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A BRIEF REVIEW OF THE PRODUCTION PROCESSES, TECHNICAL STATUS, AND COSTS FOR THREE PROPOSED TRANSURANIC WASTE FORMS: BASALT, FUETAP CONCRETE, AND FRIT

By

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A NOTE ON UNITS

For convenience, this draft report mixes SI and English units. SI units will be used if this report is released as a formal document.

ABSTRACT

Large quantities of transuranic-contaminated waste (TRU waste) are stored and buried at the Idaho National Engineering Laboratory (INEL). A Transuranic Waste Treatment Facility utilizing a slagging pyrolysis incinerator (SPI) is being planned at the INEL to process this waste into a form suitable for disposal in a geologic repository. Presently being considered is a SPI process to convert the TRU waste into a granular frit form which may then be consolidated for final disposal. Research is under way on a process to convert this frit into a rock-like waste form called iron-enriched synthetic basalt. Research is also under way to encapsulate the frit into an advanced concrete waste form called FUETAP (formed under elevated temperature and pressure). This report evaluates the relative merits of the basalt, FUETAP, and unprocessed frit waste forms. Large scale production techniques, technical status, and costs for producing, shipping, and disposing of the waste forms in a federal repository are reviewed and compared.

I. INTRODUCTION

1. Background

The U.S. Department of Energy (DOE) is developing the technology for the permanent geologic disposal of transuranic (TRU) wastes.[1] TRU wastes are solid wastes contaminated with long-lived, alpha-emitting isotopes, principally isotopes of plutonium and americium. Nuclear weapons production is the primary source of these waste products, although some are produced by research, nuclear fuel reprocessing, and commercial activities. Most TRU wastes are stored at eight DOE sites and five commercial sites in the U.S., although the commercial sites are no longer licensed to receive this waste.

The Idaho National Engineering Laboratory (INEL), one of the DOE sites, has ~57,000 m^3 of buried TRU waste, ~105,000 m^3 of potentially contaminated soil, ~40,000 m^3 of retrievably stored TRU waste, and is accumulating TRU waste at a rate of ~2,600 m^3/year.[1] (The approximate composition and volumes of the INEL TRU waste are shown in Table I.) EG&G Idaho, Inc., the principal subcontractor at the INEL, is conducting research for DOE's TRU Waste Management Program on the development of technology for processing and disposing of TRU waste.

The major research project is the design of a Transuranic Waste Treatment Facility (TWTF) to be built at the INEL to process TRU waste by a slagging pyrolysis incineration (SPI) technique. TWTF would subject the retrieved and sized waste to a high temperature (gas temperature of 2100 K) combustion and oxidation process which would convert the waste into a molten slag. This molten slag would be quenched in water to produce a granular, glassy frit waste form.[a]

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a. The exact operating mode of the TWTF has not been decided. This report assumes that all of the TRU waste will be processed through the SPI. In practice, some of the waste may be segregated and processed separately, e.g., by direct melting.

TABLE 1. APPROXIMATE QUANTITIES OF TRANSURANIC WASTE PRESENTLY LOCATED AT THE INEL

Waste	Est. Vol. (m^3)	Est. Wt. (10^6 kg)
Stored Waste	40,000	12.8
Chemical Sludge	-	2.7
Combustibles	-	2.5
Noncombustibles	-	1.6
Metals	-	3.7
Miscellaneous	-	2.3
Buried Waste[a]	57,000	-
Contaminated Soil	105,000	-

a. Composition largely unknown. Includes some beta-gamma contaminated waste.

The possible further processing of this frit is the subject of additional research at EG&G Idaho and elsewhere. EG&G Idaho is investigating converting the frit into a synthetic basalt rock. Oak Ridge National Laboratory (ORNL) is investigating encapsulating the frit into an improved concrete called FUETAP (formed under elevated temperature and pressure). A third waste form that might be considered is the TWTF-produced granular frit itself. Frit does not have the apparent advantage of basalt and concrete of being a low surface area, monolithic waste form. However, frit clearly has production cost advantages, since it would require only minimal additional processing before shipment to a repository.

Research has shown that basalt, FUETAP concrete, and frit are promising ultimate waste forms for a large fraction of the existing and future TRU waste. However, the research has also shown that these waste forms vary substantially in their durability, TRU capacities, ease of scale-up to commercial production, and their relative costs for implementation.

These three waste forms are by no means the only potential forms for TRU waste. DOE's Transuranic Waste Management Program is supporting research on a variety of waste forms. Borosilicate glass monoliths, for example, have been suggested as one waste form capable of immobilizing a significant fraction of TRU waste.[2] However, for extremely heterogeneous TRU waste such as that stored at the INEL, borosilicate glass does not appear to be a particularly attractive waste form. While borosilicate glass monoliths could probably be prepared by remelting TWTF frit, adding B_2O_3, and casting and cooling the melt, it is not certain that the full range of TRU waste constituents--particularly the large quantities of metals--could be incorporated into a borosilicate glass. Also, if a large, relatively crack-free monolith was desired, controlled cooling periods could extend to several weeks.[3] Research on borosilicate glass as a TRU waste form seems to be a result of its relative acceptance as a high level waste form. However, the generally homogeneous nature of high-level waste (typically a calcined liquid) is in marked contrast to the generally heterogeneous nature of TRU waste.

Research is under way on other TRU waste forms: bitumen, other concretes, other glasses, ceramics, cermets, and tailored mineral phases ("SYNROC"). These products are not discussed in the balance of this report because they appear to have limited, albeit perhaps important, applications for the disposal of large quantities of TRU waste.

2. Purpose, Limitations, and Assumptions

The purpose of this report is to compare the technical performance, production complexity, and cost of the basalt, FUETAP concrete, and frit waste forms. Performing such comparisons is difficult because basic research on the development of these waste forms is still underway. Thus, many extrapolations to commercial-scale operation will be necessary. Nevertheless, these comparisons (1) suggest waste form superiorities, (2) identify areas for additional research, and (3) reflect the relative total costs of TRU waste disposal by these processes. The last factor is often overlooked in the early stages of waste form development.

The following assumptions and limitations apply to this report:

1. The discussions refer only to the TRU waste stored at the INEL. This highly heterogeneous waste consists of contaminated combustibles (paper, plastic, wood, etc.) and noncombustibles (metals, chemical sludge, concrete, soil, etc.)

2. It is assumed that the TWTF, as presently conceived, will be built at the INEL. The TWTF will process all of the INEL waste (stored, buried, and contaminated soil) into a TRU-bearing frit. From this starting point, the production, packaging, shipment, and disposal of the three reference waste forms will be evaluated.

3. It is assumed that the TRU waste form will be disposed of in the Waste Isolation Pilot Plant (WIPP) in New Mexico. Although numerous other locations and geologic formations are being

evaluated, the WIPP repository is the most advanced, and the reference TRU waste forms can be evaluated against the WIPP waste acceptance criteria.

Section II of this report discusses the fabrication and preparation procedures for the basalt, FUETAP concrete, and frit waste forms. The waste form production processes are evaluated in Section III. The technical performance of the reference waste forms is reviewed in Section IV, based on present laboratory-scale data. The relative costs of processing the full inventory of INEL TRU waste with the reference waste forms are estimated in Section V. In Section VI, the important technical, operational, and cost parameters for each of the waste forms are reviewed and summarized in a concise tabular form, and tentative waste form conclusions are given.

II. PRODUCTION OF THE WASTE FORMS

The TWTF slagging pyrolysis incinerator will process ~93 tons/day of material.[4] This will consist of ~44 tons of TRU waste, ~48 tons of added combustibles (coal and wood chips), and 1 ton of miscellaneous additives. These feed materials will produce ~38 tons/day of slag or, when the molten slag is quenched by pouring into a water bath, the equivalent amount of granular frit. Calculations[5] indicate that, over the life of the TWTF, the processing of the present INEL waste--as well as the newly generated waste--will produce ~240,000 tons (~4.8 x 10^8 pounds) of frit. Thus, if the TWTF operates for 200 days/year at a production rate of 38 tons/day, it will require ~30 years to process all of the TRU waste.

This section will discuss the general procedure for converting this frit into large monoliths of basalt and FUETAP concrete, and the packaging of these monoliths in a form suitable for offsite shipment. Obviously, for the consideration of the frit itself as a waste form, only packaging is required. Basalt, FUETAP concrete, and frit are discussed in subsections II.1, II.2, and II.3, respectively.

