION TO THE IRON-ENRICHED BASALT WASTE FORM

Iron-enriched basalt (IEB) is a waste form under development by EG&G Idaho, Inc., at the Idaho National Engineering Laboratory. The principal sponsor of the research and development effort is the Department of Energy's (DOE) Transuranic Waste Systems Office. IEB is being developed primarily for the immobilization of transuranic wastes, although research has indicated that IEB has applications to the immobilization of high-level waste calcines and special category nuclear wastes such as TMI core debris and West Valley fuel reprocessing wastes.

### 1.1 The Production of Iron-Enriched Basalt

Iron-enriched basalt is a man-made analogue to natural basalt rock; it is produced by melting TRU waste with certain mineral additives at approximately 1773 K, as shown in Figure 1. Noncombustible TRU wastes would probably be processed by first shredding the waste into manageable sizes. Industrial shredders can readily shear an entire 208-L drum and its noncombustible contents into pieces a few tens of centimeters in size. This waste can then be sorted (unnecessary if the contents are accurately known) and fed directly into the IEB melter.

Combustible TRU wastes would first be incinerated. The resultant ash, primarily metal oxides, would then be added to the IEB melt.

After a hold time at 1773 K to oxidize the constituents, the melt is cast into a monolith. The conceptual design for an IEB production facility calls for the molten basalt to be cast into common, mild steel 208-L drums. The casting is then transferred to a furnace where it undergoes a controlled cooling cycle to devitrify the basalt.[a] The controlled

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[a] A non-optimized basalt product can be made by bypassing the controlled cooling step and allowing the casting to cool in ambient air. While this might be a somewhat less expensive process, it results in a basalt product which has a high glass content and is less durable than the devitrified iron-enriched basalt.

