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Process System Evaluation - Consolidated Letter Reports - Volume 3 - Formulation of Final Product

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Summary

Glass discharged from the low-level waste (LLW) melter may be processed into a variety of different forms for storage and disposal. The purpose of the study reported here is to identify and evaluate processing options for forming the glass. The glass forms selected included:

- *Cullet* - glass is water quenched
- *Flake* - glass is cooled over dry rollers
- *Cullet in sulfur* - water-quenched cullet is dried and encapsulated in sulfur polymer cement (SPC)
- *Marbles* - glass is processed into 2.5-cm-dia. (1-in.-dia.) marbles
- *Pressed shapes* - glass "gobs" are pressed into a rectangular block
- *Plate* - glass is floated over a molten metal and cooling is controlled to prevent cracking
- *Monolith* - molten glass is poured into a large container where it cools.

Each form was then qualitatively evaluated and given relative rankings in the areas of

- *Performance* - waste form environmental performance
- *Capacity* - ability to achieve required production capacity
- *Retrievability* - ability to retrieve following disposal
- *Operability/maintenance* - ability to operate and maintain the equipment in a radioactive process
- *Volume cost* - efficiency of disposal volume use
- *Equipment cost* - cost of equipment and plant space
- *Quality assurance* - ability to control the process to produce quality glass and recycle poor quality glass, if required.

Generally, larger forms received better qualitative scores than smaller forms. Cullet and flake have very high surface areas, which results in low environmental performance scores. Adding sulfur cement to the cullet improves the performance but complicates the operation and maintenance of the process.

Marbles have less surface area than cullet or flake, but their production process is more difficult to operate and maintain. Because marbles are spherical, their packing efficiency in the storage/disposal container is reduced. Larger forms such as pressed shapes and plate glass have greatly reduced surface area, but require equipment that is difficult to operate and maintain in a radioactive environment. In addition, the cost for the initial equipment and plant space is higher.

The preferred form for the LLW glass is the large casting or "monolith." Casting monoliths is a simple process that produces high marks in nearly all of the evaluation criteria. The surface area is relatively small (even after cracking during cooling), the relative cost for equipment and plant space is low, a high production capacity is possible, and the equipment is relatively easy to maintain. In addition, selection of the monolith form minimizes constraints on the melter operation and glass formulation. The weakest point for the monolith form was the difficulty involved in recycling any out-of-specification glass back to the melter for reprocessing. However, large castings are the standard form for high-level glass production. Process control methods have been used at high-level waste (HLW) vitrification plants in Britain and France to mitigate the difficulties of recycling out-of-specification glass. Thus, this apparent weakness has been addressed successfully.

The selection of monoliths as the preferred form for the glass raises several issues and data requirements that need investigation. Glass within a monolith may tend to devitrify because of the slow cooling rates associated with the large mass. Data concerning the extent of nucleation and growth of nonvitreous phases as a function of cooling rate, combined with data on the effects of devitrification on product quality, may have important impacts on the monolith size. Data on the extent of cracking for given cooling conditions and the availability of the surface area within small cracks to corrosion may have important impacts on the estimate of long-term environmental release for monoliths. Other useful data include the glass thermal conductivity and viscosity as a function of temperature and knowledge of the deformation of the container during glass pouring, all of which would allow the monolith container to be properly designed.

Contents

Figures

Tables

1.0 Introduction

Input collected from stakeholders through the renegotiated Tri-Party Agreement (TPA) has identified glass as the preferred medium for stabilizing low-level waste (LLW) at the Hanford Site (Ecology et al. 1994). There are many different types of glass. The particular glass composition and its form must be defined to ensure that the final waste disposal system complies with exposure limits and other applicable regulations governing disposal. As part of the process to define the glass composition and form, this task reviewed methods used by the glass industry to form and shape glass and identified advantages and disadvantages of particular processes for producing the final waste glass form. The task focused on identifying an approach to forming and shaping LLW glass, not on selecting specific equipment.

The glass industry offers an immense variety of products, from tableware to fiber optic cable to solar reflective construction panels. Methods for manufacturing these products have been developed based on the production needs for the product. Blowing, drawing, pressing, casting, and extrusion are very general methods that have been used to form molten glass into products. However, not all of the manufactured glass forms would be practical for forming and storing LLW glass. In this study, the approach used to evaluate potential glass forms was to 1) develop minimum functional requirements for the forming system, and then 2) evaluate a few candidate processes representing the forming methods used in commercial industry and the shapes those methods would form. The candidate processes were established by searching the glass-manufacturing literature and contacting glass equipment vendors. As specific glass-forming processes were evaluated, each process was compared to the minimum functional requirements and the previously identified processes. If a process could not meet the minimum functional requirements, it was eliminated from further consideration. For example, extrusion was not considered a candidate process because it is used to make only low volume products. It didn't appear to meet the necessary capacity requirements. If a process was similar to another process already considered a candidate, the one appearing to best meet the functional requirements was selected for further evaluation. For example, the process used to form billets (logs of glass) is similar to that used to form plate glass (i.e., drawing). Forming billets wasn't considered in detail. If drawing glass into plate is selected as a preferred process, further investigation would consider billets as a specific option of that general forming method.

The rest of this report reviews a few candidate systems that are typical of the basic processes and product forms available from the commercial sector and that could contribute to the LLW glass disposal mission. Because the glass-manufacturing industry is very competitive and individual companies consider their processing information proprietary, specific data on glass processing and formation could not be obtained. Ancillary equipment such as annealing ovens, presses, and conveying equipment is available from vendors. The core process equipment for individual companies, however, is not available on the open market. The major glass manufacturers develop that equipment internally and build their own plants, or have one of a few glass design engineering companies work with them under a confidentiality agreement. Major glass producers that could have contributed greatly to this task (e.g., Corning, PPG, Libby-Owens-Ford) would not, and the task did not have sufficient funding to enlist the expertise of design engineering companies.

The main source of information was from the open literature and vendors of ancillary equipment. For the purpose of surveying the industry as a whole, the published literature is probably sufficient. For the extra detail necessary to consider actual design and operating experience, contracting with one of the glass engineering firms or a glass maker as a consultant would be very beneficial.

2.0 Functional Requirements

The first step in evaluating the commercial glass processes was to establish the requirements for a forming system to process Hanford Site LLW. These requirements would then provide the criteria for evaluating candidate processes. The approach was to select several processes that could probably be adapted, then judge each process to determine which one best meets the requirements. The following sections list basic functional requirements established by the task team for the forming process.

2.1 Performance Assessment

The glass-forming process can affect the performance assessment (PA) through the surface area-to-volume ratio of the waste, inclusion of matrix material (i.e., sulfur polymer cement [SPC]), or application of additional coatings or protection. Estimates of how the forming process would affect the final PA model were made based simply on the surface area-to-volume (mass) ratio of the product form and extrapolated from a model of spheres with and without a sulfur matrix (Piepho et al. 1994). Detailed PA modeling for each system was beyond the scope of this task and would require data not yet available (i.e., glass leach rates for the proposed composition and devitrification data).

When all the data are available, a detailed performance model for the whole system (glass, matrix [if used], secondary containment, barriers, etc.) will be developed. The whole system must meet requirements to protect the general public for at least 1,000 years after disposal (U.S. DOE/RL 1994), plus groundwater protection requirements (U.S. DOE/RL 1988).

2.2 Production

The system must be capable of producing 100 MT/d of glass to process 100,000 MT of waste oxides. The total waste oxides represent about 20% to 25% of the total glass to be processed in a +20-year operating time (U.S. DOE/RL 1988). The system may include more than one line—in fact, parallel lines would be desirable to permit maintenance on a line—but too many parallel lines to process 100 MT/d is impractical. For screening purposes, only systems with line capacities greater than 20 MT/d will be considered.

2.3 Retrievability

The final product form must be retrievable so that, if deemed necessary, it may be collected and transported to a permanent waste storage/disposal facility. It could be argued that any waste form could be retrieved, even if mining were necessary for the retrieval. For this task, the team concluded that retrievability would not have been included in the DOE requirements unless the requirements intended relatively easy retrieval. In general, the team has assumed that the final form needs to be in discrete units that can be packed in containers. The container size doesn't affect the analysis, but the container is expected to be manageable by forklift, conveyor, or small crane.

2.4 Operability/Maintenance Exposure

The design standard for exposure to operating personnel is 500 mrem/yr (U.S. DOE, Radiological Control Manual, Section 128). For purposes of this evaluation, it was assumed that automatic controls are needed to make the process operable—not a standard system feature in all areas of commercial glass making. Although automatic controls are commonly used in many areas of commercial operation, nearly all process lines still rely heavily on operators to adjust machines, lubricate machine components, "dope" molds, and oversee other areas of process operations. Processes that would require major redesign to eliminate routine operator intervention have been considered negative.

It was assumed for purposes of this study that the process will be contact maintainable (Brown 1994). Commercial equipment from the glass industry, especially new equipment, has evolved and been designed to make precision products. Consequently, the equipment has become increasingly complex and intricate. The glass industry is also very sensitive to equipment down time. Therefore, even though the equipment is quite intricate, it is also robust and can operate with little maintenance. The necessary maintenance, however, is performed through direct contact or (i.e., "hands on"). If it is found that capability for contact maintenance cannot be universally applied, then some of the commercial forming equipment would have to be so completely redesigned it would be impractical for further consideration.

In keeping with the assumption that maintenance will be conducted through direct contact, intricate equipment has been allowed in this evaluation. Generally, "complexity" has been considered a negative because of the greater potential for failure and because any maintenance would lead to increased personnel exposure. Allowances have been made, however, for equipment that appears to be based on a modular design, which would allow the components to be changed remotely.

2.5 Minimize Waste Volume

Previous studies comparing costs of alternative glass forms determined that the cost for waste storage dominated all the other processing costs (building facilities were not estimated) (Whittington and Peters 1992). A study conducted for Fernald LLW in 1992 cited the cost of storage volume at \$740/m^3 (\$21/ft^3) (Whittington and Peters 1992). Assuming the same cost for storage volume, which is probably too low now, a form that effectively doubles the volume incurs a storage cost penalty of at least \$180 million.

For purposes of this task, greater waste volumes were considered a negative.

2.6 Equipment and Building Cost

No attempt has been made to estimate actual equipment or installation costs. For the purposes of this task, relative costs are based on the equipment's complexity and size. Size will impact costs because of the costs to build operating areas that contain the equipment; e.g., large equipment will increase costs mainly because of the costs to build and maintain enclosure cells.

2.7 Quality Assurance

The quality assurance (QA) criteria examines how each process must be controlled to assure quality of the product and smooth operation of the process. Forming processes that require special controls to maintain a specific production rate, glass viscosity-temperature relationship, or process temperature to properly form the product are graded lower. Forming processes that produce a product difficult to recycle to the melter are rated lower. Processes that must be carefully controlled to avoid operability or maintenance problems are also scored lower.

The ease of sampling the final product was not considered an evaluation criteria because it was assumed that process sampling and control will be sufficient to assure overall product quality.

3.0 Selecting Processes for Evaluation

As discussed in the Introduction (Section 1.0), glass-manufacturing processes were briefly reviewed for this task. Processes appearing to have the greatest potential for manufacturing 100 MT/d of glass in a continuous, automatic process were selected for further evaluation. Processes that used the same basic forming method (casting, pressing, etc.) were considered to have similar operating limitations and advantages.

Quenching glass to make irregular broken shapes (cullet) was included as a forming method, with cullet considered to be a potential final form. While many may not consider quenching to be a glass-forming method, a water-quenching (cullet) tank is used in nearly every glass plant. It is used as part of the recycle process when the forming system is down, and serves to rework glass from the furnace. Including cullet in an SPC matrix to increase durability is also included as a form option (U.S. DOE/RL 1994).

Processes representing the forming methods of pressing, casting, and drawing were also selected because they will produce shapes covering the range of potential waste form sizes. Each specific process is better suited to a glass product of a particular size range. The processes selected for comparison are listed in Table 3.1, grouped according to the size of the product they will make. The general forming method is also indicated. Blowing, which is used to make hollow shapes such as containers and light bulbs, wasn't considered to be a practical forming method for LLW glass. Because LLW glass is not going to be used as a product and hollow shapes inherently increase the required storage volume, blowing was not considered for further evaluation.

Table 3.1. Selected Forms[a]

Small shapes (<1 inch)
Cullet--wet process (quenching)
Cullet (flake)--dry process (drawing)
Cullet with sulfur
Marbles (casting, rolling)
Medium shapes (1 inch to 2 feet)
Pressed shapes--bricks, spheres, etc.
Plate and float glass
Large shapes
Monolith--square, cylinder, hex, etc. (casting)

(a) Shape and size are optimizing variables, not separate processes.

3.1 Quenched Cullet Process

Manufacturing cullet by quenching molten glass in water is a common practice throughout the commercial glass industry (Figure 3.1). Almost every glass plant uses water quenching to quench molten glass when the main forming line is down and the molten glass has to be diverted. At any plant, the glass furnace is large and it can be difficult to establish the target composition of glass. Rather than upset a stable furnace operation, nearly every glass plant will "bypass" a disabled forming line and quench the glass so it can be remelted later.