1. Production of Basalt

1.1 Introduction

Basalt is a general term for lava rock containing plagioclase, feldspar, and augite mineral phases. The major constituent is SiO_2 (approximately 50 weight percent). Basalt is generally dark in color, finely crystalline, and often contains a glass phase. Basalt can be prepared by the remelting and homogenization of the TWTF granular frit,[a] followed by controlled cooling to produce the devitrified basalt product.

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a. The molten slag produced by TWTF is expected to be nonhomogeneous because its residence time in the molten state is short. Thus, it does not appear possible to prepare homogeneous basalt by direct cooling of the TWTF slag. At present, consideration is being given to the production of granular frit as an intermediate step in the production of basalt and all other waste forms.

As shown in Table I, the INEL TRU waste is high in metals. The basalt waste form under development at EG&G Idaho is similar in composition to natural basalt. However, the iron oxide content is higher than in natural basalt (approximately 20 weight percent versus approximately 10 to 15 weight percent). This composition difference has given the waste form its name of iron-enriched synthetic basalt (IESB).

1.2 Process Overview

Figure 1 illustrates the process flow for the preparation of IESB. The granular frit waste is recovered from the quench tank, drained, and dried in a rotary drier. (The frit is dried to improve its handling and storage properties.) The frit is then fed to the melter where it is heated to approximately 1500°C.[a] The mixture is held at this temperature for about 60 minutes (estimated) to ensure complete oxidation of residual metals[b] and melt homogenization. The molten slag is then poured into canisters and begins a lengthy controlled cooling cycle, presently estimated to require 96 hours. This cooling cycle is required to obtain devitrification of the slag into a polycrystalline basalt with very little residual glass phase.

The basalt monoliths would then undergo weighing, inspection, lid welding, surface decontamination, container leak testing, TRU assaying, labeling, and temporary storage awaiting shipment. A number of IESB canisters would be loaded into shipping containers and the containers loaded into approved railcars for shipment to the federal repository.

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a. The average INEL TRU waste composition, when mixed with ~40 weight percent soil, has a basalt composition. The report assumes that some waste blending will be done in the TWTF so that the basalt composition can be produced without additives.

b. Because of the high average concentration of metals in the INEL waste, it is likely that some unoxidized metals will pass through the slagging pyrolysis incinerator and be present in the frit waste form.

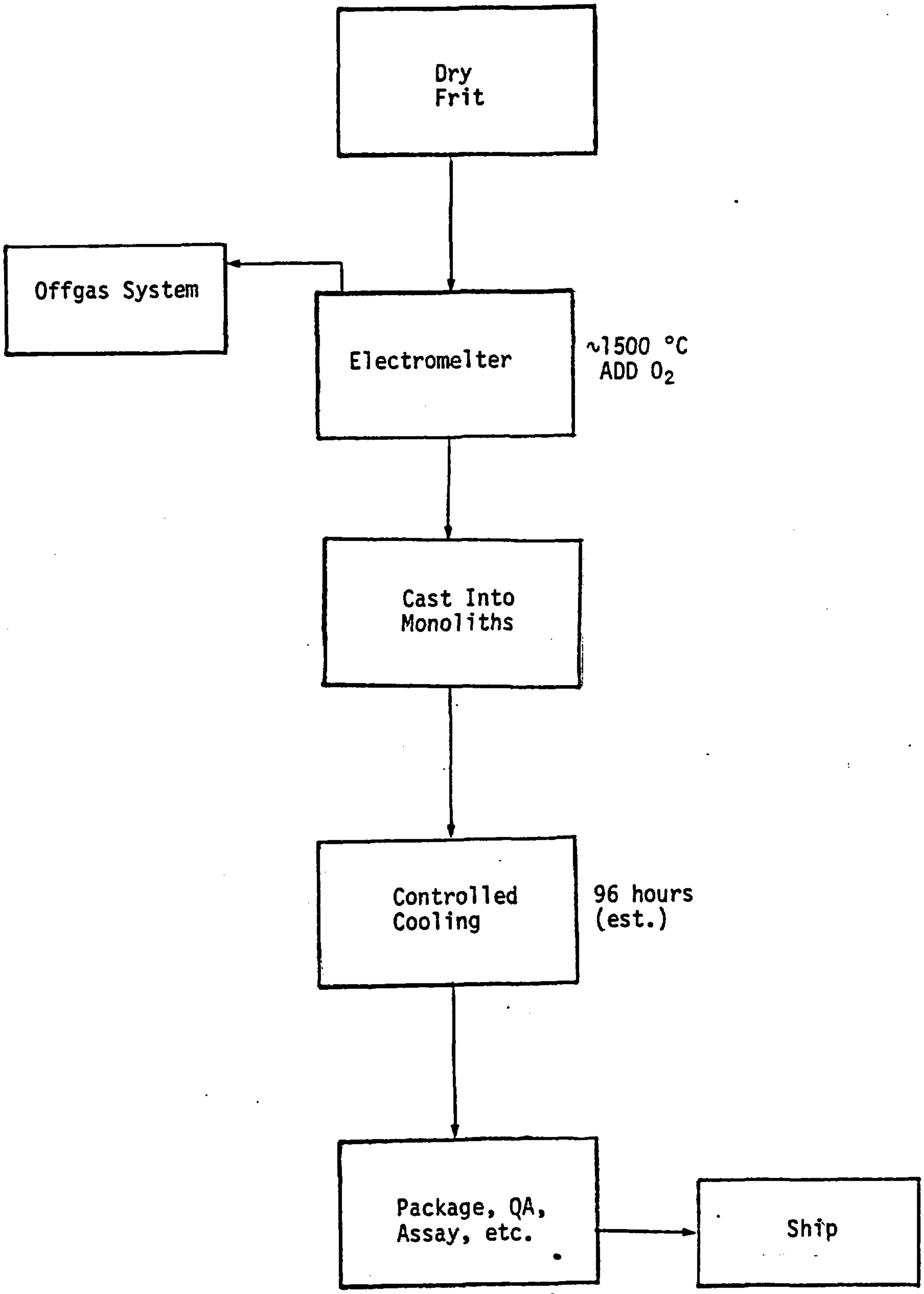

Fig. 1: Simplified Process Flow Sheet for Basalt

1.3 Additional Process Information

Research is presently underway on the design and operation of an electromelter to study the process of remelting frit and casting basalt monoliths. As presently conceived, the melter is a refractory lined, molybdenum electrode resistance melter with ancillary heating (gas jets or glow bars) to create the initial melt. The electromelter would be equipped with air bubblers to oxidize the residual metals and provide melt mixing. Alternatively, oxygen-bearing additives could be added to the melt.

The size and number of electromelters remains to be evaluated. For the purpose of this report, it is assumed that two electromelters, each capable of holding two hours of frit production, will be used. While one melter is undergoing initial frit melting and residual metal oxidation, the second melter could be in the frit-charging or melt-pouring mode. At a frit production rate of 38 tons per 24 hour period, approximately 6,000-pound capacity electromelters are required. The melters would have tilting reservoirs with pour spouts on either side of their major axes.

Arc melting and induction melting have also been suggested for basalt production. In the case of the induction melter, the residual metals in the frit feed would deliberately not be oxidized. Being heavier than the slag, the metals would settle to the bottom of the melter. They would be used as the suscepting phase to start the melter. The metal phase would be poured off periodically when it built up to unacceptable levels. Since an electromelter was used for the successful pilot scale production of IESB,[6] and since research is presently underway on electromelter design and operation, this report assumes that electromelters, rather than arc or induction melters, will be used for basalt production.

The canisters (molds) used for basalt production are assumed to be common, mild steel 55 gal. drums. Casting into such containers has been successfully demonstrated for arc melter castings containing simulated TRU waste.[7] If the containers were filled to 90% capacity and the slag density were 3.0 g/cm^3, the production rate of 38 tons per day would produce ~60 drums per day, each containing ~1250 pounds[a]. The electromelters would hold the slag equivalent of ~10 drums.

2. Production of FUETAP Concrete

2.1 Introduction

Concrete has been used for many years as a matrix for the solidification of low- and intermediate-level liquid wastes. Its common availability and ease of processing makes it a convenient waste form. Common concrete has a number of limitations, however, as a matrix for large volumes of TRU waste requiring shipment to a federal repository. These include gas generated by radiolysis of residual water, relative lack of strength (with implications for radionuclide dispersal during a transportation accident), and relatively high leachability.