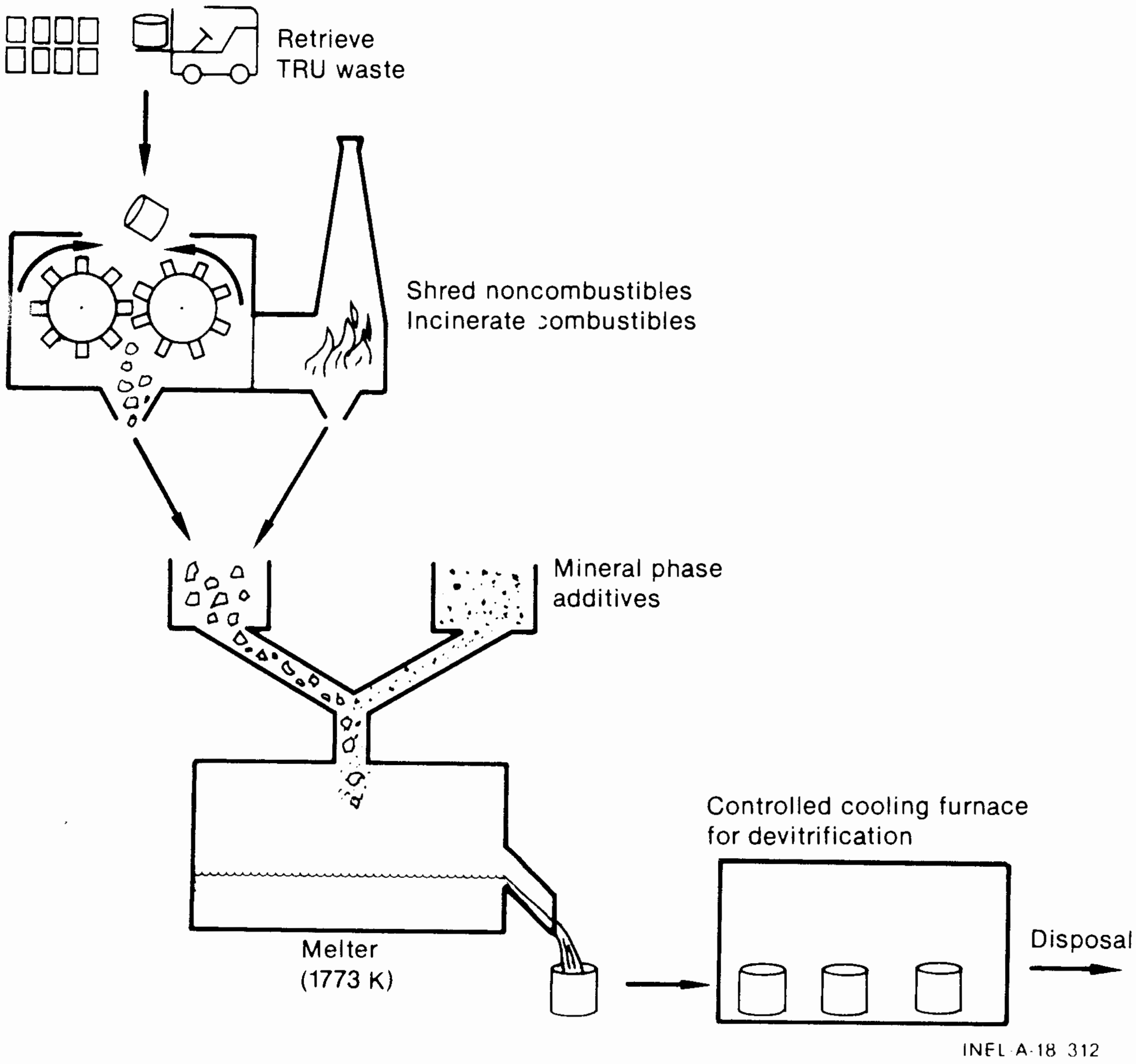

Figure 1. Iron-enriched basalt production schematic.

cooling cycle is performed in three steps: a brief temperature hold at 1220 K for nucleation of mineral phases, a longer temperature hold at 1370 K to promote growth of the mineral phases, and a thermal stress relief during final cooldown to relieve residual stresses. The microstructure of the devitrified product is shown in Figure 2. After TRU assaying and container lid welding, the waste form monolith is ready for shipment to a disposal site.

The nominal composition of IEB is shown in Table 1. However, as illustrated in Figure 3, IEB can be prepared over a broad composition range and does not require a highly tailored waste feed material.

TABLE 1. APPROXIMATE AVERAGE COMPOSITIONS OF IRON-ENRICHED BASALT AND NATURAL BASALT

| | Iron-Enriched Basalt (weight %) | INEL Natural Basalt[a] (weight %) |
|---|---|---|
| $SiO_2$ | 51 | 47 |
| $Fe_2O_3$ | 19.5 | 14 |
| $Al_2O_3$ | 10 | 16 |
| $CaO$ | 9.5 | 10 |
| $MgO$ | 3.5 | 7 |
| $Na_2O$ | 3 | 3 |
| $K_2O$ | 2.5 | 0.1 |
| $TiO_2$ | 0 | 3 |