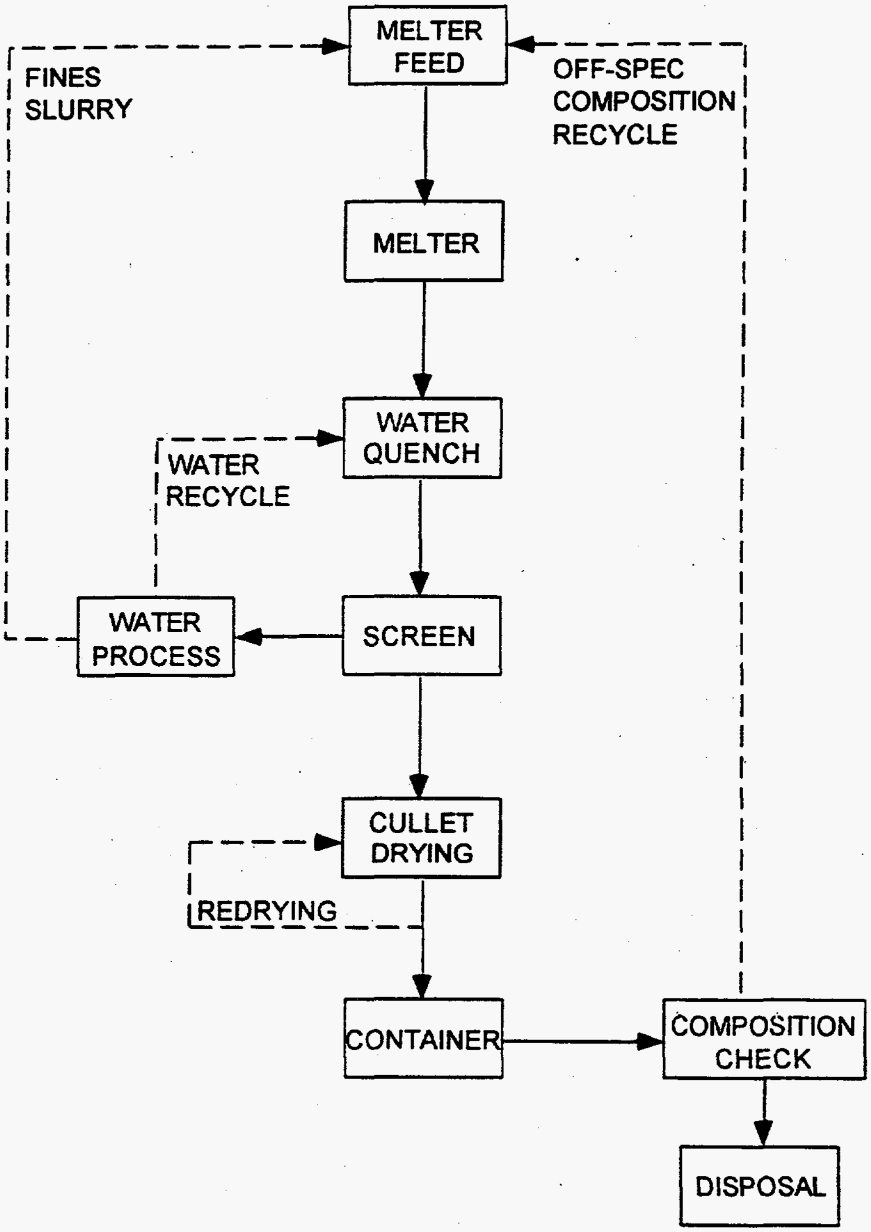

Figure 3.1. Wet Cullet

This section discusses quenching and drying cullet for storage in containers. Later, in Section 3.3, a process that uses sulfur cement to encapsulate cullet within a retrievable container is considered. For comparison, the TWRS-proposed process described by Orme (1994) is shown in Figures 3.2a through 3.2f. The approach of casting sulfur cement/cullet in large vaults as shown in Figure 3.2e was not considered in this report because the form is not considered retrievable.

3.1.1 Process Description

The optimum quenched product will have a narrow size distribution and large particles to minimize surface area. Process variables affecting these are the temperature of the glass, the temperature of the water, and the nature of the contact where the quench occurs. The first process step will be to control the glass temperature. Temperature is controlled using a forehearth, a slow-moving trough of molten glass with controlled heating provided on the sides and overhead. Depending on the melter, the forehearth can also be used to separate gases from the molten glass and to provide extra residence time for the glass, thereby assuring there are no inhomogeneities in the glass.

Molten glass from the forehearth is dropped into a trough of flowing water where it fractures. At this step, the size distribution is very broad and lots of fines (<22 micron) are generated. The fines are not a significant fraction of the mass, but contribute greatly to the surface area of the distribution. Also present are significant masses of highly fractured glass that still hold together in large pieces; these pieces may cause some plugging problems in the subsequent slurry piping. They could easily be broken into smaller pieces by passing the slurry through rollers.

The off-gas from the quenching trough contains mainly steam, but also entrains fumes from the glass. In a waste processing application, the fumes would have to be captured and scrubbed. Scrubbing the fumes is not necessary at a commercial glass plant.

The slurry of broken glass and water collects in a holding tank. The heat from the glass is removed from the water either by evaporation, or by cooling the water through a heat exchanger.

The next step is to separate the bulk of the water from the glass. The TWRS-proposed process would do this by keeping the tank sufficiently mixed to completely suspend all the particles, then pumping the slurry through a screen. The water returns to the tank and the glass moves forward. Another approach is to adapt the bottom of the quench water tank to act as a hopper. The tank is not aggressively mixed, so the glass falls to the bottom of the tank where it is picked up by a chain or screw-type conveyor (Whittington and Peters 1992) (Figure 3.3). The water flows back down the incline and into the tank.

Both slurry-separating systems accumulate fines in the quench water tank. The fines can be removed by filtering the tank wash water. The TWRS-proposed process would accomplish this by using two wash water tanks. The fines accumulate in one of the tanks and are returned to the melter feed preparation

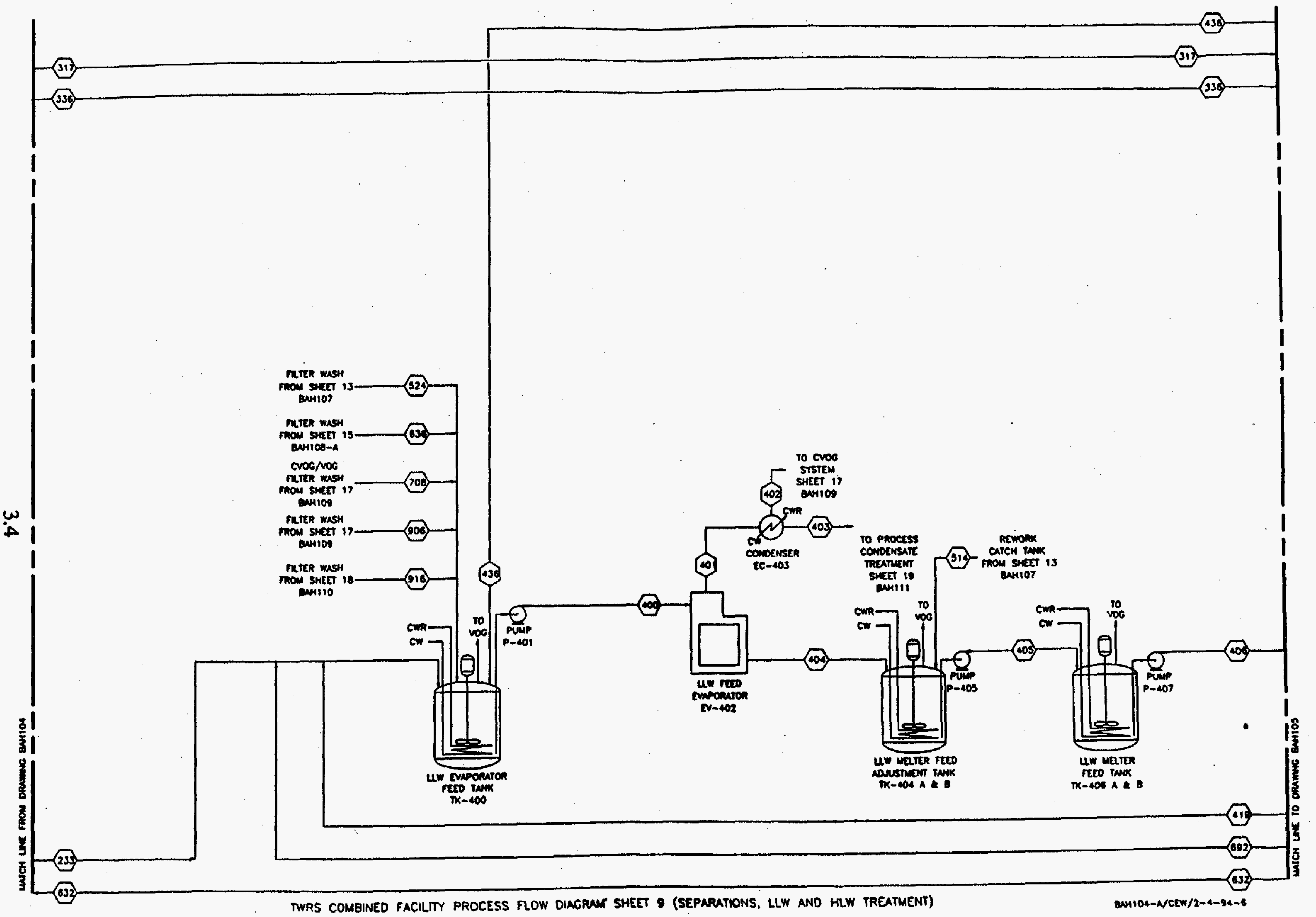

Figure 3.2a. TWRS-Proposed Process: Feed Treatment (Orme 1994)

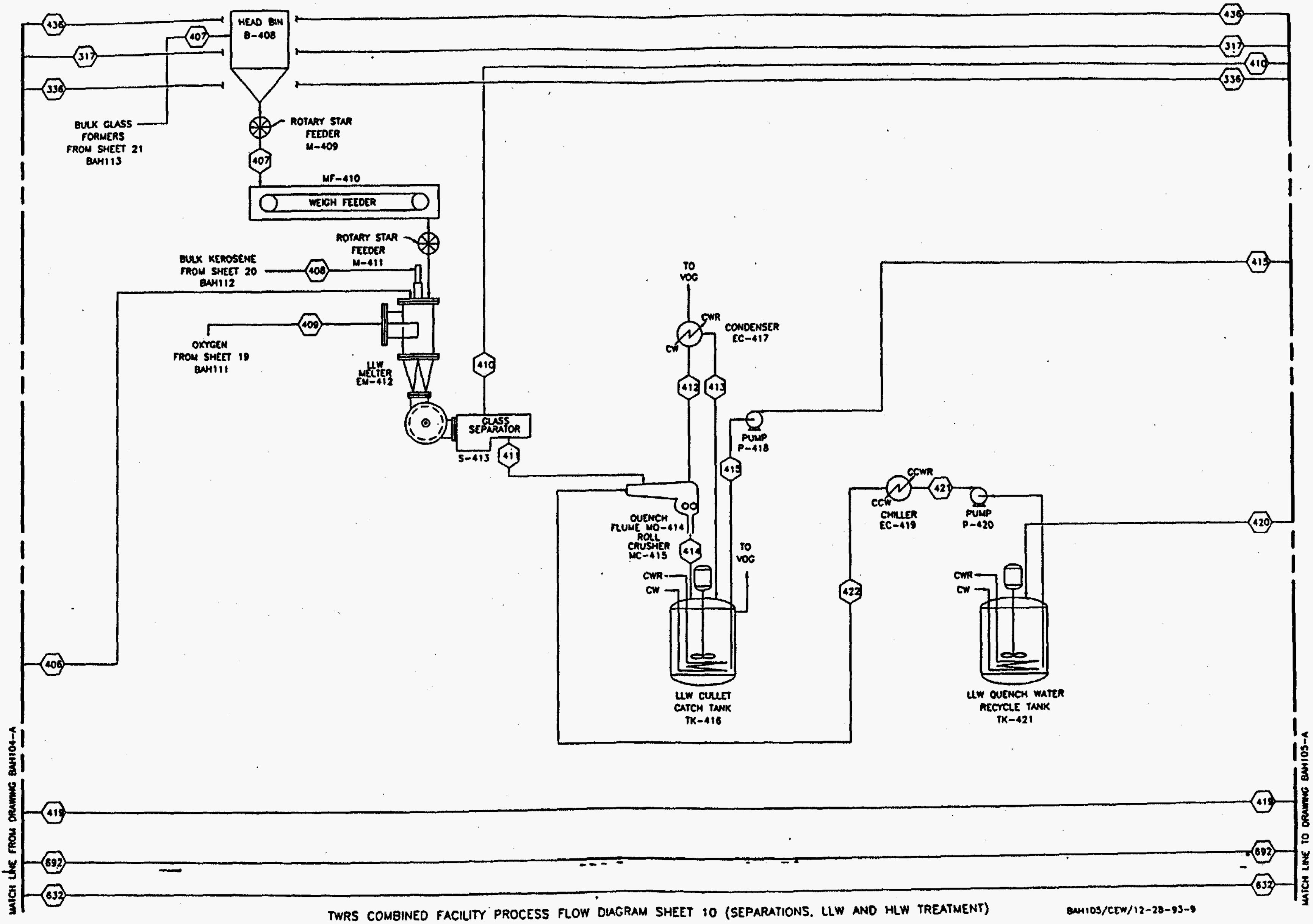

Figure 3.2b. TWRS-Proposed Process: Melter and Quench (Orme 1994)