Oak Ridge National Laboratory (ORNL) is developing FUETAP concrete, a demonstrably superior concrete product waste form suitable for encapsulation of TRU waste. The elevated temperature and pressure used during processing produce rapid curing of the concrete. The final product contains only a small quantity of free water.

FUETAP concrete could be used in a variety of ways, depending on the physical form of the TRU waste. For the purposes of this report, FUETAP is envisioned as the encapsulation matrix for TWTF-produced frit. That is, frit would act as the aggregate phase in the concrete.

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a. Present policy limits the weight capacity of 55 gal. drums to 840 pounds. For the purposes of this report it is assumed that such weight restrictions are unnecessarily conservative and will be relaxed. Obviously, mechanical tests on full drums would be required to substantiate this assumption.

2.2 Process Overview

Figure 2 illustrates the process flow for the preparation of FUETAP concrete encapsulated frit. As in the case of the basalt, the granular frit is first recovered from the quench tank, drained, and dried. Even though wet frit could be added directly to the FUETAP concrete mix, drying is deemed necessary to improve frit handling and interim storage properties. The frit is then mixed with cement and other dry additives in a batch mixer, and a measured amount of water is added. The batch is mixed, and the resultant paste is cast into a mold. The mold or canister is sealed, heated to 100°C, and pressurized with gas to approximately 0.1 MPa (15 psi). The pressure and temperature are maintained for 24 hours. The canister is then vented and heated to 250°C for 48 hours to evaporate excess free water. The canister is then cooled, weighed, inspected, seal welded, decontaminated, leak tested, assayed, labeled, and placed in temporary storage awaiting shipment. As in the case of basalt, a number of FUETAP concrete monoliths would be placed in a shipping container and the containers loaded into approved railcars for shipment to a federal repository.

2.3 Additional Process Information

Research is presently under way at ORNL on the development and optimization of FUETAP concrete for the containment of TRU waste. At present, no pilot-plant-scale castings have been prepared. As the process is developed and research is conducted on large-scale production, it is likely that the processing parameters discussed here may change.

Frit loadings in FUETAP concrete have just begun to be studied at ORNL, using municipal waste frit produced by slagging pyrolysis incineration. FUETAP specimens with approximately 40 weight percent frit have been prepared but have not yet been subjected to extensive testing. ORNL staff believe loadings of up to 50 weight percent are possible.[8] For the purpose of the study, it is assumed that FUETAP concrete containing 45 weight percent TWTF frit can be prepared.

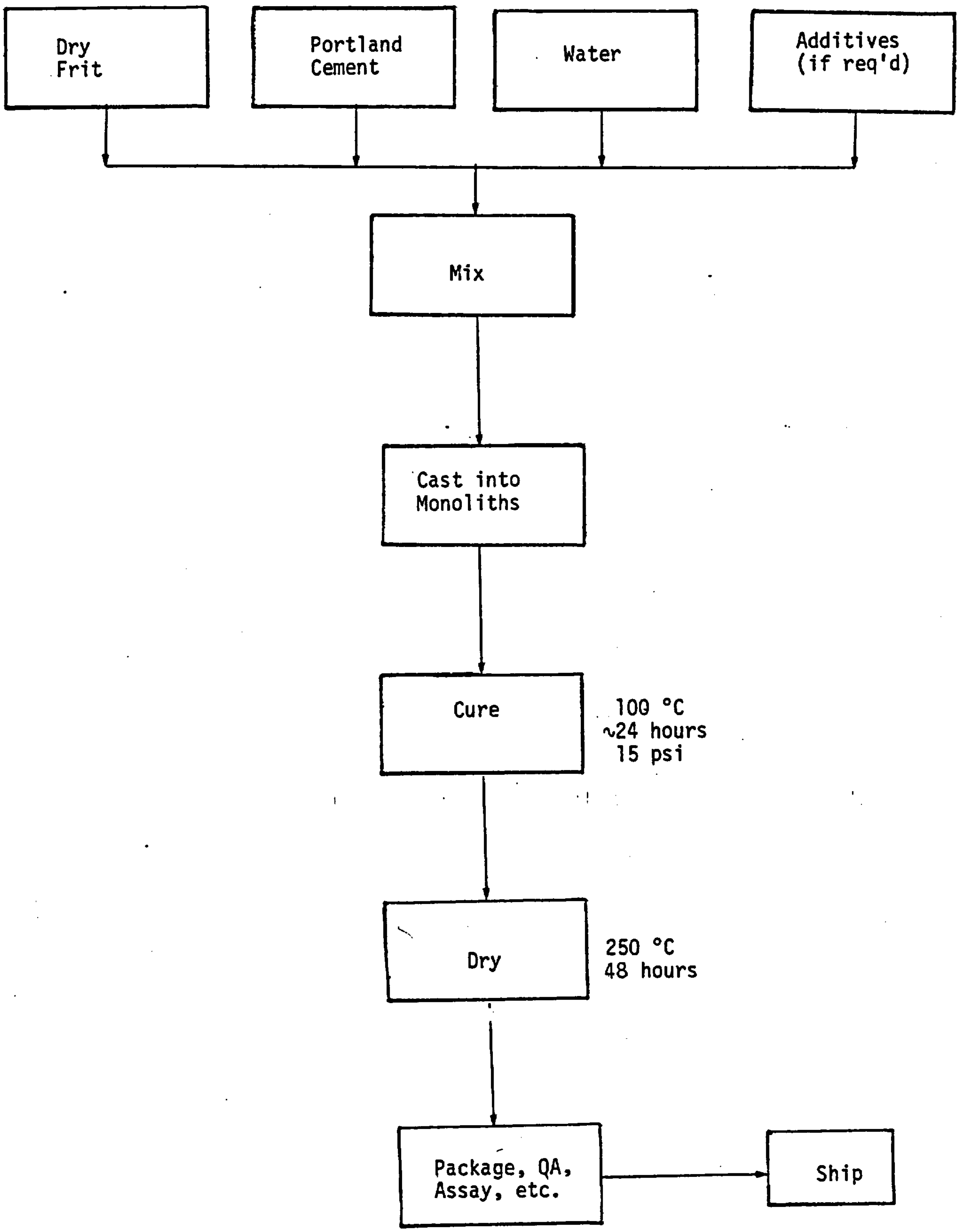

Fig. 2: Simplified Process Flow Sheet for FUETAP Concrete

The scale-up of the FUETAP process to encapsulate the 3200 pounds/hour of frit produced by TWTF has not been thoroughly analyzed. However, a conceptual study[9] has been done on the use of FUETAP concrete as an encapsulation medium for TWTF particulates, a mixture of fly ash and chemical salts removed from the TWTF offgas/spray dryer system. TWTF would produce only 340 pounds/hour of particulates, 10% of the frit production rate. Nevertheless, the conclusions reached on large scale production of FUETAP monoliths for particulates can be extrapolated to the higher production rates required for frit.

As conceived in Reference 9, screw feeders will charge large rotary mixers with frit, Portland cement, water, and other additives (sand, clay, and wetting agents may also be required in the final formulation). The resultant slurry will be discharged directly into 55 gal. drums. Each drum, filled to 90 percent capacity, would weigh ~700 pounds; ~315 pounds of frit (45 weight percent), ~245 pounds of cement plus additives (35 weight precent), and ~140 pounds of water (20 weight percent). The weight of the drum itself (15 to 20 pounds) is negligible. At a frit production rate of 38 tons/day (~3200 pounds/hour), about 240 drums of FUETAP concrete encapsulated frit would be produced each day.

After filling, the drums would be conveyed to pressurized curing ovens. If all drums are to be cured in a common oven, entrance and exit air locks would be required. Individual curing ovens would eliminate this requirement. Curing requires 24 hours at 100°C and 15 psi. Calculations[9] have shown that ~10 hours may be required to heat the center of the FUETAP monolith to curing temperatures. Thus, the total elapsed curing time would be ~34 hours.

After curing, the drum is conveyed to a drying oven to evaporate the free water. Drying times of 48 and 24 hours have been used on small specimens. Required drying times have not yet been determined for large monoliths. A tunnel-type drying oven, in which the drums move on a conveyer belt, is envisioned for the drying process. The containers

(55 gal. drums) will require an inner lining of wire mesh or a porous metal sleeve to create a small air space between the drum wall and the concrete. This will reduce the effective diffusion path length for water from the interior of the monolith. Drums will cool by natural convection after leaving the oven.