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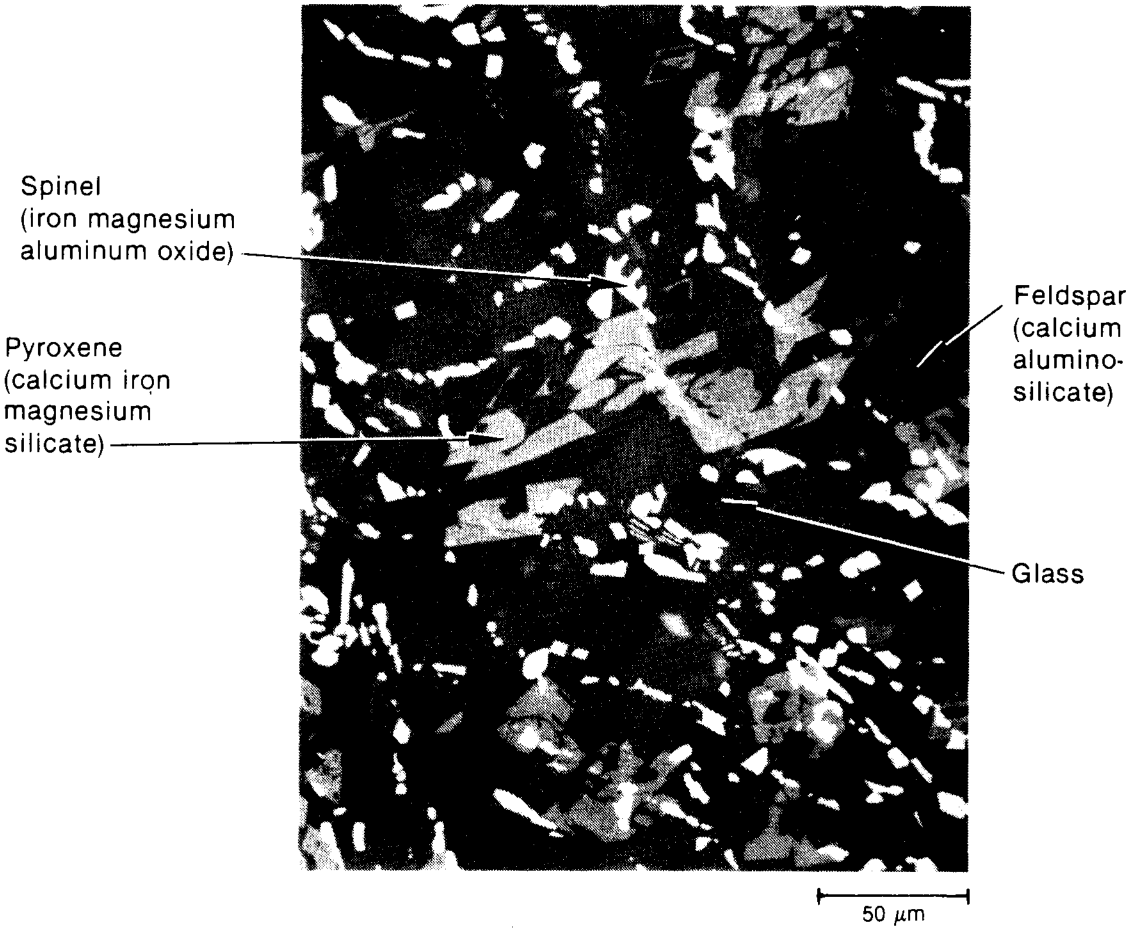
a. Natural basalt found in the vicinity of the Idaho National Engineering Laboratory in SE Idaho.

## 1.2 Properties

The suitability of a TRU waste form is generally measured in three ways. The first consideration is the long-term durability of the waste form, i.e., its ability to retain radionuclides over periods of geologic time. One measure of this ability is the NRC's proposed 10 CFR 60 rules,



Note: This specimen was produced with a large grain size to illustrate the microstructure. Actual waste form specimens have substantially smaller grains.

Figure 2. Structure of devitrified iron-enriched basalt.