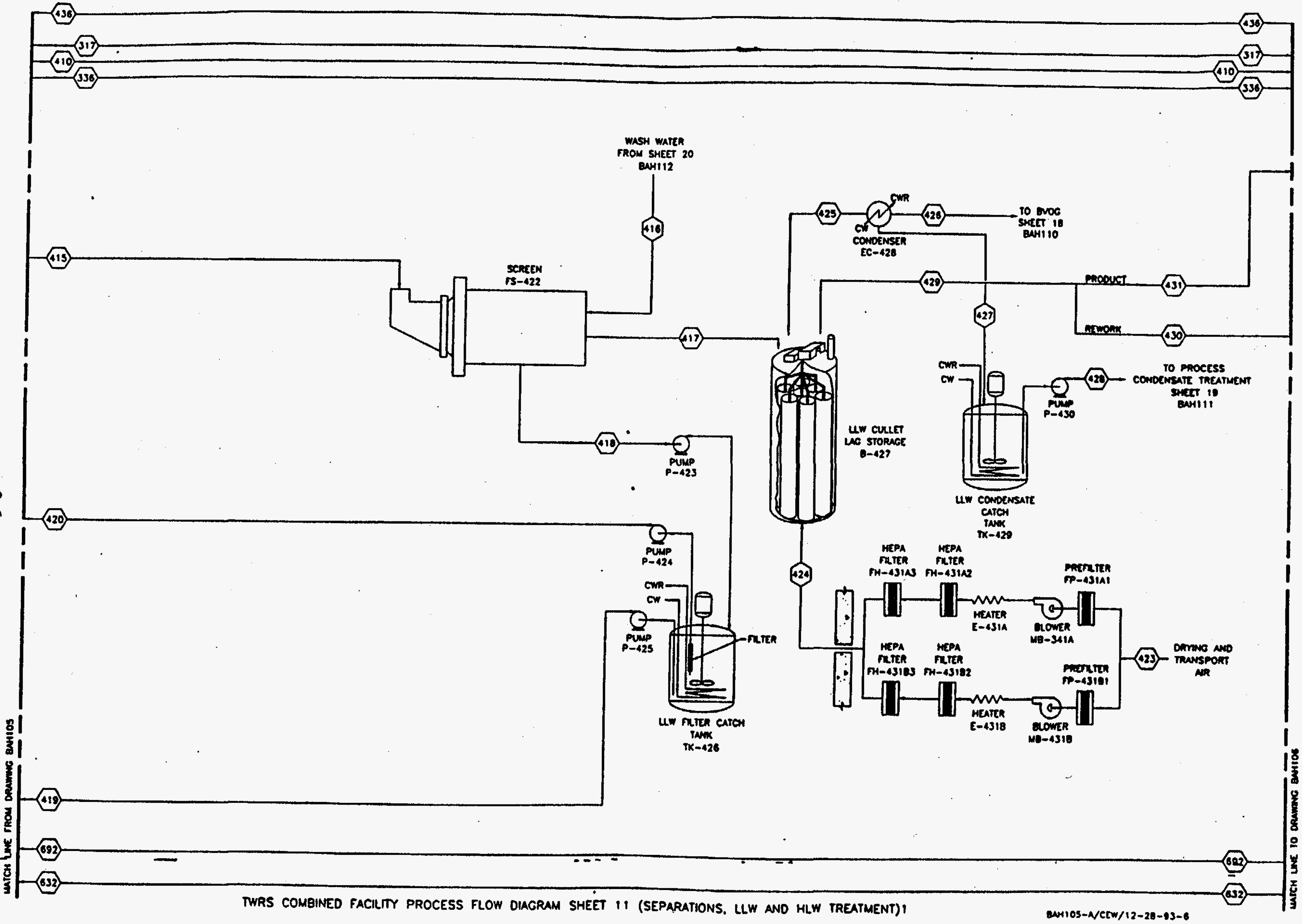

Figure 3.2c. TWRS-Proposed Process: Screening and Dryer (Orme 1994)

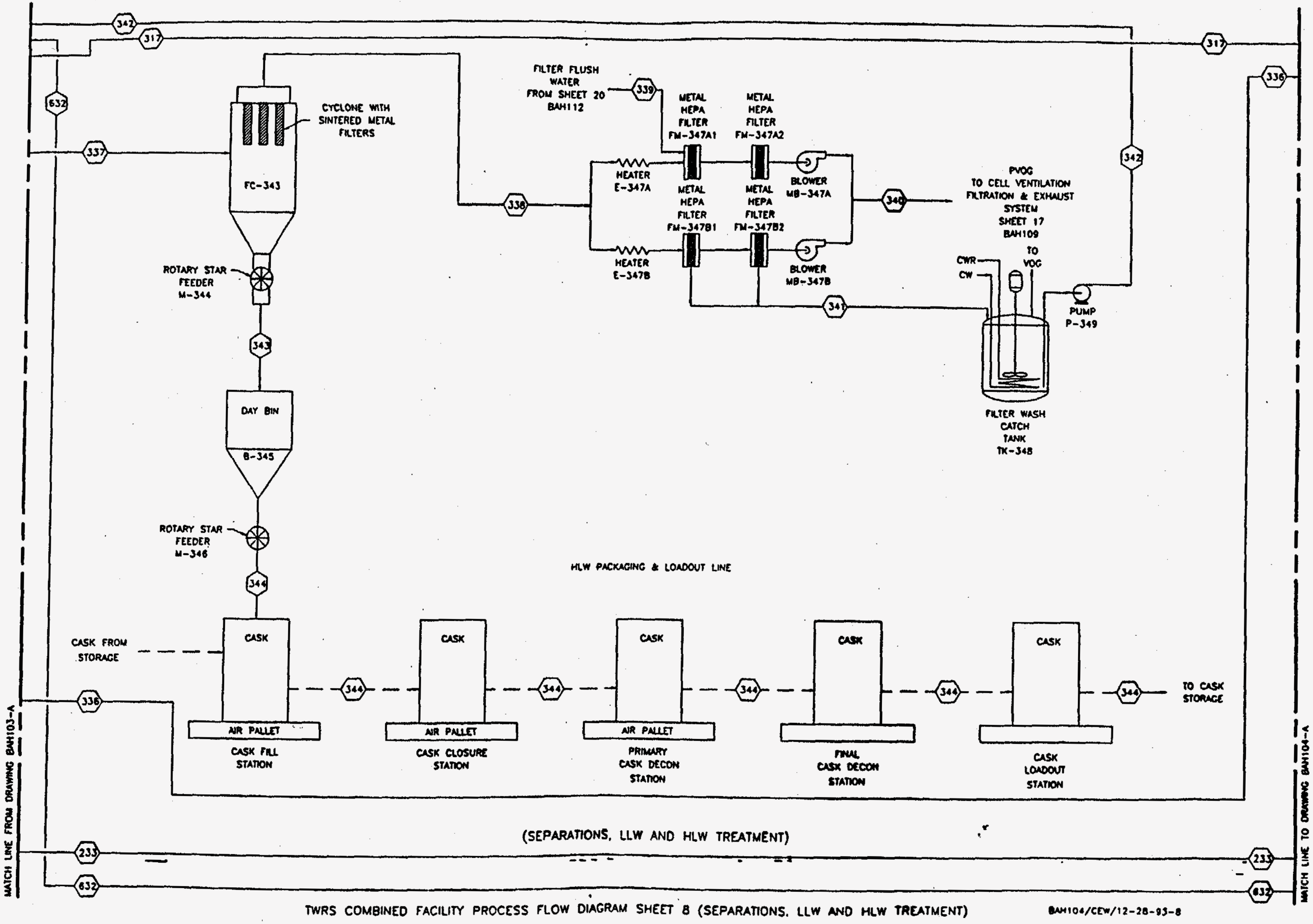

Figure 3.2d. TWRS-Proposed Process: Loading Storage Containers (Orme 1994)

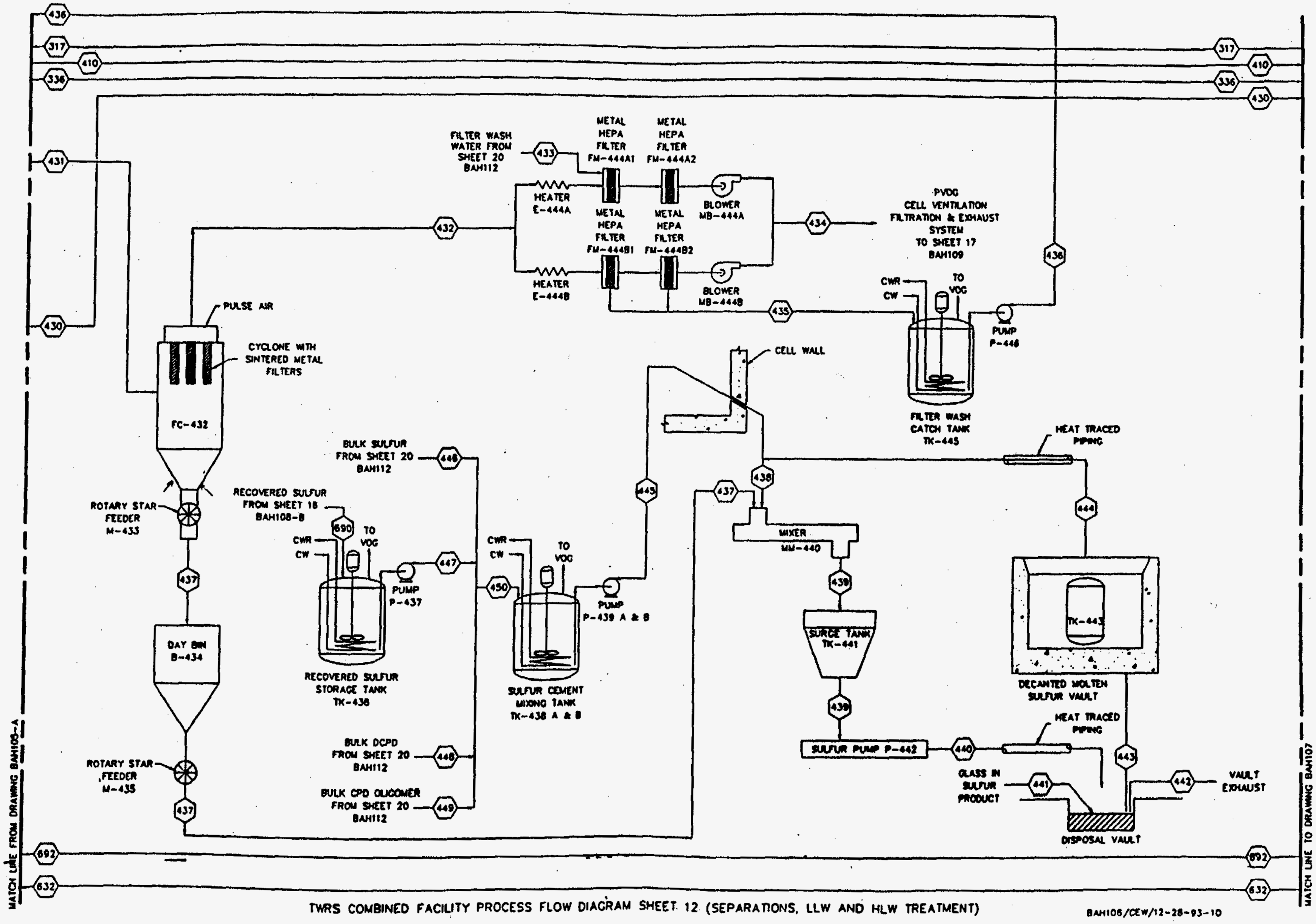

Figure 3.2e. TWRS-Proposed Process: Sulfur System "Nonretrievable" Storage (Orme 1994)

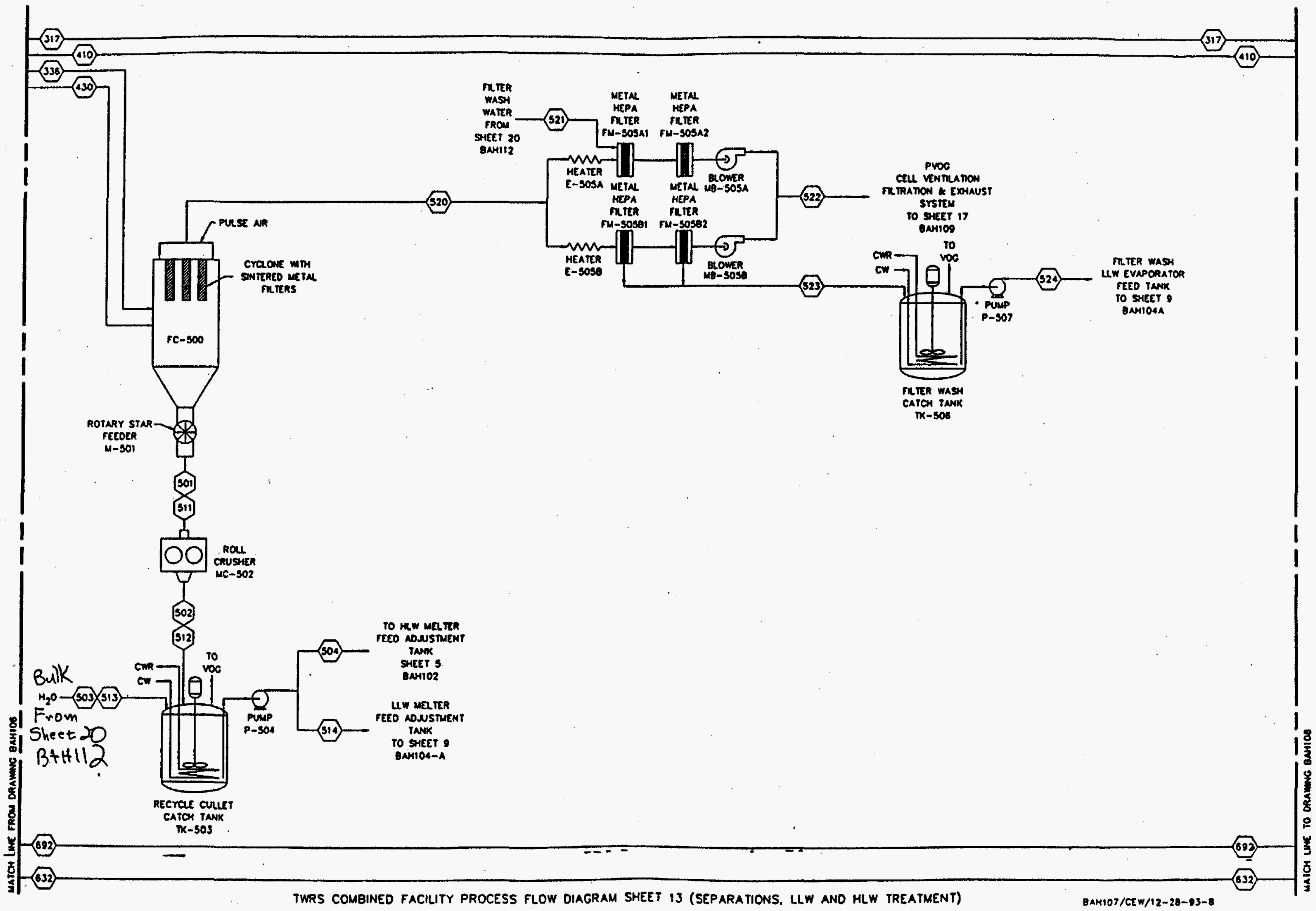

Figure 3.2f. TWRS-Proposed Process: Bin Storage and Recycle (Orme 1994)