3. Processing of Frit

3.1 Introduction

One present concept of TWTF calls for the production, drying, and consolidation or immobilization of frit. It may be that the frit itself is an acceptable waste form, in which case disposal could consist of packaging the frit in a sealed canister and transporting it to a repository. At this point it is not clear whether frit would be acceptable at a repository. The generalized WIPP TRU waste acceptance criteria state that "... particulate materials will not be accepted for disposal at WIPP unless they are immobilized in a binder..."[10] They also state that, "Any solid material that contains less than 1% (by weight) of powder (less than or equal to 10 microns in size) is considered immobilized." (Particles $<$10 microns are commonly considered to be respirable.) Frit produced by slagging pyrolysis incineration of municipal waste and frit produced by melting and quenching of simulated INEL TRU waste have both been shown to contain $\ll$1% respirable fines.[11,] Thus, by the first quoted WIPP criterion frit would be unacceptable, whereas by the second quoted criterion it could be accepted.

Ultimately, waste form acceptability will be based on many considerations, not simply on the percent of respirable fines. Much additional research on frit properties is required. It is true that frit does not meet the common concept of an optimum TRU waste form--a low surface area monolith which has been especially tailored to be strong and leach-resistant. Nevertheless, the frit is a conceptually simple waste form to process. Frit, therefore, is useful as a basis for comparison with other candidate waste forms.

3.2 Process Overview

Figure 3 illustrates the process flow for the frit waste form. After drying, frit would be conveyed to storage canisters. For the purposes of this report, it will be assumed that mild steel 55 gal. drums will be used. The drums would probably be filled to 95% capacity and then topped off with an overpack material to minimize frit movement and abrasion. The canister would then be weighed, inspected, seal welded, decontaminated, leak tested, assayed, labeled, and placed in temporary storage awaiting shipment. It should be noted that because of the particulate nature of frit, a canister more durable than mild steel drums might be required.

Based on the measured bulk density of municipal waste frit (1.8 g/cm^3)[11] and a frit production rate of 38 tons/day, $\sim$100 55 gal. drums of frit would be produced each day.

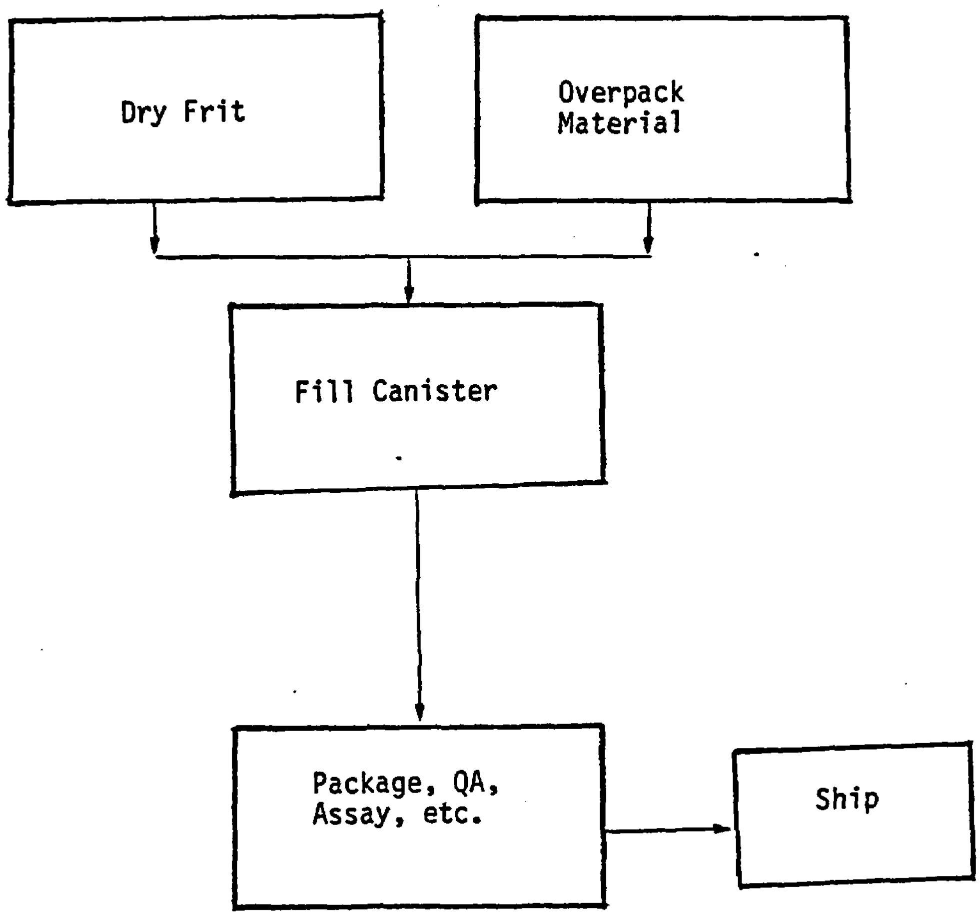

Fig. 3: Simplified Process Flow Sheet for Frit

III. EVALUATION OF THE WASTE FORM PRODUCTION PROCESSES

The waste form production processes, as described in Section II, vary substantially in complexity. Because of fundamental differences in the process requirements--temperature, pressure, additives, equipment, etc.--direct comparison of the production processes is difficult. This section provides a quantitative measure of the relative complexity of the waste form production processes.

Another aspect of waste form processing is the quality assurance measurements that must be performed to assure that the waste forms meet specified shipping and repository criteria. The problems of quality assurance for the three reference waste forms are also addressed.

1. Process Complexity

One of the assumptions of this report is that the product of TWTF will be a granular frit, and that frit must undergo drying to improve its handling and storage properties, Thus, the three candidate waste form production processes reduce to:

1. Basalt--remelt frit, cast into drums, cool under controlled conditions, package for shipment,

2. FUETAP Concrete--mix frit and concrete, cast into drums, cure and dry under controlled conditions, package for shipment,

3. Frit--transfer into drums, package for shipment.

The method of Ross et al.,[12] for ranking the complexity of high-level waste form processes was selected for application to the basalt, FUETAP concrete, and frit waste forms. The method, which is intended to provide only a general indication of relative complexity, employs a point system as follows:

- 10 points for each process step

- 1 point for each 100°C required for each process step
- 1 point for each 100 psi of pressure used in each process step
- 5 points for each process additive or each auxiliary operation

The processes and their numerical rankings of complexity, according to this method, are listed in Table 2. The process steps are based on the process descriptions of Section II.

The process of preparing TWTF frit as a waste form is substantially simpler than either IESB or FUETAP concrete. The IESB and FUETAP concrete processes are of comparable complexity. The FUETAP concrete process is slightly less complex than the IESB process, primarily because of the lower processing temperatures required.

2. Process Quality Assurance

Regulatory agencies will certainly require that any TRU waste form be demonstrably safe to ship and dispose. Thus, quality assurance (OA) measurements on the waste form will be required. The detailed nature of the QA is unknown at this time. The purpose of this section is to suggest the relative ease of QA for the candidate waste forms.

For the reasons stated in subsection III.1, QA tests proposed for TRU waste forms might include leachability tests and mechanical strength or abrasion tests. Conceivably, combustion tests, gas-generation tests, canister-integrity tests, and residual-metal measurements, might also be required.

For a particulate waste form such as frit, the sampling procedure would be a simple periodic sampling from the frit product line. For basalt and FUETAP concrete products, however, the sampling technique, presumably by a process such as core drilling, would compromise one of the principle features of the waste form, its monolithic structure. Leachability

TABLE 2. RELATIVE WASTE FORM PROCESSING COMPLEXITY

Waste Form	Process Step, Operation, etc.		Points
Iron-Enriched Synthetic Basalt	1. Add material to melter		10
	One process additive (frit)		5
	One auxiliary operation (O_2 bubbler)		5
	2. Melt frit		10
	1500°C temperature		15
	3. Cast basalt into mold		10
	4. Cool basalt		10
	1500°C to ambient		15
	5. Final packaging		10
	IESB	=	90
FUETAP Concrete	1. Add ingredients to mixer		10
	Four process additives (frit, cement, water, other additives)		20
	2. Mix ingredients		10
	3. Cast into mold		10
	4. Cure		10
	100°C curing temperature		1
	15 psi curing pressure		~0
	5. Dry		10
	250°C drying temperature		2.5
	6. Final packaging		10
	FUETAP	=	83.5
Frit	1. Add frit to canister		10
	2. Fill canister with over-pack mtl. to reduce loose frit abrasion		10
	3. Final packaging		10
	Frit	=	30

measurements, which generally require many days to perform, would require that the waste facility have considerable storage space for the waste forms pending the test results. Also, negative QA results on the monolith specimens would require expensive facilities to pulverize and recycle them.