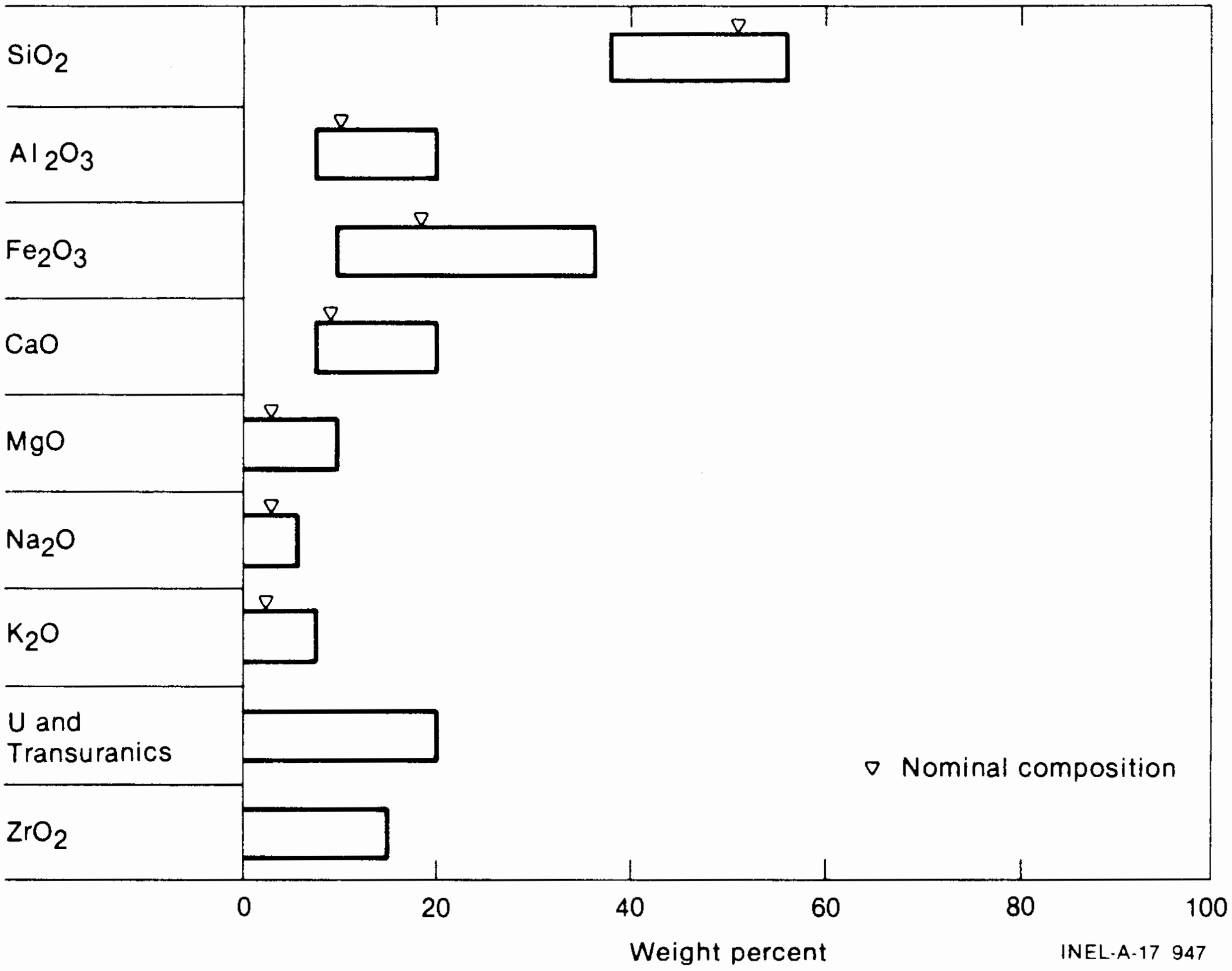


Figure 3. Tolerance range of major oxides in iron-enriched basalt.

which specify that the annual radioisotope release from a geologic respository must be $\leq 1$ part in $10^5$. This release limit corresponds to a leach rate of approximately $10^{-7}$ g/cm$^2$-day under repository conditions. Figure 4 shows that IEB meets this leach rate criterion.

A second waste form requirement is short-term durability, i.e., the ability to survive a transportation accident without radionuclide dispersal. The mechanical strength of IEB is shown in Figure 5. Recent Class A drop tests (approximately 1.25 m) on a full-scale (approximately 550 kg) IEB monolith failed to produce measurable quantities of respirable particles.

The ability to produce the waste form on a large scale with existing technology is a third measure of waste form suitability. The IEB waste form has been produced in both pilot-plant scale and full scale (Figures 6 and 7) using melters similar to those used in the commercial glass industry.