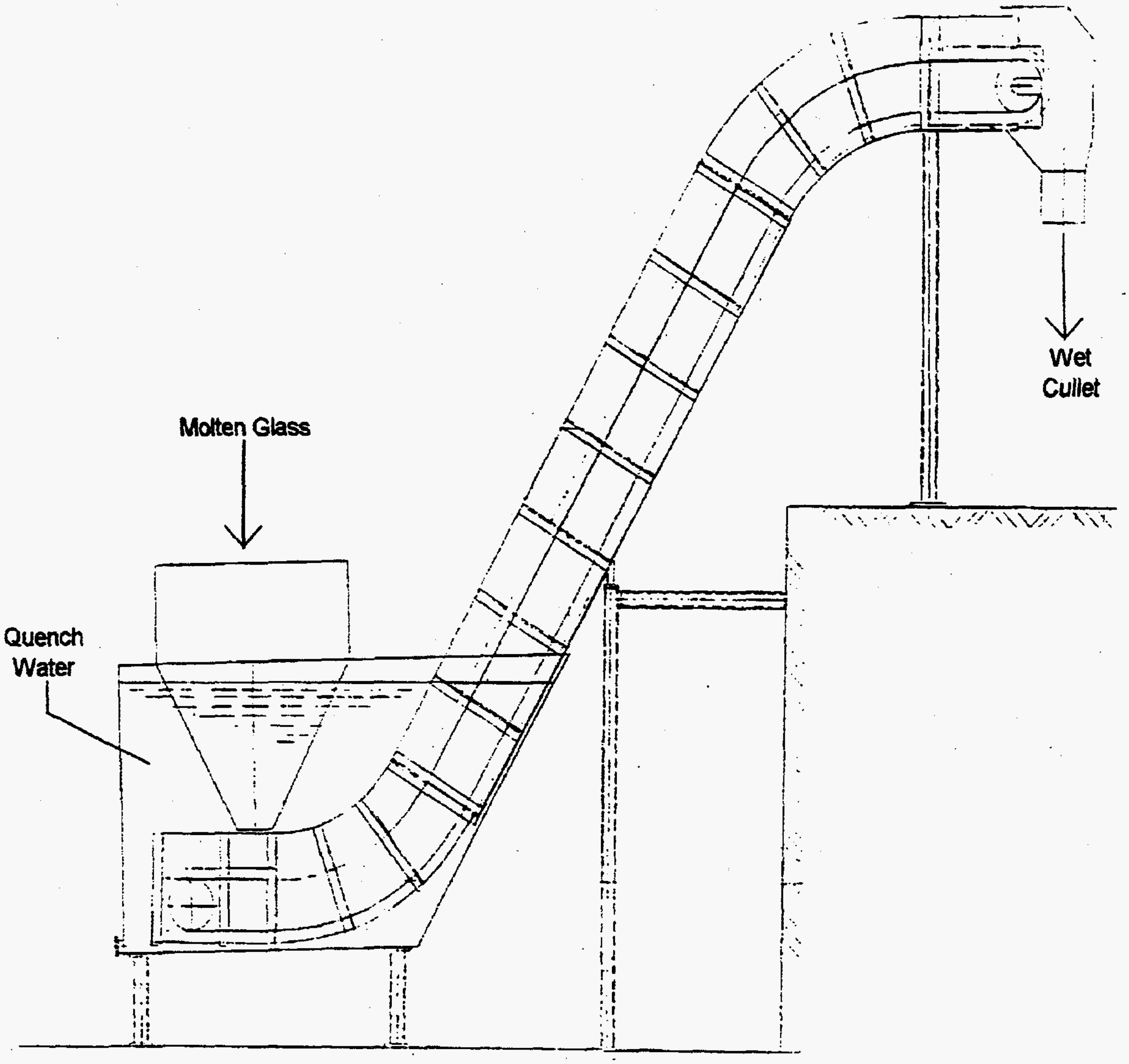

Figure 3.3. Quench Tank and Cullet Conveyor (Whittington and Peters 1992)

step. The filtered water is returned to the quench water tank. The fines that are returned contribute relatively little to the melter throughput. The greater impact is from the water heat load.

After the water is drained from the glass, the glass must be dried for storage. Any water remaining on the glass will increase the corrosion rate of the glass and greatly increase corrosion of a metal container. The glass is dried by blowing heated air over it using various types of equipment.

Experiments on samples of cullet indicated that the cullet retained water at 23.9% of its dry weight (see Appendix A). The water was not from hydration, but was surface water held around each particle. Drying the cullet requires significant energy. Even more energy would be required to cool the air and remove moisture before discharging the air through high-efficiency particulate air (HEPA) filters. Air flows around 10,000 SCFM would be needed. The water condensed from the moist air could be returned to the quench tank.

A recirculation system would be much more practical than filtering and discharging all that air for a one-pass system. For a 10,000-SCFM recirculation system, the air would have to be heated to nearly 400°F to provide enough enthalpy to dry the cullet. More moderate temperatures would require recirculation of even more air. Optimization was not attempted for this task. The significance of this step is that drying quenched cullet incurs a high energy cost.

After the cullet is dried, it can be packaged in the final storage/disposal canisters. To facilitate processing, the packaging step is separated from the quenching and drying processes by storing the dried cullet in a storage bin of adequate volume. The final packages could be loaded from the storage bin. To achieve maximum storage density, the final filling step would also have to densify the mix. Dust control would be necessary when handling the dried cullet.

After the packages are filled, they can be sealed and decontaminated for transport to the storage facility. The final step before transport would probably be to load the package into a secondary container to protect personnel from radiation during transport and final placement in the storage facility. The characteristics of the containers themselves were outside the realm of this study. Although this task did not address the containers to be used for transport, reusable transportation containers may be practical for this purpose.

3.1.2 Equipment

As described in the previous section, forehearths are used to control the glass temperature. Forehearths are commonly used in the glass industry. They are reliable and trouble-free. They are usually gas heated, although electrically heated units are probably available. The durability of the electrical heaters depends on the temperatures desired in the forehearth. Other than heater replacements, the only maintenance requirements are infrequent major rebuilds of the refractory. Rebuilds normally are required after several years of operation (i.e., 6 to 7 years).(a)

Equipment used with the quenched cullet includes several types of rotating equipment (e.g., pumps, agitators, rollers, and conveyors) that periodically require lubrication and maintenance. Seals are also used to contain water around flooded pieces of equipment. While leaks in the water system are common and expected in commercial glass-making operations, they cannot be allowed to occur in a radioactive waste-processing application. When used in a waste-processing application, it can be expected that equipment wear, especially on seals and rotating equipment, will be greater than it is in normal industrial uses. Therefore, the equipment components will require more frequent maintenance because of the abrasive nature of the glass.

(a) Personal communication, Owens-Brockman Glass Co., Portland, Oregon, April 20, 1994.

A 100 MT/d system could easily circulate several hundred gallons of quench water per minute, thereby requiring pumps and tanks with a large capacity. For example, a 30 MT/d cullet system at RECOMP of Washington circulated about 150 gal/min of quench water (Whittington and Peters 1992).

Separating water from glass is a simple process in terms of filtration. The glass is not hydroscopic and it dewaters readily. Nevertheless, a large screen that can separate several hundred gallons per minute will be required. The screen will have to include automatic cleaners to clean out glass particles that become wedged in the mesh. It will also have to be quite fine to minimize the amount of glass returned for rework. A preliminary estimate in the proposed flowsheet indicated 99% retention of glass, which for separations would require a screen of about 300 microns, 50 mesh (see Table 4.2--particle size of quenched cullet). Screens would be replaced as part of routine maintenance. A screen with a large mesh would be more durable, although the tradeoff would be more glass passing through that would have to be remelted.

Bulk drying, storing, and packaging of solids is commonly done in many industries (e.g., foods, fertilizers, agriculture) besides the glass industry. Numerous approaches exist for drying the solids and packaging them in storage bins. Although off-the-shelf equipment could be used to handle glass cullet, the radioactivity of LLW glass must be considered when selecting equipment. Bulk solids have the potential to cause plugging and bridging problems. Air blasters, rappers, vibrators, and many other devices are used to correct problems with bulk powder. Nevertheless, commercial equipment design relies on manual cleaning as a final option to relieve difficult plugs. Manual clearing would not be an acceptable option for LLW bin design.

Experiments on samples of cullet indicated that the normal poured bulk density of cullet is only about one-half that of solid glass. Achieving a higher packaged density would require densification equipment. As the simplest approach, strong vibrators attached to the outside of the package might be able to achieve the necessary settling.

In the commercial glass industry, container filling is usually controlled by weight because sales are made by weight. Containers are sized to accommodate variations based on the least dense product. This necessarily produces free space above the product when the product is of normal or high density. In a waste processing application, where volume optimization is more important than container weight, container filling would probably be controlled by some means other than weight.

The last steps of container packaging for the cullet process, as for all the candidate processes, involves complex automated handling. Empty containers are moved, located in position, moved to new locations, sealed, and decontaminated. Equipment for the handling steps is used commonly in the glass industry, and handling a few hundred or thousands of packages per day, up to pieces weighing multiple tons, is not unusual. However, all commercial equipment requires routine maintenance and adjustments. The more precise the needs and complex the system, the greater the maintenance requirements.

3.1.3 Quality Assurance

Control of the quenching process should be fairly simple and the system operation should be very tolerant of out-of-specification conditions. Some alternate forming approaches require close control of temperature to achieve a specific viscosity range or the forms will plug and stick, potentially closing down the line. Comparatively, water quenching is foolproof. Control of the glass temperature, water temperature, and contacting system (water flow and mixing) can affect process optimization, but should not jeopardize product performance, nor cause process failures.

Control of the drying conditions is more complex. Leaving the glass in a wet condition is likely to produce out-of-specification glass that requires recycle. However, recycle would be necessary only back to the dryer, not back through the melter. Extra capacity would need to be designed into the dryer so the dryer could hold out-of-specification moist material for subsequent redrying.

The densification process is another step that can deviate from optimum conditions and lead to greater storage costs. Out-of-specification conditions, however, will not cause the product performance to fail.

Recycling glass cullet would be relatively easy. As the out-of-specification cullet exits the dryer, it could be recycled to the melter directly or reduced into frit for inclusion in a liquid feed stream.

3.1.4 Design Information Needed

It will be simple to select water flows and equipment to quench glass and make cullet. Designing a system to minimize fines production and surface area, however, will require some experience and trials with the expected glass compositions. Such testing may or may not significantly improve the surface area.

The achievable slurry density (glass-to-water ratio) will greatly affect the slurry volumes, a quantification that is needed to size the tanks, piping, agitators, and screen. Some of this information may be available from commercial glass designers, although it is likely that commercial designers simply use lots of water because quenching is a secondary, infrequently used process not worth optimizing. The process may not benefit from optimization. It is simple and a conservative approach could be taken just to ensure that it works.

The accumulation rate of hydroxide in the quench solution may be needed to prevent adverse effects on product quality. Also, the accumulation rate of radionuclides may be required to assess maintenance and secondary waste issues if this stream leaves the vitrification plant.

The drying operation includes the potential for process failures. The system must be designed so that, during the final drying stages, particles don't fuse and cause plugging. Likewise, the holding bins must have the unfailing capability to break up plugging no matter how rarely it occurs. With perhaps several tons of radioactive glass inside the bin, this area cannot be "contact maintained."

The final densification process probably cannot be predicted accurately without some testing to determine the best equipment and attainable bulk densities. As with slurry density, this is an optimization issue, not a step that could cause process failure. However, it should be easy to have potential suppliers test their equipment and collect the necessary data.

3.2 Cullet (Flake)--Dry Process (Drawing)

Although flake forming produces basically the same product as the quenching cullet system, the production process is simpler. There is no contact with water, and therefore no need for filtering and drying systems.

3.2.1 Process Description

To make flake, the molten glass is first conditioned in the forehearth to bring it to the proper viscosity range. It is then poured between a set of water-cooled rollers, producing a sheet of glass about 1/32 in. thick and 8 to 10 ft wide. Because the glass is so thin it is "friable," or easily crushed. The glass sheet is broken into pieces using cracking rollers and is then size reduced using a crusher (Figures 3.4 and 3.5). The glass particle sizes can be regulated by changing the cracking roller positions, crusher feed rate, rotor speed, and clearance between the rotors or hammers and grinding plate. The hammer mill is required only if a suitable packing density cannot be achieved using the cracking rollers.

The rest of the processing system is the same as that described in Section 3.1 for the quenching method. A conveyor system carries the cullet to a holding bin from which the containers are filled.

This operating sequence is fairly simple (although not as simple as that for monolith production) and is already used in industry (Figure 3.6). It has been designed to run with very little maintenance or operator interference.

3.2.2 Equipment

For a waste processing operation, the necessary equipment includes a forehearth (see Section 3.1 for description). An overflow spout or nozzle will feed the molten glass from the melter to the rollers. Hollow water-cooled rollers then form the glass into thin plate. These rollers will be motor driven and mounted on bearings. Two more motor-driven rollers, at an angle to the first, will break the plate into pieces (see Figure 3.4). The drive systems and bearings will occasionally need lubrication and maintenance.

The pieces will then be fed to a hammer mill or crusher to achieve a uniform size. The crusher will consist of hammers or teeth mounted on a motor-driven shaft that crushes the glass against another shaft or a plate (see Figure 3.5). These parts will wear and are designed to be easily replaced. A screen or grating will allow only properly sized particles to proceed. Finally, a conveyor will transport the flake to the containers.