Thus, for a variety of reasons, it appears that QA measurements which impact throughput and cost should be avoided by performing QA on process parameters, not on the final waste form. The basalt process might require QA measurements on parameters such as melt temperature, partial pressure of important species over the melt, casting temperature, cooling rates, etc. QA measurements for FUETAP might include residual free metals in the frit, measurements of mixing ratios, curing and drying temperatures, rate of water evolution, etc. Frit QA might include slag temperature, quench bath temperature, residual free metals, temperature limits during drying, etc. If measurements of process variables are supported by an extensive body of data correlating the process variables to properties of the waste form, then QA may be a relatively direct process which does not significantly increase cost or reduce throughput.

IV. WASTE FORM TECHNICAL PERFORMANCE

Waste form technical performance is measured in three ways. First is the long-term durability of the waste form; i.e., its ability to retain transuranics and minimize their release to the environment for a period of 10^3 to 10^6 years. Second is the short term durability of the waste form; i.e., its ability to survive a transportation accident without radionuclide dispersal. Third is the ability to meet repository handling requirements. For the WIPP these requirements include limits on gas generation, free powders, and pyrophorics; prohibitions on free liquids, explosives, corrosives, and toxic materials; and waste form container requirements on dimensions, weight, design life (10 years), etc.

The high-temperature pyrolysis to which the TRU waste is subjected in TWTF effectively eliminates any organic, combustible, explosive, and pyrophoric materials from the resultant frit. The frit drying procedures and the nature of the basalt and FUETAP production processes effectively eliminates any free water in the waste forms, and thus prevent any radiolytic gas buildup. Experience at the INEL has shown that mild steel drums containing TRU waste and stored in a controlled environment will remain intact for $>$20 years.[13] Thus, the problems of technical performance are largely reduced to problems of long-term and short-term durability. These are commonly reduced to measurements of waste form leachability in ground water and mechanical strength.

1. Waste Form Leachability

Waste form research has been hampered by the lack of a standard test designed to determine long-term leachability. The creation of the Materials Characterization Center[14] should eventually solve this problem, but at present a wide range of leaching methods are being used.

The WIPP acceptance criteria do not address waste form leachability. The most widely quoted leachability criteria are those proposed by the NRC for a radionuclide release of zero for the first 1000 years and a fractional release of 10^{-5}/year thereafter.[15] That these were proposed for the entire engineered system (waste form, canister, overpack, and repository), has not prevented researchers from using them as a TRU waste form leachability benchmark.

A common method of reporting leach rates is in g/cm^2-day. This is not an ideal expression for leach rates because different constituents leach at different rates and because leach rates will change (because leach mechanisms will change) over geologic times. Other problems with the reported leach rates include: experiments at a variety of temperatures, a dearth of experiments on TRU-bearing waste forms (so that "bulk" leach rates rather than leach rates on the TRU-bearing phase are reported), use of different leachants, conducting leach experiments with and without agitation, etc.

Moore et al.[16] have developed a useful nomograph for evaluating leach rates. The nomograph, shown in Figure 4, has been prepared for a waste form monolith of density 2 g/cm^3 and the size of a 55 gal. drum. The nomograph allows the intercomparison of leaching time, leach rate, and fractional radionuclide release. A fractional release of $\sim$0.1 in 10,000 years (the dashed line on the figure) is an approximation of the NRC criteria of zero release in the first 1000 years, 10^{-5}/year thereafter. The nomograph indicates that a waste form system (waste, canister, overpack, and respository) should leach at a rate of $< 6 \times 10^{-7}$ g/cm^2-day to meet the proposed NRC criteria.

Current data on the leachability of iron-enriched synthetic basalt, FUETAP concrete (not containing frit), and granular frit are summarized in Table 3. None of these data was obtained on waste form specimens containing actual TRU waste.

Note that the leach data are reported at three different temperatures. The most meaningful temperature at which to make leach measurements is unresolved. If a repository will mix high-level and TRU waste, then the higher temperatures (e.g. 90°C) may be more appropriate. For a repository storing only TRU, temperatures near 25°C may be more meaningful.

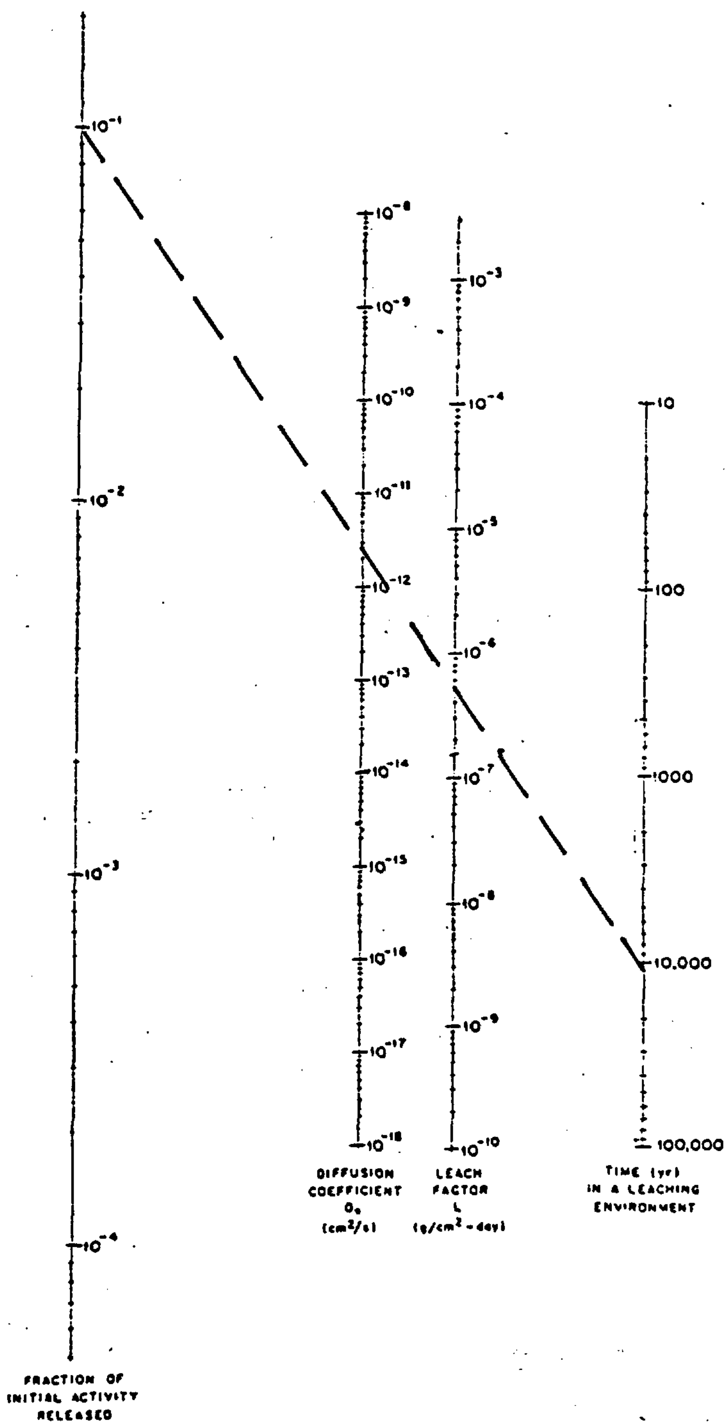

Fig. 4 Nomograph for the Comparison of Leach Rates, Leach Times, and Fractional Releases.

TABLE 3. WASTE FORM LEACH RATES

Waste Form	Leach Rate (g/cm^2 -day)	Reference
Iron-Enriched Synthetic Basalt[a]	$2x10^{-7}$ to $1x10^{-6}$ at 70°C	17
FUETAP Concrete[b]	$<10^{-8}$ to $<9x10^{-5}$ at 25°C	18, 19
Frit[c]	$3x10^{-5}$ to $1x10^{-4}$ at 90°C	20

a. Data are for a wide range of basalt compositions tested at 70°C in pure water for 28 days under static and semistatic conditions. Leachates were analyzed for nine elements.

b. The value of $<10^{-8}$ is for Pu leaching, the value of $<9x10^{-5}$ is for Cs leaching.

c. These data are for specimens of municipal frit which were remelted to produce small monoliths for leach testing. The remelting process may have oxidized residual free metals in the slag. These were short duration tests conducted at 90°C. Leach rates are usually highest during the first several days and decrease thereafter. Thus, the leach rates were probably underestimated as a result of remelting, and overestimated as a result of the short duration testing.