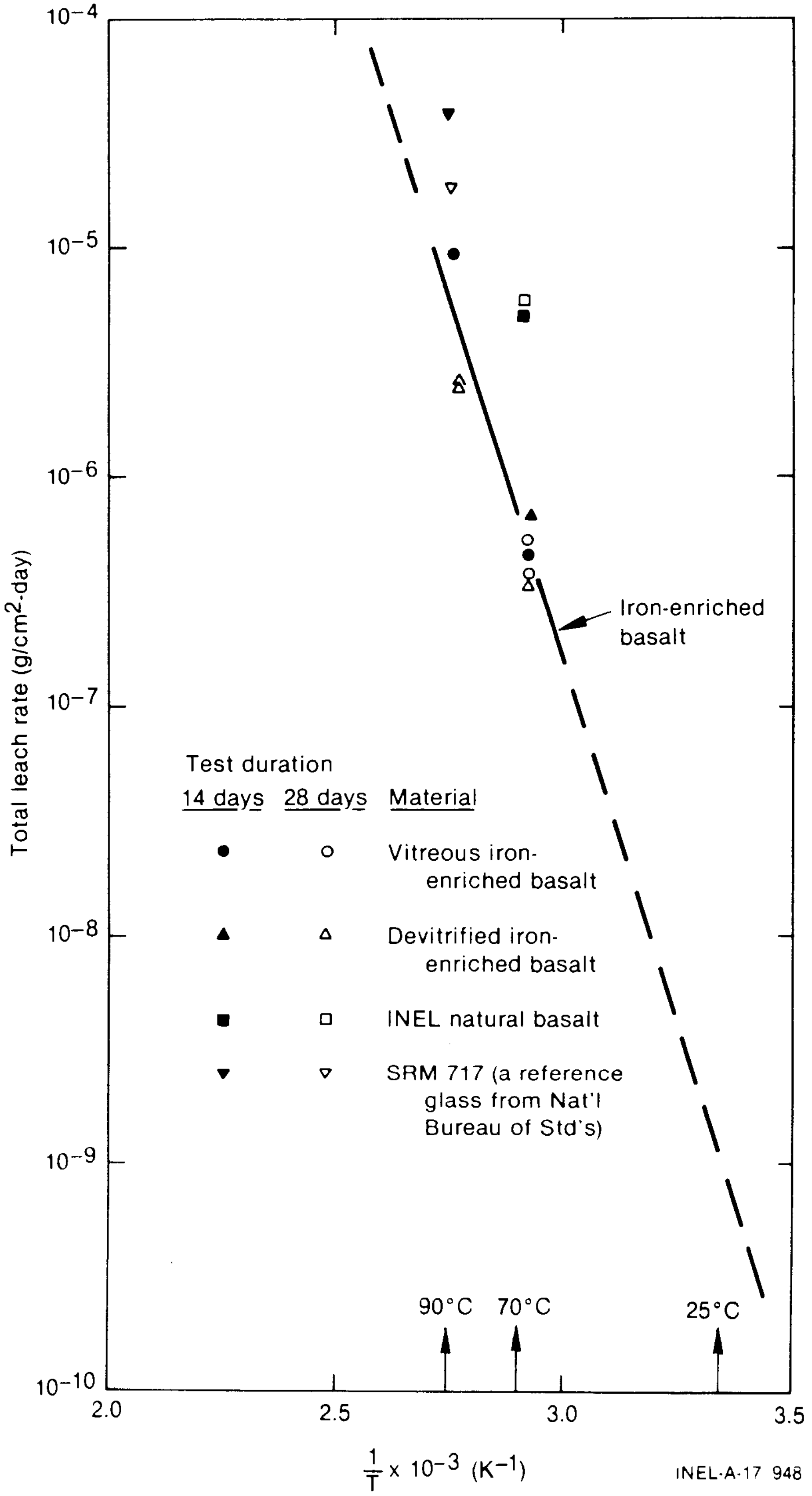


Figure 4. Leach rate in deionized water.