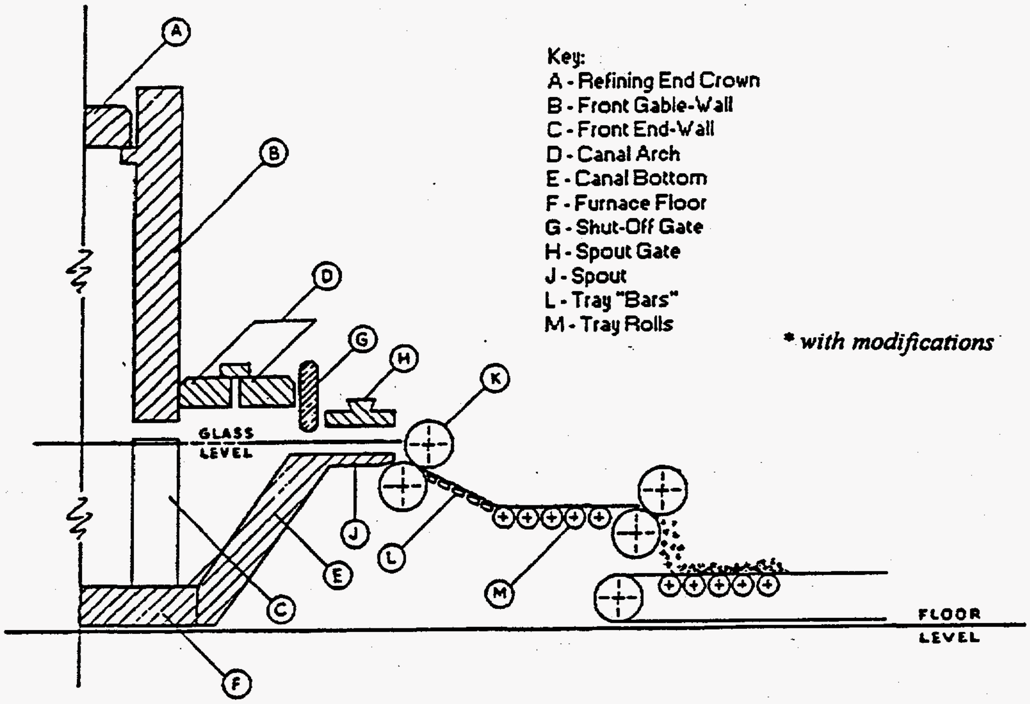

Figure 3.4. Flake Conceptualization (Tooley 1974)

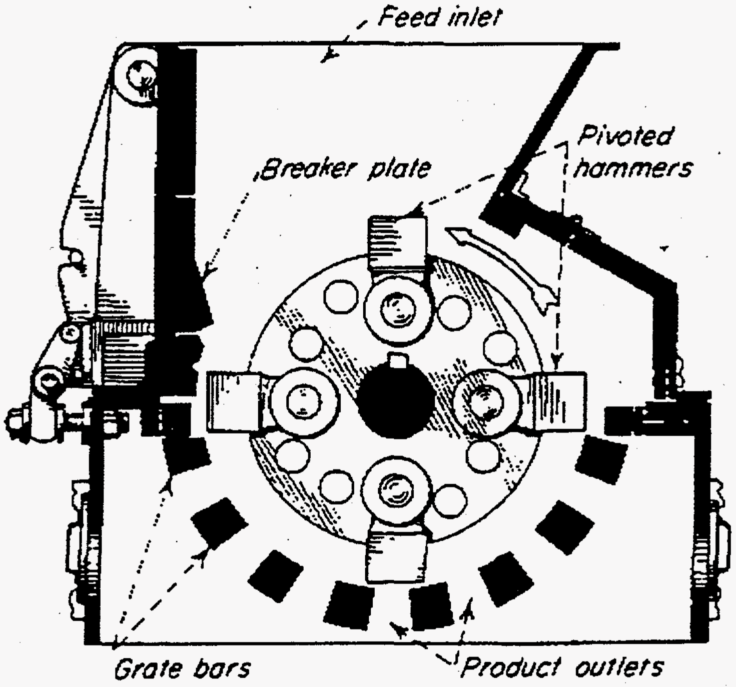

Figure 3.5. Hammer Crusher (Perry 1984)

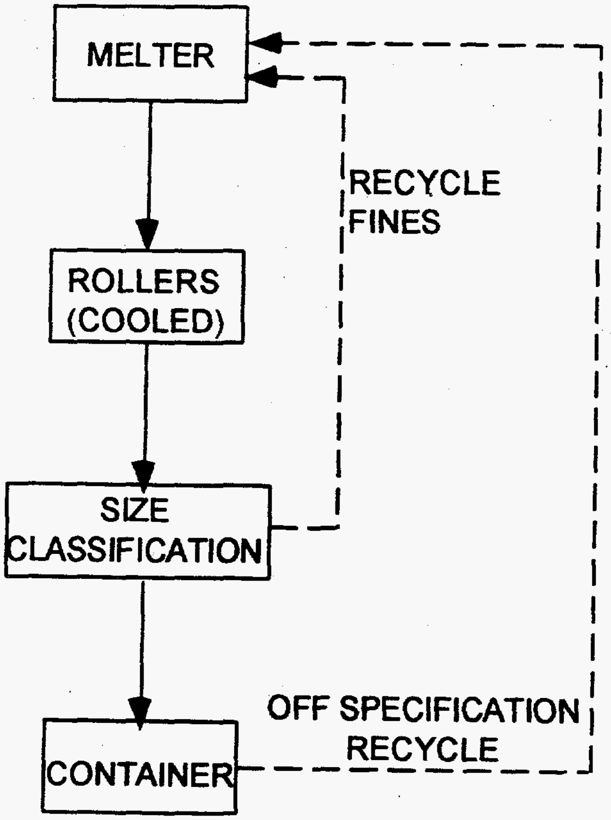

Figure 3.6. Flake (Dry)

The necessary production rate of 100 tons/d should be easy to achieve with this system. Because only one machine is needed, the complexity of the system is not great. Occasionally, maintenance will be required on the rollers and the hammer mill; however, any maintenance needs should be easy to schedule during planned outage times.

3.2.3 Quality Assurance

A feature of this system is its ability to easily accommodate changes in glass composition and feed temperature. Almost any glass can be rolled and cracked. Because the glass will be rolled at a fairly low temperature, fuming will be less of a problem. Composition testing should be performed periodically at the melter. The final product to be tested can easily be diverted from the conveyor system to the containers.

Any glass that does not meet specifications can easily be recycled by conveying it back to the melter after it has been crushed. The recycled glass will be dry and will therefore contribute a much smaller load on the melter than the wet cullet.

3.2.4 Design Information Needed

Glass properties will be needed to determine feed temperature and to design plate thickness. Greater plate thickness may be possible to reduce surface area.

It may be possible to eliminate the crushing operation if the cracking rollers are properly designed. The rollers would need to consistently produce the desired glass particle size, thereby reducing system complexity.

3.3 Cullet With Sulfur

The release of radioactive materials from glass particles may be reduced by adding secondary barriers between the radioactive material and the environment. The concept of multiple layered barriers was presented very early in the development of radioactive containment options. Many materials have been considered over the years, but no one layer has been found to completely stabilize all radioactive components. As layers are added the performance weaknesses of inner layers may be mitigated, leading to better performance but vastly more complex processing.

Glass is a good stabilizing medium for the LLW materials. Its weakness is that it may be slowly attacked by water and eventually release its radioactive components. Methods to prevent moisture from attacking the glass surfaces are being considered. One method is to mix the glass with molten sulfur and polymer modifiers to make SPC. SPC has been considered to be "impermeable" and could therefore limit the attack of water on the glass surface. Sulfur may also chemically bind with some of the released materials to form insoluble sulfides that further reduce release (Mattus and Mattus 1994).

SPC may be used to encapsulate cullet or other small pieces such as marbles. The cullet may be formed using either the wet-quench process or the dry-flake process. The SPC process is described below with the understanding that some glass-forming process must be coupled with it.

3.3.1 Process Description

Bulk commercial sulfur is a relatively cheap and available commodity chemical. At normal temperatures sulfur is a solid. It is shipped in bulk in tank cars as a solid. Handling sulfur always requires melting the bulk solid and transferring it in heated, insulated piping. The recommended temperature range for handling is 135 +/- 6°C (Mattus and Mattus 1994). Outside this range the material becomes too viscous to practically pump. At temperatures above 150°C, poisonous gases (H_2S and/or SO_2) are evolved. Polymer additives are added to the molten sulfur to enhance the mechanical performance of the concrete. Commercially available sulfur "cement," Chement 2000, is formulated with oligomers of cyclopentadiene at 2-5% by weight (Mayberry et al. 1993).

In a waste processing application, the sulfur would be mixed with the glass pieces after the sulfur is melted. Compared to typical concrete, the glass pieces would serve as the aggregate and the sulfur as the cement. Good mixing at this step is essential to get good dispersion that does not include air. Air in the mixture would lead to a high porosity and possibly the form's failure as an impervious barrier. Mixing the material may not be a straightforward process. Mattus reported that "finding the appropriate mixer was not as easy as it might appear" (Mattus and Mattus 1994). The viscosity of molten sulfur cement at 135°C is around 50 cP. However, when a high solid fraction slurry (i.e., 70%) is mixed, the effective mixing viscosity may be very high indeed. Moony's correlation for slurry viscosities predicted a viscosity ranging between 200 P to 600,00 P for the range of possible constants (Perry 1984). Mixing will be a major process step.

Before the mixing step, the glass and the container would need to be preheated. If the glass isn't preheated, agglomerates will solidify some sulfur on their surfaces and prevent complete wetting, causing voids to form in the matrix.

Another critical factor for using glass with sulfur is that the glass must be completely dry. Moisture below 1% by weight is necessary and 0.0% is preferred. Achieving a moisture content below 1% should not be difficult for glass, but doing so will require process control. Mayberry suggests materials to be combined with sulfur should be heated to 200°C to ensure dryness (Mayberry et al. 1993). Heating to this temperature would add considerably to the heating requirements for a quenched-cullet forming process. The flake or marble processes would be much more applicable because they do not require direct contact with water.

After the glass and sulfur are mixed, they would be poured into a preheated container. With a mixture of high viscosity (still unknown how high), the pour will need to be maintained at temperature for a while and possibly vibrated (like concrete) to settle and displace air. Full-scale tests performed at Idaho National Engineering Laboratory (INEL) filled a 1-m^3 container in 1 to 5 hours (Mattus and Mattus 1994). These pour rates would handle 42 to 8 MT/d of glass, respectively.

More than one production line will probably be required to accommodate full-scale production.

Another option being considered for containing the SPC is to transfer the molten materials directly to the temporary storage facility, or "vault," and allow the matrix to solidify as a monolith. For that process the viscosity concern discussed above would be critical. It probably would not be feasible to pump a slurry such as SPC and cullet any distance over a few hundred feet. Such a system would need to transfer the dried glass to the storage site and then mix it with the SPC. Bulk transfer of solids over long distances may, likewise, not be practical. If glass material is put into a container for transport, pouring large volumes into a vault to form a monolith would no longer be easier than filling the container at the plant.

3.3.2 Equipment

Equipment to handle bulk sulfur is well developed and readily available. Systems to heat rail cars filled with solidified sulfur and pump the molten sulfur for processing are common and not very complex. They are not, however, foolproof. Transfer lines and pumps must be insulated and heated to keep the sulfur fluid. Steam tracing lines are subject to steam trap failure and electrical tracing lines are subject to burning out. In either case a failed heat tracer will cause the line to plug. The failure, however, is not catastrophic because once the heat source is repaired the sulfur will again melt and processing can commence. Difficulties with this part of the system are not a significant concern because all the equipment can be located outside of the radioactive environment. Maintenance is simple.

Special off-gas equipment will be needed to control gases during melting. Special safety measures will also be necessary in case temperatures higher than 160°C lead to the release of SO_2 and/or H_2S (both toxic gases). The off-gas treatment for these materials will also have to collect off-gas from the mixing step, which may contain radioactive isotopes. Perhaps three systems will be used: radioactive process off-gases, sulfur process off-gases, and mixed process off-gases.

Equipment for the mixing step is rather difficult to find. Simple in-line mixers as used to mix liquids will not work. The viscosities will almost certainly be too high. Batch mixers have been used for all the work done so far with SPC. This process will need multiple batch mixers or some type of continuous mixer, like a continuous ribbon blender.

If the mixed SPC is immediately poured into containers, the containers will need to be preheated before loading. This could be accomplished outside of the radioactive cell in an oven (such as a Lehr oven, as used for annealing, but at a lower temperature). The containers would then be quickly transferred to the fill location in the cell.

If the process were to pump molten, mixed SPC to a storage site hundreds of yards distant, the pressures could be very high. High pressures would require positive displacement pumps. The abrasive slurry would increase maintenance difficulties. Pumps, piping, and pipe heating systems would have to be maintained in a radioactive environment.

3.3.3 Quality Assurance

Control of the molten sulfur temperature is critical to the handling and safety of that process step. Fortunately, sulfur is widely used and systems for handling it safely are well established. The main unloading steps and temperature control can be done outside of the radioactive areas. Quality control requirements here do not add to the process difficulty. The mixing step, however, must be conducted within a containment area. Because the equipment for this step may be difficult to find, control of the step will also present some difficulties. Not only must temperature and mix proportions be controlled, but air entrainment must be minimized in this step and in subsequent filling steps.

At the filling location, the containers must be filled as completely as possible to minimize storage volumes. Batch mix and air entrainment also must be accurately controlled.

Parameters affecting the final product performance for the matrix system will be glass properties, sulfur properties, mix ratio of glass and sulfur, and air entrainment in the matrix. Like concrete and glass, it is assumed that under certain conditions the matrix may crack. Larger forms would therefore need to cool much more slowly than small forms. The severity of the cracking is yet to be determined. Of these parameters, glass and sulfur properties will be determined from their individual testing. Their QA is straightforward. Assurance of mix ratio, air entrainment, and cracks will have to rely mainly on statistical process control. Testing the final product will be difficult, because testing would involve opening the radioactive containers and core sampling the matrix material. It was outside the scope of this task to determine just what types of tests would be optimum. However, it is readily evident that the testing could not practically be conducted on each container or individual section of a continuous monolith.

3.3.4 Design Information Needed

Design of an SPC process system will rely heavily on data from sulfur vendors for the unloading and handling system, including temperature controls. Further development in this area will not be necessary. The mixing step, however, still needs significant development. The design of the mixing system requires data on the size distribution and variability of the glass (i.e., cullet) and the target mix ratio. The mix ratio will need to be determined from an optimization of cost for disposal vs. performance assessment. Much more needs to be known about the SPC to determine its impact on the performance assessment. It was assumed in this task that those studies are conducted successfully to define a practical operating envelope of sulfur-to-glass mix.

The effective viscosity of the mix will need to be determined to design transfer pumps and piping. The mixing equipment should be selected through scale testing. In the testing, the power, shear, and time requirements will need to be established to ensure intimate contact without excessive air entrainment.