Within the large uncertainties for these leach data, IESB and FUETAP concrete have comparable leach resistance. Either waste form would probably meet the proposed NRC criteria. The leach data for frit are so compromised by the specimen preparation procedure (see footnote c, Table 2) that no reliable conclusions on the leach resistance of granular frit are presently possible. However, it does appear that the leach resistance of frit is substantially less than for either IESB or FUETAP concrete.

2. Waste Form Mechanical Strength

The relevant mechanical strength parameters are those which show the propensity to form respirable particles (assumed to be particles $<10\ \mu m$). The concern is the release of these respirable particles during a transportation accident on the way to the repository. The sources for these fine particles are the waste form preparation process itself, and the abrasion of the waste form during handling, transportation, and conceivable accidents. Based on the WIPP acceptance criteria, the waste form packages must contain $<1\%$ respirable fines.

Large-scale melts quenched in water to produce frit have been analyzed for particle size.[7] These results showed 0.8 weight percent of the frit was <325 mesh ($\sim 45\ \mu m$). Thus, frit production does not generate $>1\%$ respirable particles. This statement applies only to the slag quenching process. It is recognized that the slagging pyrolysis will generate fine particulates which must be filtered and recycled by an offgas system. Fine-particle production during the processes of frit drying and transfer to storage hoppers could result from particle abrasion. These processes have yet to be evaluated.

Data have been obtained on fine particle production during handling and shipping of granular frit. Municipal frit shipped from New York to the INEL was subjected to a seive analysis upon receipt.[11] The results showed that $<1\%$ of the particles were <325 mesh. These results indicate that routine shipment of granular frit does not generate $>1\%$ respirable particles. It may be inferred that the more consolidated basalt and FUETAP waste forms would yeild similar results.

Though no experiments have been performed, it is likely that neither the basalt casting and cooling process nor the FUETAP casting and curing process would generate significant fine particles in the 55 gal. drum waste form container. Again, the frit melting required for basalt production will generate a fine particulate fly ash requiring separate treatment.

Drums of solid slag (similar to IESB but cooled faster so that phase and structure are different) and granular frit encapsulated in concrete (not FUETAP) will be subjected to standard accident tests at the Sandia Transportation Technology Center. The results will be available in fiscal year 1981.

Research remains to be done on respirable particle production during frit drying and handling, and during transportation accidents involving frit, baslat, and FUETAP concrete. It appears, however, that none of the candidate waste forms will contain or develop significant quantities of respirable particles.

V. WASTE FORM COSTS

1. Introduction

In this section an attempt is made to estimate the costs for TRU waste disposition by the iron-enriched synthetic basalt, FUETAP concrete, and frit waste forms. Each waste form is evaluated for production, shipping, and repository costs. All costs are given in 1980 dollars. Because it may be several years before INEL TRU waste is processed, actual costs may escalate dramatically. Nevertheless, it is hoped that these estimates will accurately reflect the relative costs of processing the waste via these candidate waste forms. As a point of comparison, the estimated cost to build the Transuranic Waste Treatment Facility, the facility to process the INEL TRU waste into frit, is ~$350,000,000 1980 dollars, ~$920,000,000 actual expenditures.[4]

The TWTF is assumed to have processed the TRU waste (stored, buried, and contaminated soil) into a dry, granular frit. The cost estimates given are for transforming that frit into a basalt, FUETAP, or packaged frit waste form, and subsequently shipping and disposing of that waste form. The costs are based on a frit production rate of ~38 tons/day, 200 days/year, for ~30 years, with a total frit production of ~4.8×10^8 pounds.

A number of detailed conceptual design studies have been performed for the TWTF Project Office by the Ralph M. Parsons Co. These studies have examined a number of ways of processing the TWTF frit and offgas particulates. Melting and casting, common concrete encapsulation, pressing and sintering, pelletization, and FUETAP concrete encapsulation have all been examined, the processing problems investigated, and the cost estimates obtained. These studies have been relied upon heavily in preparing this section because they are reasonably thorough and the cost estimate assumptions between studies are consistent. Nevertheless, the studies are not entirely adequate for the cost comparisons attempted herein; some additions and changes have been necessary. Where changes or revisions have been required, they are explained by remarks and footnotes. Numerous explicit references are given so that the interested reader can reconstruct the cost estimates from the original documentation.

2. Iron-Enriched Synthetic Basalt

2.1 Basalt Production Costs

Over the life of the TWTF, the estimated total cost to convert granular frit into iron-enriched synthetic basalt monoliths is $94.0 million (see Table 4). The most significant cost components are the operating staff labor charges ($43.0 million, 46% of the total), and electromelter electricity costs ($17.3 million, 18%).

2.2 Basalt Shipping Costs

The waste form canisters are assumed to be shipped to the WIPP respository in ATMX railcars. These are special railcars of the type currently used for shipment of TRU waste to the INEL. They have a volume capacity of 140 55 gal. drums and a weight capacity of ~101,300 pounds.

Based on 1250 pounds of basalt per 55 gal. drum (see subsection II.1.3), each ATMX railcar will reach its weight limit with a payload of 81 waste form drums. Over the life of the TWTF, about 4.8×10^8 pounds or 3.8×10^5 drums of basalt would be produced, requiring ~4700 railcar shipments for transportation to the repository.

As shown by the calculations of Appendix A, the total cost of the basalt waste form shipments, expressed in 1980 dollars, is about $38.4 million.

2.3 Basalt Repository Costs

The actual costs for waste form emplacement and permanent disposal in a federal repository are very uncertain at this time. For the WIPP repository, one method that has been used is to amortize the construction

TABLE 4. TOTAL BASALT PRODUCTION COSTS[a]

Item	Number Req'd	Cost ($)	Installation Cost ($)	Total Cost ($)	Reference	Remarks
Equipment						
Electromelters (includes power supply and refractory)	2	4,500,000	1,500,000	6,000,000	Ref 21 pg 6-12	Total cost could be reduced to $1.4 to 2.1M if arc melting or induction melting furnaces used.
Iron oxidation unit	1	750,000	300,000	1,050,000	Ref 21 pg 6-12	Cost uncertain because technology development required
Frit charge bin	1	3,000	1,000	4,000	Ref 21 pg 3-50	
Frit conveying system	1	90,000	10,000	100,000	Ref 21 pg 3-50	
Drum handling unit	2	10,000	2,000	12,000	Ref 21 pg 3-50	
Drum conveying system	1	122,000	12,000	134,000	Ref 21 pg 3-50	
Refractory pallets	180	450,000	--	450,000	Ref 21 pg 3-50	
Electromagnetic lifting device	1	2,000	--	2,000	Ref 21 pg 3-50	
Piping and ducting	1 lot	10,000	5,000	15,000	Ref 21 pg 3-50	
Controlled cooling tunnel furnace	2	720,000	75,000	795,000	Ref 9 pg 7-4	Assumed 2 required. Doubled cost estimate of reference unit because must operate at substantially higher temperature than reference unit.
Drum weighing, welding, and leak checking unit	1	100,000	10,000	110,000		Engineering judgement
TOTAL EQUIPMENT				8,672,000		
Maintainence and replacement costs				13,008,000		Based on 5% of capital equipment costs per year for 30 years.
Electrical installation (4,000 KW at $220/KW)				888,000	Ref 21 pg 3-50	4000 KW based on arcmelter. Electromelter assumed to be the same.
Consumables[b]						
55 gal. drums for canisters	$3.8x10^5$	$20 ea		7,600,000		Based on $4.8x10^8$ pounds of basalt produced over the 30 year life of the facility. Each canister holds 1250 pounds.
Electricity				17,280,000		Based on 200 days per year, 24 hours per day operation, 30 year lifetime, $0.03 per KWh
Basalt additives				2,000,000		Engineering judgement. Necessity for additives uncertain. See footnote, subsection II.1.2.
Building space (365,000 ft^3 at $4.25 per ft^3)				1,551,000	Ref 21 pg 3-50	Reference building space based on use of arcmelters. Reference increased by 50% to accomodate electromelters and tunnel furnaces.
Operating cost[c]				43,008,000		See footnote c. 32 people working 8 hours per day 200 days a year, 30 years, $28 per hour (salary + OH).
TOTAL PRODUCTION COST				94,007,000		

a. All values are in 1980 dollars. A facility lifetime of 30 years is assumed.