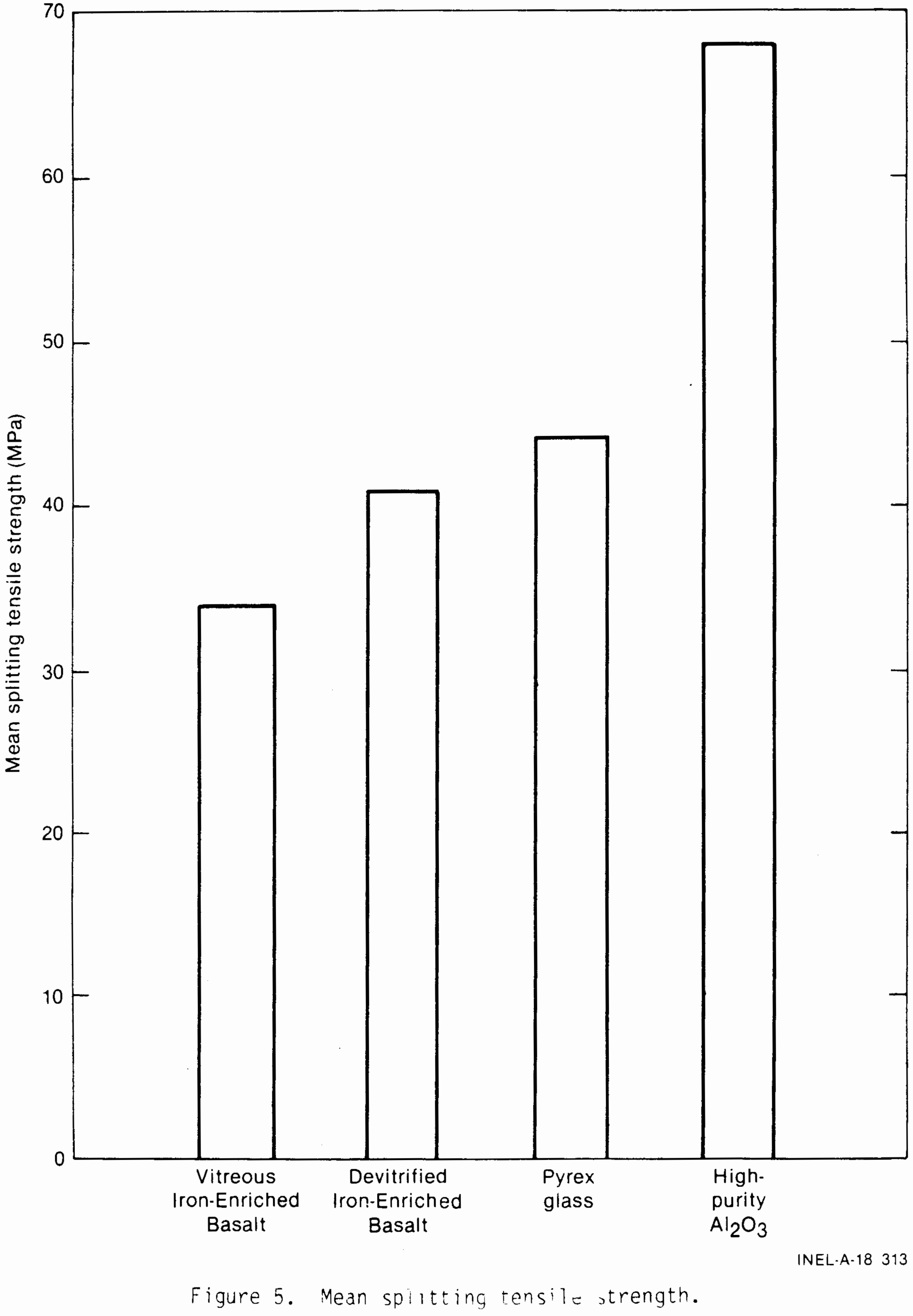


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Figure 5. Mean splitting tensile strength.