The cooling time requirements to avoid cracking will need to be established.

A design of a continuous poured monolith will require similar data considering a much larger system. Retrievability of a large monolith will also require experiments to determine how to melt a very large system when the working temperature range of the melt is small. Melting large blocks would normally require the melt near the heat source to be heated well above its melting temperature so the outer regions of the block will melt. This may not be practicable with sulfur.

3.4 Marbles (Casting, Rolling)

Marbles are an ideal shape in terms of surface area. They are small, making them easy for a conveyor to handle. They also have the lowest possible surface area for their size.

3.4.1 Process Description

In a waste processing application, the marble-forming process (Figure 3.7) would follow the melter step with a temperature and flow control step. The temperature must first be controlled to meet viscosity requirements of the forming machine. The glass flow can be configured to recycle out-of- chemical

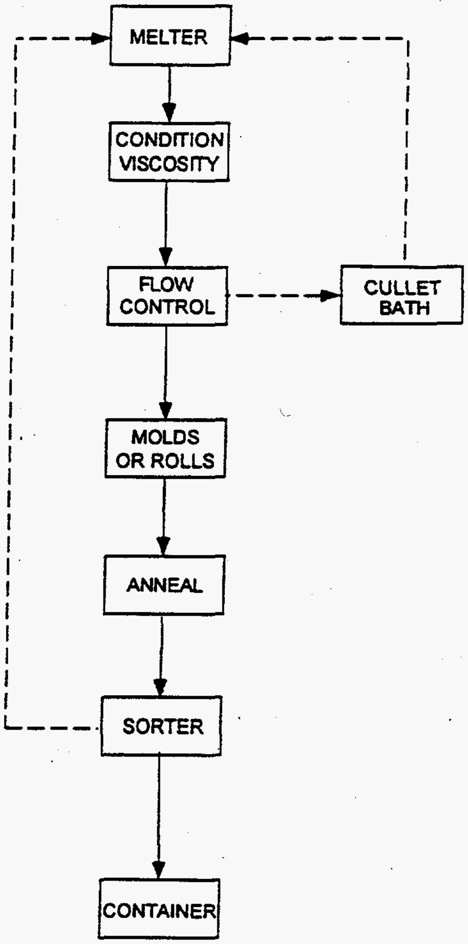

Figure 3.7. Marble - Forming

specification glass and to permit the forming machine to be shut down without shutting down the melter. The flow control equipment will also need to distribute the glass flow to as many forming machines as required, and to break the stream as needed by each forming machine.

The forming machine will then roll or mold the marbles into shape. If QA requirements consider surface area to be important, then a sorter will separate any broken pieces to be returned to the melter. Again, if surface area is important, annealing would also be performed to relieve residual stresses and prevent major breakage. Finally, the marbles would be placed into the storage container.

The complexity of the system is significantly greater than the system for monolith production because the flow control step must feed multiple machines and "gob" the glass for the forming machine. Adding to this difficulty is the complexity of the forming machine and the need to convey the finished product to the containers. A sulfur system as described in Section 3.3 could also be used, although its use would increase complexity still more.

Assuming glass properties can be held quite constant, the machinery should be fairly easy to automate, with limited contact needed to inspect and adjust the forming machinery. If the glass cannot be controlled, frequent adjustments may be necessary to maintain proper operation (Whittington and Peters 1992).

3.4.2 Equipment

Two marble-forming machines have been investigated. The conventional method used by U.S. marble makers and a method patented by Corning Glass Works (U.S. Patent 3254979) are discussed below.

Conventional U.S. Marble Machine

Conventional marble production in the United States uses a gob feeder device that shears the molten glass stream into globs (Figure 3.8). The globs drop onto a marble former consisting of a pair of counter-rotating, threaded cylinders called marble rolls. The globs travel down the cylinders in the threads, rotating and forming a sphere. At the end of the marble roll, the marbles are not completely hardened and must roll down a cooling tray before they can be stored (Whittington and Peters 1992). Machines currently in use can produce 1-in. marbles at a rate of around 54 MT/d. Two lines would be required in a waste processing application to achieve the 100 MT/d goal.

Annealing for approximately 1 hour is required to prevent significant cracking. This could easily be accomplished with conventional equipment. Section 3.8 discusses the annealing step in detail.

To produce high-quality marbles, the surface of the cylinders is rubbed with waxed paper or oily rags. The right level of "stickiness" must be maintained or the glob of glass will be ejected from the marble rolls. Additionally, the shears often fail to completely separate the molten glass globs and require manual correction. While the maintenance requirements for this device are not excessive, the device could be difficult to maintain in a radioactive process facility. The need to maintain the "stickiness" of the rolls and the problems with the shears could potentially be eliminated by adapting the design for a radioactive environment.

The comparative cost of this system is moderate.

Vibratory Marble Machine

Corning Glass Works patented a novel design for a marble machine built by Pacific Northwest Laboratory (PNL) and used for waste glass marble production. The marble machine has a continuous conveyor arrangement of hemispherically shaped molds that are vibrated (Figure 3.9). The vibrating molds pass under the continuous molten stream of glass. The vibration causes the molten glass to separate into globs. Continued vibration causes the glob to form a sphere as it progresses down the line. At the end of the marble machine, the marbles have cooled sufficiently to retain their shape (Whittington and Peters 1992).

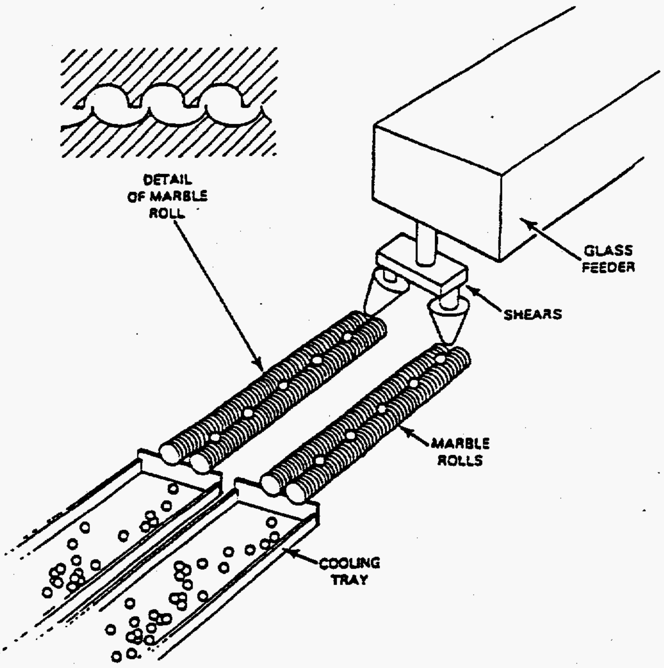

Figure 3.8. U.S. Conventional Marble Machine (Whittington and Peters 1992)

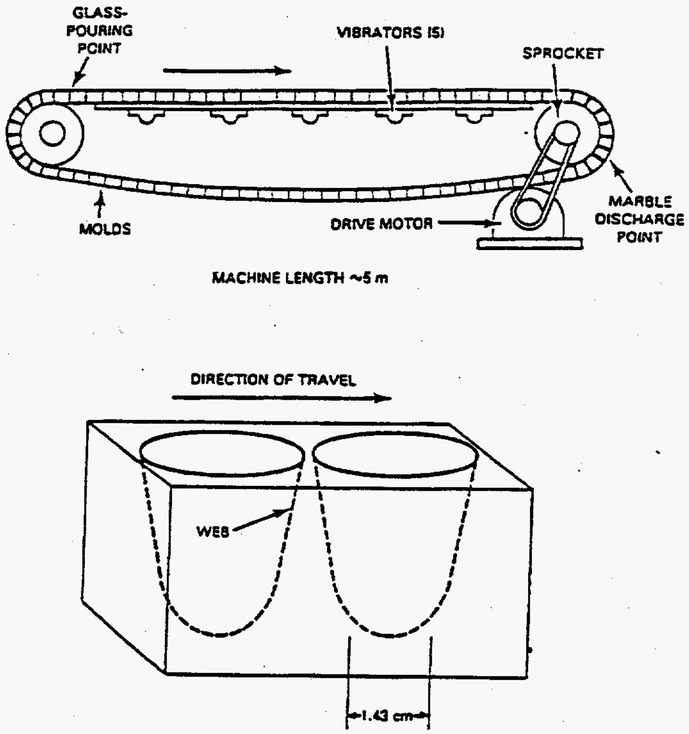

Figure 3.9. Vibratory Marble Machine (Whittington and Peters 1992)

A sorting machine separates the marbles from the nonspherical waste shapes. PNL used a vibrating plate, tilted slightly from horizontal, as a separating device. The marbles and scrap are poured onto the plate. Vibration causes the nonspherical shapes to deflect off the sides of the plate while the spherical marbles roll unhindered to the low end. The unwanted shapes are recycled directly to the melter (Whittington and Peters 1992). A grinding operation would not be needed in this system because the pieces are small.

Annealing for approximately 1 hour is required to prevent most breakage. Annealing is discussed in detail in Section 3.8.

The marbles produced at PNL varied in diameter from 3/8 in. to 1/2 in., depending on the discharge rate of the molten glass. Controlling the discharge rate of the molten glass produces marbles of a uniform size. Production rates of 130 lb/hr (1.4 MT/d) have been attained by cooling the molds with compressed air or a water stream. Corning Glass Works has achieved higher production rates by simultaneously casting molten glass streams into parallel marble molds (Whittington and Peters 1992).

Maintenance should be fairly simple on this system and should be required only for the vibrating conveyor unit. In a waste processing application, major maintenance could be performed most easily by removing the unit from the work area, thereby allowing the other machines and the melter to continue operating.

There are several requirements for producing high-quality marbles. To reduce breakage, the molds are often preheated to reduce thermal shock. The vibration of the equipment must be adequate to break hot glass strings that form between molds. The molds should have a steep-sided sharpened web, which also helps break the glass strings (Whittington and Peters 1992).

The comparative cost of this system is moderate.

3.4.3 Quality Assurance

Not all glasses are suitable for marble production. The molten glass must have a suitable surface tension and viscosity so the molten glass stream will separate into globs, as required for the vibratory marble machine. These physical properties are controlled by adjusting glass composition and feed temperature. The waste glass composition will be selected for durability and melter considerations, and the selected composition may not be suitable for marble making.

There should be a wide temperature interval between the flow point and the softening point of the glass. This "working" temperature range allows the globs of glass to be formed into spheres and provides time for uniform cooling of the marble surface. Figure 3.10 compares the working temperature range of soda-lime glass often used for marble production and a simulated high-level waste (HLW) glass (denoted ICM-II for "In-can melter, run #2"). The soda-lime glass has a temperature range of 200°C while the working temperature range of the waste glass is only 100°C. The ICM-II waste glass was found to be unsuitable for marble production (Whittington and Peters 1992).

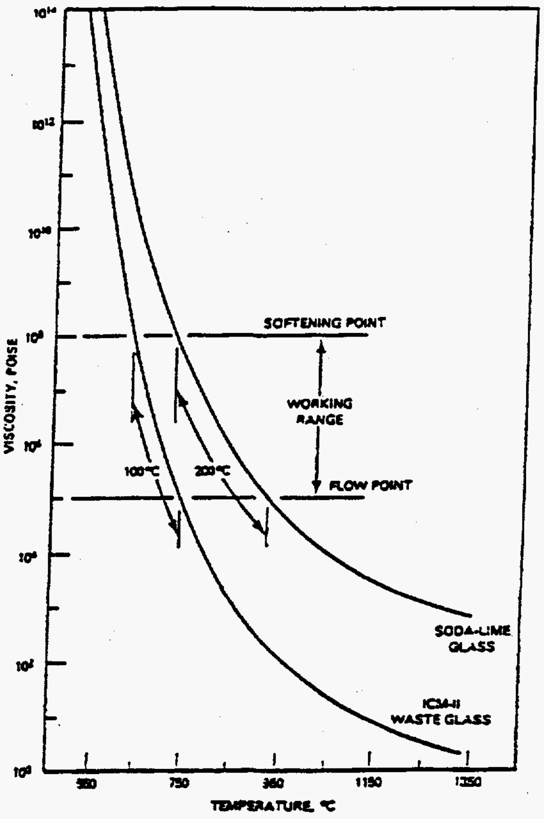

Figure 3.10. Working Temperature Range of Glasses (Whittington and Peters 1992)

A homogeneous glass composition is another important factor in successful marble making. Undissolved particles and bubbles make the marble susceptible to stress fractures. The difference in the coefficient of thermal expansion between the glass and the impurity causes stresses in the marble. Fracture of the marbles could lead to a large glass recycle stream. Thermal stresses, if untreated, will also cause much fracturing (Whittington and Peters 1992). However, about 1 hour of annealing can easily correct this problem.

Glass composition testing will need to be performed at various stages in the process. Samples can be taken from the melter at set intervals to monitor glass properties. The finished product can easily be tested by removing a marble as it comes out of the annealing Lehr. Out-of-specification glass or products can simply be diverted and conveyed back to the melter.

3.4.4 Design Information Needed

The unknown of greatest significance for this system is the projected waste glass properties (melt viscosity, surface tension, and working temperature range) and the variabilities associated with those properties. Necessary feed temperature, working time, cooling time, and annealing time will need to be determined. Methods to permanently maintain the "stickiness" of the rollers will need to be developed.

Additionally, the corrosion rate properties of the glass will need to be determined for comparison to QA requirements. Corrosion rate will determine what surface-area-to-mass ratio must be maintained. If the corrosion rate is low enough, operation without annealing and sorting might be possible. However, a rate that is high enough could eliminate the marble system altogether in favor of a shape with a low surface area such as a monolith.

3.5 Pressed Shapes

Pressing is a process commonly used in the glass industry to form viscous glass into shapes. Flat shapes like dinnerware and glass for television screens are manufactured using pressing. Even complex shapes that might be considered for this project would be simple to produce by commercial standards. Commercial equipment is readily available to make shapes as large as 40 kg. The mass of the shape is limited by the ability of the "gobbing" process to deliver a specific amount of material to the mold. The mass is also limited by the time required to cool the object sufficiently to support its own weight before it is ejected from the mold.