b. Water costs not shown because major cost is for pumping, therefore part of electrical costs.

c. Staff for production, packaging, QA, and shipment of waste form. The staff required is assumed to be a function of equipment complexity and waste form output.
Staff required per day = 3 people per 10^6\$ of equipment + 1 person per 10 drums of waste produced per day.
Staff for basalt = $(3/10^6\$)\cdot(8.7\times10^6\$) + (1/10 \text{ drums})\cdot(60 \text{ drums/day}) = 26 + 6 = 32$ people per day or about 11 per shift.
(This compares to an estimated TWTF operating staff of about 100 per shift.)

cost ($560 million 1980 dollars) and operating costs ($27 million 1980 dollars per year) over the repository capacity (6.45×10^6 ft^3). If it assumed that the WIPP will operate over the same 30-year period that the TWTF will operate, then the repository cost will be:

$$\frac{\$560 \text{ million} + (\$27 \text{ million/year} \cdot 30 \text{ Years})}{6.45 \times 10^6 \text{ ft}^3} = \$212/\text{ft}^3.$$ [a]

Conversion of INEL waste into basalt would produce $\sim 3.8 \times 10^5$ 55 gal. waste form drums, each occupying ~ 7.5 ft^3, for a total volume of 2.9×10^6 ft^3. At $212/$ft^3$, the total repository costs for the basalt waste form are $614.8 million 1980 dollars.

3. FUETAP Concrete

3.1 FUETAP Concrete Production Costs

The estimated total cost over the life of the TWTF to convert granular frit into FUETAP concrete monoliths is shown in Table 5. The total cost is estimated to be $124.3 million (1980 dollars). The most significant cost components are the operating staff labor charges ($55.1 million, 44% of the total), and waste form canisters ($36.0 million, 29%).

3.2 FUETAP Concrete Shipping Costs

Once the FUETAP concrete waste form casting is cured and dried, it weighs ~ 560 pounds, ~ 315 pounds of which is frit (see subsection II.2.3). For a TWTF lifetime production of 4.8×10^8 pounds of frit, $\sim 1.5 \times 10^6$ waste form canisters would be produced. Each ATMX railcar

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a. The figure of $212/$ft^3$ is a best estimate based on the assumptions of this report. A minimum repository cost might be obtained by assuming that the user has to pay just for the WIPP operation, not the construction. This would reduce the cost by 40% to $125/$ft^3$.

TABLE 5. TOTAL FUETAP CONCRETE PRODUCTION COSTS[a]

Item	Number Req'd	Cost ($)	Installation Cost ($)	Total Cost ($)	Reference	Remarks
Equipment						
Frit charge bin	2	5,000	1,000	6,000	Ref 21 pg 3-74	
Frit conveying system	1	126,000	19,000	145,000	Ref 21 pg 3-74	
Cement storage bin	1	51,000	15,000	66,000	Ref 21 pg 3-74	
Cement conveying system	2	50,000	10,000	60,000	Ref 21 pg 3-74	
Cement charge bin	1	6,000	2,000	8,000	Ref 21 pg 3-74	
Batch mixer	2	130,000	20,000	150,000	Ref 21 pg 3-74	
Drum conveying system	1	122,000	12,000	134,000	Ref 21 pg 3-74	
Piping	1 lot	2,000	1,000	3,000	Ref 21 pg 3-74	
Pressurized curing oven	?	See remarks	See remarks	2,880,000	Ref 9 pg 7-4	Reference is for ovens to be used for FUETAP encapsulation of offgas particulates not frit. Therefore, total cost in refrence was multiplied by ratio of hourly production rates of frit to particulates (3200 pounds per hour to 340 pounds per hour). Ratio = ~10.0
Tunnel drying ovens	?	See remarks	See remarks	1,800,000	Ref 9 pg 7-4	See above remark.
Drum weighing, welding, and leak checking unit	1	100,000	10,000	110,000		Engineering judgement
TOTAL EQUIPMENT				5,362,000		
Maintenance and replacement costs				8,043,000		Based on 5% of capital equipment costs per year for 30 years.
Electrical installation (1000 KW at $220/KW)				220,000		Engineering judgement.
Consumables[b]						
55 gal. drums for canisters	1.5×10^6	$24/ea.	—	36,000,000		Based on 4.8×10^8 pounds of frit produced over 30 years. Each canister holds 315 pounds of frit encapsulated in the FUETAP. Cost increased 20% to account for necessity of puting a porous liner inside canister.
Electricity				4,320,000		Based on 200 days per year, 24 hours per day, 30 year lifetime, $0.03 per KWh.
Portland cement				12,862,000		Based on 245 pounds per 55 gal. drum and a cost of $70/ton.
Building space (566,000 ft^3 at $4.25 per ft^3)				2,405,000	Ref 21 pg 3-74	Reference based on batch encapsulation of frit in conventional concrete. Reference increased by 50% to accomodate FUETAP curing and drying ovens.
Operating Cost[c]				55,104,000		See footnote c. 41 people working 8 hours per day, 200 days per year, 30 years, $28 per hour (salary plus OH).
TOTAL PRODUCTION COST				124,316,000		

a. All values are in 1980 dollars. A facility lifetime of 30 years is assumed.

b. Water costs not shown because major cost is for pumping, therefore part of electrical costs.

c. Staff for production, packaging, QA and shipment of waste form. See Table 4, footnote c for origin of formula used below.
Staff for FUETAP = $(3/10^6\$)\cdot(5.8\times10^6\$) + (1/10\ \text{drums})\cdot(240\ \text{drums/day}) = 17 + 24 = 41$ people/day or about 14 people/shift.

could hold 140 such canisters with a total weight of about 78,400 pounds. Transportation of these canisters to WIPP would require ~10,700 railcar shipments. The total cost of these shipments (see Appendix A) would be about \$67.2 million 1980 dollars.

3.3 FUETAP Concrete Repository Costs

The encapsulation of TWTF frit in FUETAP concrete would produce 1.5×10^6 55 gal. waste form cansiters, or 1.1×10^7 ft^3, larger than the presently planned WIPP capacity. At \$212/ft^3 (additional repository space might be cheaper), the total repository costs for the FUETAP concrete waste form would be \$2,332 million (\$2.332 billion) 1980 dollars.

4. Frit Waste Form Costs

4.1 Frit Waste Form Packaging Costs

The estimated total cost over the life of the TWTF to package the granular frit waste form is \$29.7 million 1980 dollars (see Table 6). The major cost components are the operating staff labor charges (\$14.8 million, 50% of the total), and the waste form canisters (\$12.6 million, 42%).

4.2 Frit Waste Form Shipping Costs

Each 55 gal. canister of granular frit will weigh ~760 pounds (see subsection II.3.2). Thus the entire TWTF production of 4.8×10^8 pounds of frit will be contained in ~6.3×10^5 canisters. Each ATMX railcar will reach its maximum weight payload with 133 canisters. Thus, ~4700 railcar shipments will be required to transport the frit to WIPP. The total cost of these shipments (see Appendix A) will be \$38.5 million 1980 dollars.

4.3 Frit Waste Form Repository Costs

The ~6.3×10^5 frit canisters will require ~4.7×10^6 ft^3 of repository space. At \$212/ft^3, the total repository cost for the frit waste form is \$996.4 million 1980 dollars.

TABLE 6. TOTAL FRIT PROCESSING COSTS[a]

Item	Number Req'd	Cost ($)	Installation Cost ($)	Total Cost ($)	Reference	Remarks
Equipment						
Frit charge bin	2	5,000	1,000	6,000	Ref 21 pg 3-74	
Overpack charge bin	1	3,000	1,000	4,000		
Frit conveying system	1	126,000	19,000	145,000	Ref 21 pg 3-74	
Drum conveying system	1	122,000	12,000	134,000	Ref 21 pg 3-74	
Piping	1 lot	2,000	1,000	3,000	Ref 21 pg 3-74	
Drum weighing, welding, and leak checking unit	1	100,000	10,000	110,000		Engineering judgement.
TOTAL EQUIPMENT				402,000		
Maintenance and replacement costs				603,000		Based on 5% of capital equipment costs per year for 30 years.
Electrical installation (150 kW at $220/kW)		—		33,000	Ref 21 pg 3-74	Reduced from reference value because less equipment required.
Consumables[b]						
55 gal. drums for canisters	$6.3x10^5$	$20 ea		12,600,000		Based on $4.8x10^8$ pounds of frit produced over the 30 year life of the facility. Each canister holds ~760 pounds of frit.
Electricity				648,000		Based on 200 days per year, 24 hours per day operation, 30 year lifetime, $0.03 per kWh.
Building Space (150,000 ft^3 at $4.25 per ft^3)				637,000		Engineering judgement.
Operating Cost[c]				14,784,000		See footnote c. 11 people working 8 hours per day, 200 days per year, 30 years, $28 per hour (salary plus OH).
TOTAL PRODUCTION COST				29,707,000		

a. All values are in 1980 dollars. A facility lifetime of 30 years is assumed.

b. Water costs not shown because major cost is for pumping, therefore part of electrical costs.

c. Staff for production, packaging, QA, and shipment of waste form. See Table 4, footnote c for origin of formula used below.