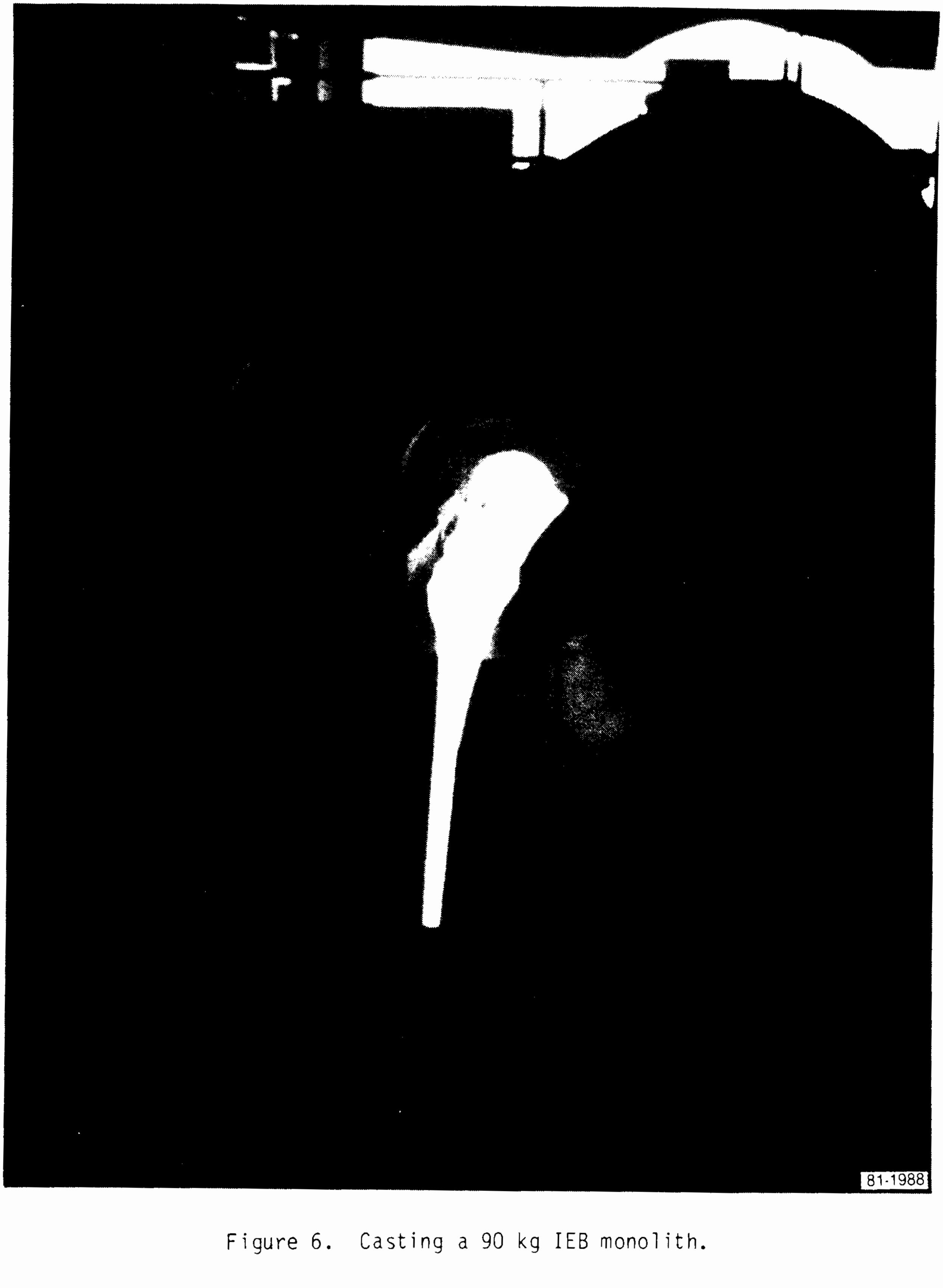

Figure 6. Casting a 90 kg IEB monolith.

Figure 7. Casting a full size (550 kg) monolith.

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