If the glass is not sufficiently durable to meet performance requirements for radioactive release, then another barrier may be added to the individual pieces to enhance their durability. Pressed shapes uniquely offer this option. It was outside the scope of this task to select or evaluate all the possible additional barriers. Possibilities could include a polymer coating or a second very durable glass coating that does not contain radioactive materials.

3.5.1 Process Description

The pressing process begins with a conditioning step applied to the molten glass (Figure 3.11). The temperature of the glass from the melter is controlled to achieve the proper viscosity. The glass must be thin enough to be pressed into the mold. The glass temperature must also be low enough so the glass can be cooled in the allotted time and ejected from the mold intact. A specific quantity of conditioned glass is then delivered to the mold. The glass is pressed to fill the mold and then cooled with compressed air. As the glass cools, its normal shrinkage separates the glass from the mold and the form can be ejected as an intact piece. As the pressed glass cools further, shrinkage causes stresses to build, which will cause the object to shatter. Each piece must be reheated and allowed to cool slowly (i.e., annealed) to prevent breakage. After annealing, the glass pieces will need to be stacked and loaded into containers for transport and storage.

If a process to add a second layer were necessary, the layer would be added before or after the annealing step. Adding such a process would add more materials handling and processing requirements, as with the sulfur matrix steps. Processing would be significantly more intensive and difficult.

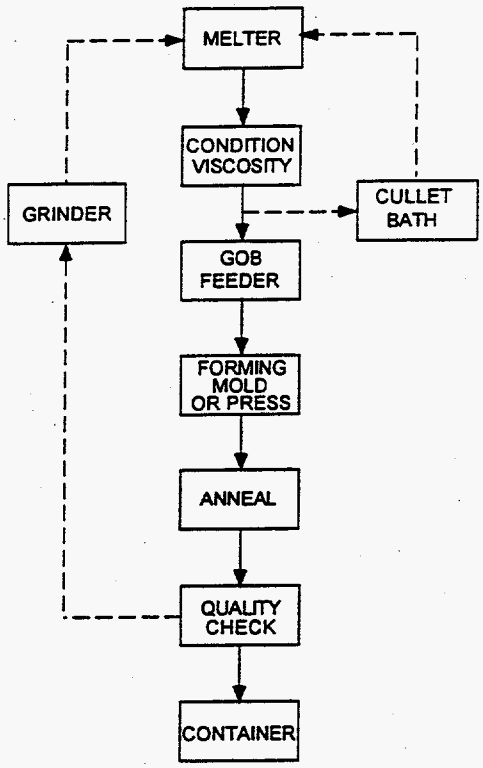

Figure 3.11. Bricks and Pressed Shapes

Off-gas treatment requirements for a pressing operation will be the least requirement of any forming system considered. The glass can be cooled to a lower temperature in the forehearth. Consequently, dusting and fuming during forming will be reduced. Air for the "wind" cooling and Lehr oven annealing can be recycled within the cell. Only exhaust air from the room will need to be treated for dust.

3.5.2 Equipment

Pressing shapes is a very common commercial glass process and equipment is readily available for each of the process steps. Inherently, the equipment is robust and has low maintenance requirements because the economics of glass production require low-maintenance equipment. Equipment with moving parts such as bearings and rollers has already been developed to operate reliably in the dirty, high- temperature environments common in the industry. Design to accommodate high temperatures will also make the equipment "hardened" for radioactive service.

The glass-conditioning step is accomplished in a forehearth using electric or gas heaters for temperature control. Forehearths are necessary for several of the processes considered and would be similar for each (Figures 3.12). Pressed shapes may require less conditioning than other forming options because the press can accommodate fairly wide changes in viscosity.

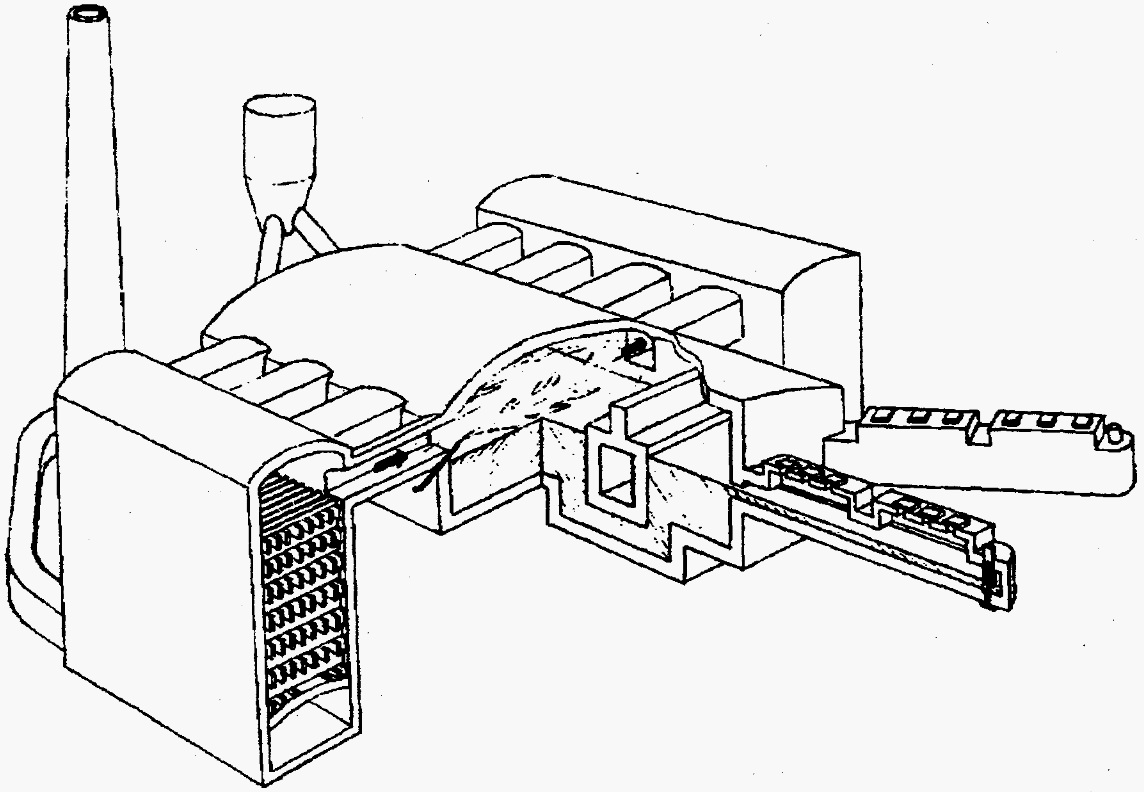

Figure 3.12. Continuous Melting Tank and Forehearth (Gas Fired With Heat Recovery) (Holscher 1972)

A commercial forehearth is often attached to a gob feeder. The gob feeder comprises a pool of conditioned glass with an oscillating piston plunger over a hole in the bottom. The "thick" glass is pushed through the hole by the plunger and cut off with ceramic shears below the hole (Figures 3.13 and 3.14). The length of the piston stroke and size of the hole determine the weight of the glob. To make larger objects, gob feeders may make globs through two or three holes simultaneously. These are then delivered simultaneously to the molds.

The piston, die, and cutter of a gob feeder operate at high temperatures and in high shear fields. These conditions create very demanding materials requirements. The materials (alumina and zirconia alloy ceramics), fortunately, have already been developed for use in the commercial industry. The life of these pieces may be 2 to 3 years for the feeder parts and 7 to 10 years for the forehearth.(a) They have to be changed out during the life of the plant.

The pressing, molding, cooling, and ejecting operations all take place on a single piece of equipment employing a rotating table indexing through each process step (Figures 3.15 through 3.17). The pressing

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(a) Personal communication, Owens-Brockman Glass Co., Portland, Oregon, April 20, 1994.

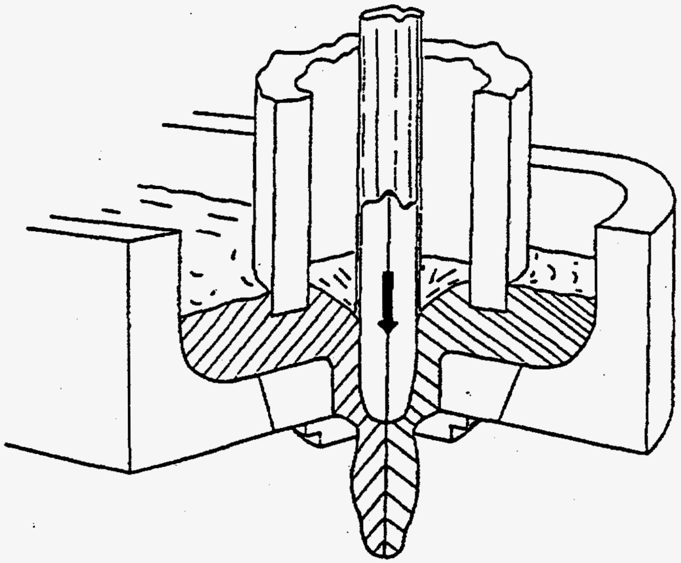

Figure 3.13. Glob Feed Operation (Holscher 1972)

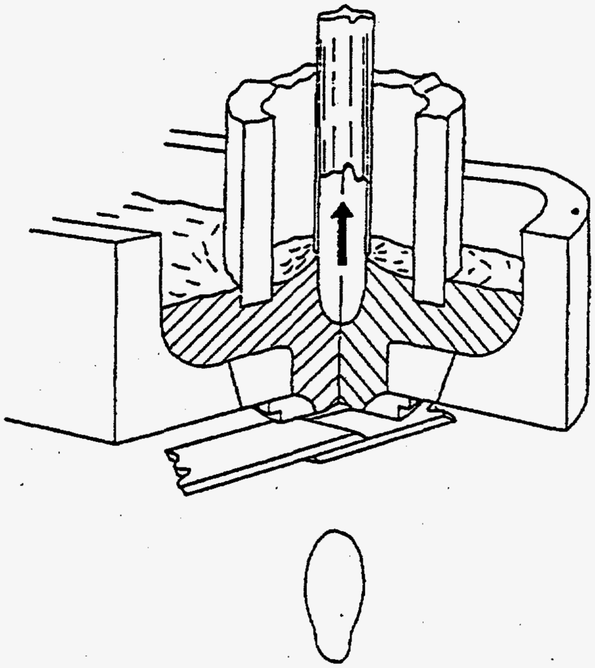

Figure 3.14. Glob Cut (Holscher 1972)

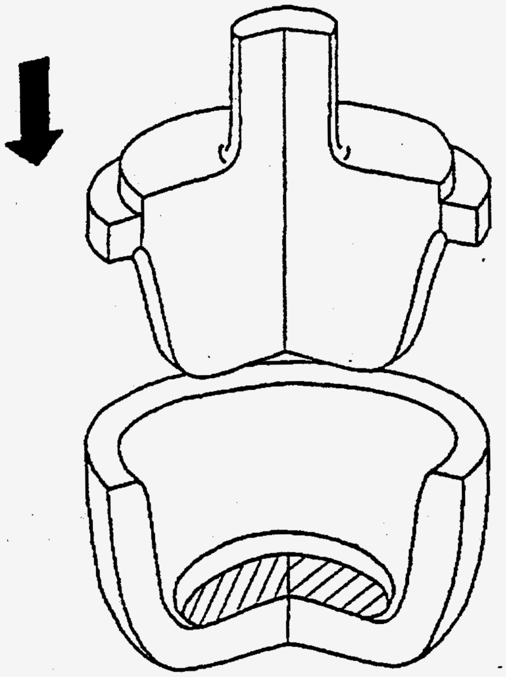

Figure 3.15. Glob in Mold (Holscher 1972)

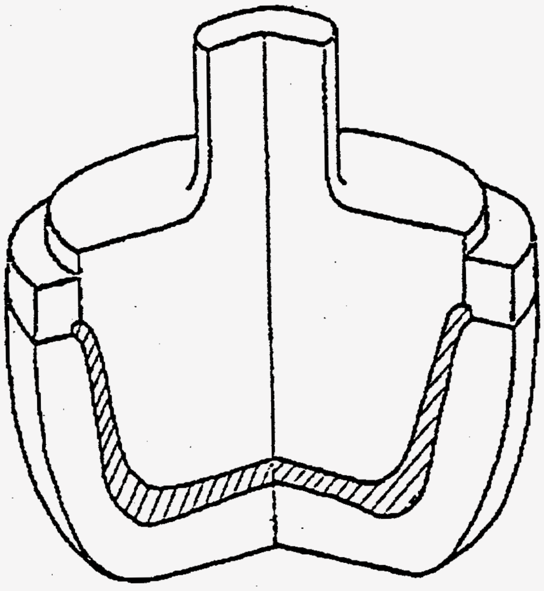

Figure 3.16. Pressed Glass (Holscher 1972)