Staff for frit = $(3/10^6\$)\cdot(0.4x10^6\$) + (1/10\ drums)\cdot(100\ drums/day) = 1 + 10 = 11$ people/day or about 4 people/shift.

VI. CONCLUSIONS

1. Introduction

It is important to realize that this preliminary report is very limited in scope and purpose. Much basic research on TRU waste forms remains to be performed, and substantial waste form improvements are likely. Large-scale production factors are only beginning to be addressed. As pilot plants are designed and built, the engineering understanding of large-volume waste form production will increase significantly. Because of the long time that will elapse before TRU waste is actually processed and disposed, the cost estimates herein are certainly tenuous. Nevertheless, it is hoped that this study illuminates some important differences in the basalt, FUETAP, and frit waste forms. It is hoped that comparative studies like this continue to be performed, so that the entire TRU waste disposal process is scrutinized.

2. Tabular Summary and Conclusions

A concise summary of this report is contained in Table 7. Processing, technical, and cost parameters are compared and areas of uncertainty are discussed. The information contained in this report leads to the following conclusions:

- Packaging of the granular frit produced by the TWTF is a substantially less complex process than either basalt production or FUETAP concrete encapsulation.

- Production of 55 gal. drum monoliths of the basalt and FUETAP concrete waste forms are processes of approximately equal complexity and cost.

- Comparable leach rate data for basalt, FUETAP, and frit waste forms containing actual TRU waste are badly needed. This is particularly important for the frit and FUETAP encapsulated frit

TABLE 7. WASTE FORM SUMMARY

	Processing			Technical				Cost			
Waste Form	Process Complexity[a]	Number of Waste Form Canisters	Remarks	Leachability	Mechanical Strength	Respirable Particle Problem?	Remarks	Est. Production Cost	Est. Shipping Cost	Est. Repository Cost	Est. Total Cost
Iron-Enriched Synthetic Basalt	90	3.8×10^5	Production process complex. Processing equipment durability unknown. Technology for oxygen addition to melt to oxidize residual metals not proven. Arc melters and induction melters should be investigated, though these will require equipment to cast unoxidized metals. Electromelter process has been successfully demonstrated on 100 kg castings. Lengthy controlled cooling process reduces potential throughput. QA on the final waste form difficult, close control of process variables may have to suffice for QA. Process produces a substantial waste volume reduction relative to the TWTF frit product.	Good	Good	No	No tests yet with actual TRU waste. Leach data needed over a wide temperature range. Preliminary tests indicate waste form alone could probably meet the proposed NRC leach critera.	$94.0 million	$38.4 million	$614.8 million	~$747,000,000
FUETAP Concrete	83.5	1.5×10^6	Production process complex. Processing equipment durability unknown, but is probably better than basalt because of lower temperatures. Process has not been demonstrated on a pilot plant scale. Frit will contain unoxidized metals. Frit loadings in FUETAP have not been determined. This process produces a substantial waste volume increase relative to the TWTF frit product. Lengthy controlled curing and drying process reduces the potential throughput. Kinetics of water release from large monoliths have not been evaluated. QA on the final waste form would be difficult, close control of process variables may have to suffice for QA.	FUETAP phase good. Frit phase probably relatively poor.	Moderate	No	No tests yet with actual TRU waste. Leach data needed over a wide temperature range. Leach data needed on specimens containing heterogeneous frit. Preliminary tests indicate FUETAP phase could probably meet the proposed NRC leach criteria.	$124.3 million	$67.2 million	$2,332 million ($2.332 billion)	~$2,524,000,000
Frit	30	6.3×10^5	No final waste form production processes required except packaging. Packaging technology is proven. Canister overpack materials require evaluation. Frit will be heterogeneous, e.g. will contain unoxidized metals as well as granular glassy slag. Particulate nature of the waste form may require a canister more durable than a 55 gal. drum. QA on the frit product is easily accomplished by periodic sampling.	Probably relatively poor	Probably low	No	Very little data available. No [illegible] with actual TRU waste. Very preliminary leach data not promising. Much more research needed on respirable particle production during all phases of producing and handling of the waste form.	$29.7 million	$38.5 million	$996.4 million	~$1,064,000,000

a. For discussion of complexity ranking method see Subsection III.1.

waste forms because the transuranics will be present in the potentially heterogeneous and variable frit phase.

- Additional comparable data on basalt, FUETAP, and frit waste form mechanical strength and respirable particle production are needed. Respirable particle production during frit handling and conveying processes, which are common to all three waste forms, is particularly important.

- The relative costs for shipping and repository storage of these waste forms indicate that waste from processes which minimize the volume of waste offer substantial cost reduction incentives, which can greatly outweigh increased production costs.

- Repository costs may be far larger than either production or shipping costs and could dominate the economics of waste-form disposal.

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APPENDIX A: COST ESTIMATES FOR SHIPMENT FROM THE INEL TO THE WIPP REPOSITORY

Data were obtained[A1] on the present costs of shipping TRU waste from the Rocky Flats Plant to the INEL. A cost schedule is in effect which varies from \$4.77/100 pounds to \$4.27/100 pounds as the payload weight increases. The cost includes return of the empty railcars. For the purposes of this calculation it was assumed that an average cost of \$4.50/100 pounds was applicable. It was further assumed that the cost was linearly proportional to distance. Thus, the value of \$4.50/100 pounds was multiplied by the ratio of the distance from the INEL to WIPP (1411 miles) to the distance from the Rocky Flats Plant to the INEL (788 miles). This yielded a rate of \$8.06/100 pounds which was rounded to \$8.00/100 pounds.

A.1 Basalt

An ATMX railcar will reach its weight limit of 101,300 pounds with 81 drums of basalt, each weighing 1250 pounds. Thus the cost to ship each railcar would be:

$$(101{,}300 \text{ pounds}) (\$8.00/100 \text{ pounds}) = \$8100$$

The total transportation cost required over the life of the TWTF project would be:

$$\frac{(4.8 \times 10^8 \text{ pounds of basalt}) (\$8100/\text{railcar})}{(1250 \text{ pounds/drum}) (81 \text{ drums/railcar})} = \$38{,}400{,}000.$$

A.2 FUETAP Concrete

As stated in subsection II.2.3., each 55 gal. drum of FUETAP concrete, when cured and dried, would contain 315 pounds of frit and 245 pounds of cement (including additives), for a total weight of 560 pounds per drum. The number of drums produced over the life of TWTF would be:

$$\frac{4.8 \times 10^8 \text{ pounds of frit}}{315 \text{ pounds/drum}} = 1.5 \times 10^6 \text{ drums.}$$

An ATMX railcar would reach its volume limit with 140 drums each weighing 560 pounds, for a total weight of 78,400 pounds per railcar. The total cost of transportation would be:

$$\frac{(1.5 \times 10^6 \text{ drums})\ (78{,}400 \text{ pounds/railcar})\ (\$8.00/100 \text{ pounds})}{(140 \text{ drums/railcar})} = \$67{,}200{,}000.$$

A.3 Frit

As stated in subsection II.3.2., each 55 gal. drum of frit would weigh 760 pounds. An ATMX railcar would reach its weight limit at 133 drums. As shown in Section A.1, the full railcar would cost $8100 to ship. Thus the total cost to transport the frit waste form would be:

$$\frac{(4.8 \times 10^8 \text{ pounds of frit})\ (\$8100/\text{railcar})}{(760 \text{ pounds/drum})\ (133 \text{ drums/railcar})} = \$38{,}500{,}000.$$

A.4 Reference

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