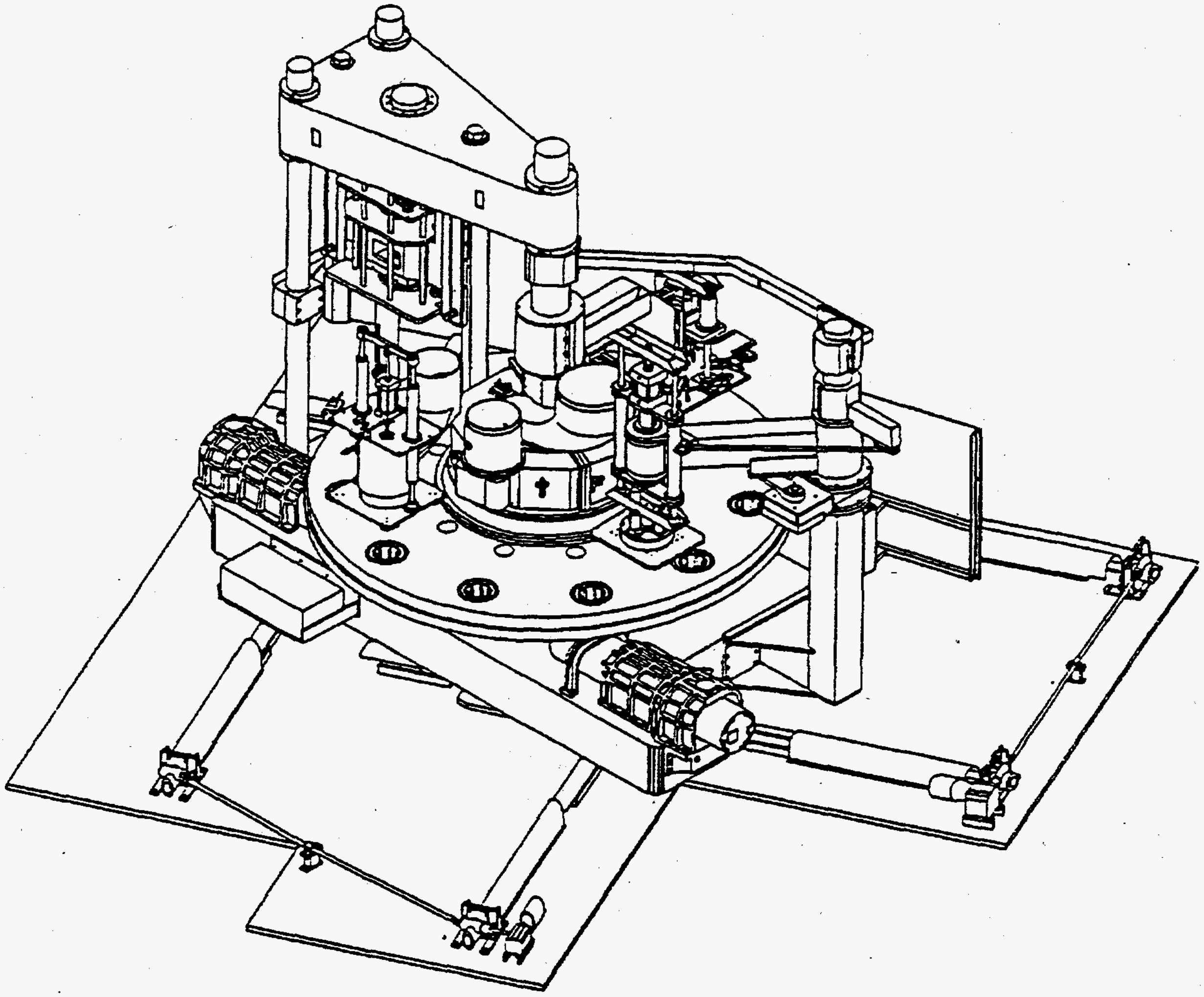

Figure 3.17. Lynch Rotary Table Press

machine is hydraulically driven and can press the glass into molds with forces up to 100 tons.[a] This makes the process much more tolerant of changes in glass temperature (viscosity) than a marble or plate glass process. This type of machine is designed for long-term operation and easy maintenance. Nevertheless, the complexity of the machine would make maintenance in a radioactive environment very difficult. It is considered only because the machine is modular and could be completely replaced remotely. The malfunctioning machine could then be repaired externally after it is decontaminated.

Commercial glass plants emphasize throughput. Press machines index through their stages at 30-55 pieces per minute (Howard 1985). For the example considered in Table 4.1 (see Section 4.0) (12 in. x 6 in. x 6 in. [.3 m x .15 m x .15 m] building block), each block would weigh approximately

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(a) Machine specifications, Lynch Machinery-Miller Hydro, Inc.

17.7 kg and the machine could produce more than 40,000 pieces per day. Production rates of 100 MT/d could be achieved with one machine. Nevertheless, two machines operating in parallel would be preferred because they would provide spare on-line capacity in case one machine must be shut down.

The cooling operation involves blowing metered amounts of air onto the objects in the cooling locations of the press machine. In a radioactive environment, the cooling air, called "wind," would need to be recirculated and cooled to minimize air discharges. This would require an air compressor system in the cells. Air requirements wouldn't be very great and the air compressor would be modular. Alternatively, the air could be provided from outside the cell and then removed through the cell ventilation.

After the press machine step, the pieces would be transferred and grouped to go through an annealing oven and on to a packing operation. Equipment for these steps is described separately because it is generally required for all the forming process systems.

3.5.3 Quality Assurance

The pressing system will require some control of the glass viscosity, although the control will be less stringent than that required for plate glass or marbles. The high pressing forces allow significant deviation from the ideal target. For the same reasons, the pressing operation will be feasible even if the waste glass composition is very "short" (i.e., if the waste glass has a very steep viscosity-vs.-temperature relationship). Control of this parameter will be less critical than for other processes.

As a system, the press forming equipment must include the process controls for the annealing step. The pieces would have to be monitored for breakage. A video camera could be used for monitoring.

Assurance that the final product meets design specifications would be straightforward for this forming system. The final surface area available for radioactive release is positively set by the size and integrity of the blocks. The integrity of the blocks can be verified visually. If a block requires testing, it could be removed. Final product testing, if required, would be the easiest of any operation.

Recycling out-of-specification pieces might require a size-reducing step for the large blocks. A grinding or milling machine is typically used in the glass industry to reduce the size of large pieces.

3.5.4 Design Information Needed

Design of commercial glass-pressing equipment is already well established. Design of equipment for pressing the LLW glass could begin as soon as the viscosity-temperature-time relationship of the glass is established. Additional laboratory or pilot trials should not be necessary.

The pressing machines have evolved to make products with dimensional tolerances much tighter than would be required for simple close stacking. They have also evolved to reduce downtime and maintenance needs. However, it is inconceivable that such a complex machine will be as trouble-free as will be needed for use in a radioactive environment. The machine vendor will not be accustomed to the special hardware requirements for operation in a hot cell. The machine designers and Hanford Site personnel familiar with hot cell operations will need to consult frequently to develop a low-maintenance machine that can accommodate remote operations.

3.6 Plate and Float Glass

Flat glass is a shape that, like blocks, can be handled by piece and stacked into containers. In a waste processing application, the extent of cracking will be very limited because it will be annealed.

3.6.1 Process Description

The flat glass production process (Figure 3.18) begins by flowing the molten glass over a weir or through a slot to form a sheet of approximately the desired thickness. The molten glass then passes through water-cooled rollers or is allowed to spread out on a pool of molten tin to flatten and smooth it. Next, rollers carry the plate through an annealing Lehr and to the cutter. The plate is cut into standard lengths, checked for size, and automatically stacked in the container. Incorrectly sized parts are sent to a crusher and returned to the melter.

The glass industry uses automated flat glass systems. Automated cutting, inspection, and handling machinery is already being used. In a waste processing application, adjustments to the machinery to set

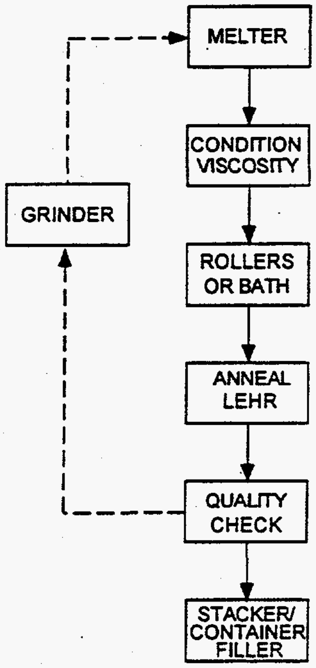

Figure 3.18. Plate Method

glass width and thickness, necessary during start-up, probably would not be necessary during normal operation. Computers would be used to control the temperature zones in the tin bath, eliminating the need for manual setup.

System complexity is moderate because various machines are needed. However, only one line would be required to achieve desired production rates. Production rates of over 360 tons/d have been achieved for rolled glass (Tooley 1974). Single-line float glass plants achieve rates as high as 810 tons/d (Tooley 1974).

3.6.2 Equipment

Equipment necessary to produce rolled plate glass and float glass in a waste-processing application is discussed below.

Rolled Plate Glass

The rolling machine will consist of two large water-cooled rollers that form the glass into a continuous ribbon up to 11 ft wide and 1 in. thick (Figures 3.19 through Figure 3.21) (Tooley 1974). The rollers would be motor driven and bearing mounted, with one movable roller to adjust plate thickness. A roller conveyor will then carry the glass ribbon through the Lehr and to the cutter. The Lehr will consist of an electrically heated tunnel followed by an air-cooling section (Engineered Materials Handbook 1991). Annealing Lehrs are discussed in Section 3.8.

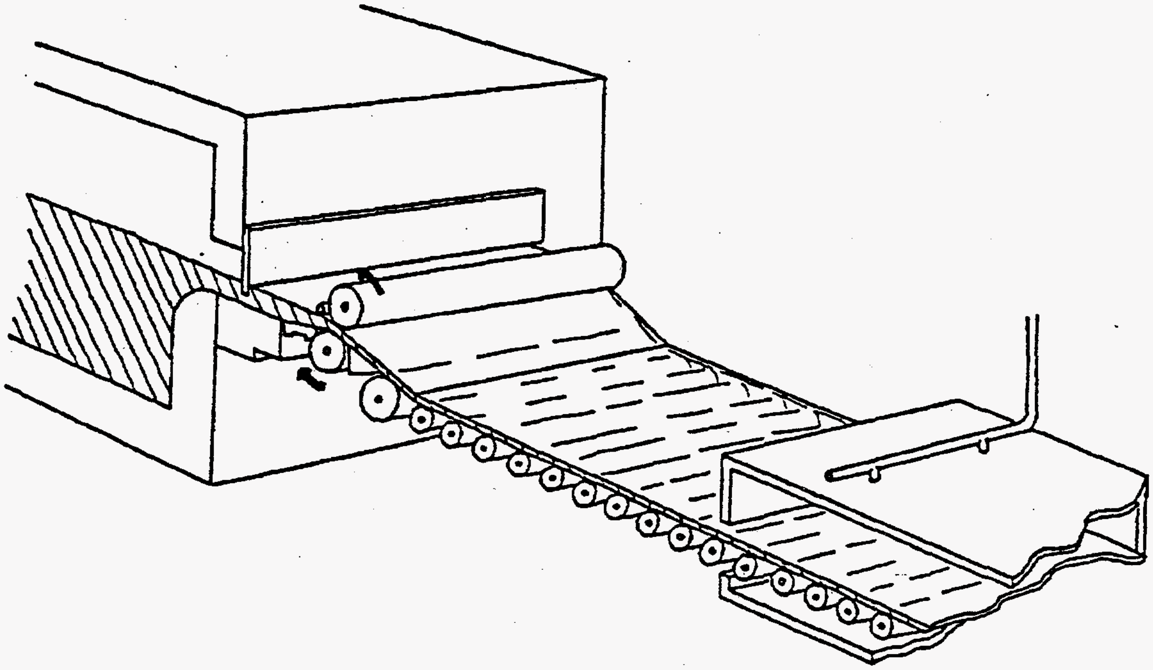

Figure 3.19. Continuous Casting of Plate Glass (Perry 1984)

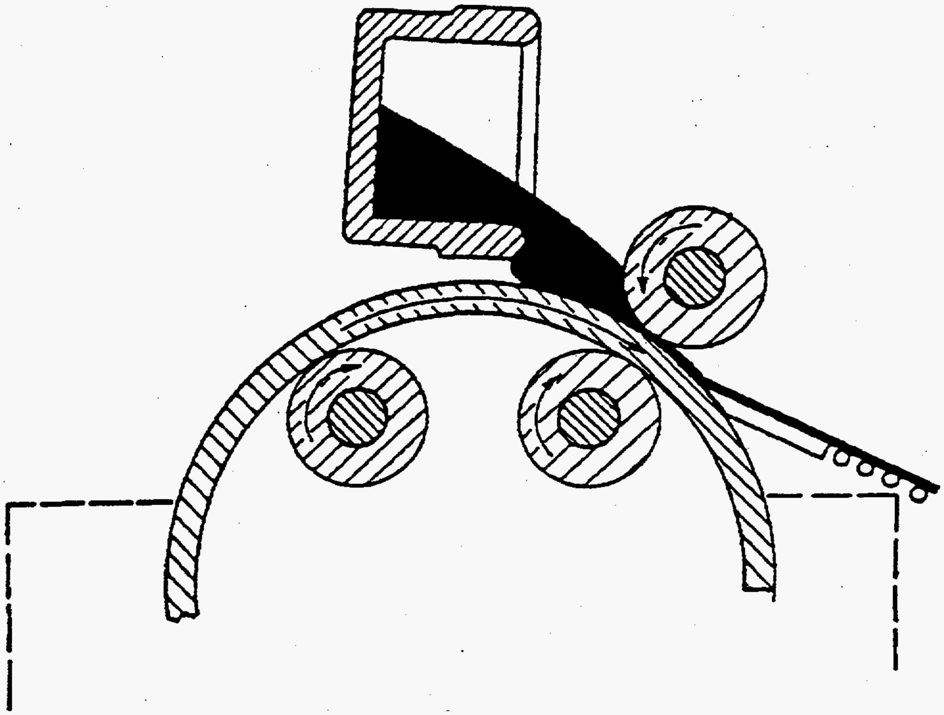

Figure 3.20. Ring Roll Rough Casting Machine (Engineered Materials Handbook 1991)

The glass cutter will be a computer-controlled machine that automatically cuts the glass ribbon to the desired length. Optical scanning will be performed next to ensure the glass will fit in the storage container. Depending on the results of the scan, a computer can have the glass robotically stacked in the container or sent by conveyor to a crushing machine to be recycled.

The stacking robot could be a two-axis robot with suction cups to grip the plates. The plates would be stacked in a rectangular box with a lid to be welded on after the box is filled. Another idea is to stack the plates on the inside of the box lid. As they are set in place, or after they are stacked, their edges would be slightly melted to fuse them. Fusing the edges would prevent water from seeping between the plates during storage, effectively reducing the surface area to the area just outside of the fused block. A computer-controlled burner, or ring of burners, would easily melt the edge of the plates. Finally, the box could be placed over the stack and welded.

Recycled pieces, on the other hand, would be fed to a hammer mill or crusher to reduce their size before they are fed back to the melter. The crusher consists of hammers or teeth mounted on a motor-driven shaft that crush the glass against another shaft or a plate (see Figure 3.5). These parts will wear and are designed to be replaced easily (Perry 1984). A screen or grating allows only properly sized particles to proceed to the melter feed.

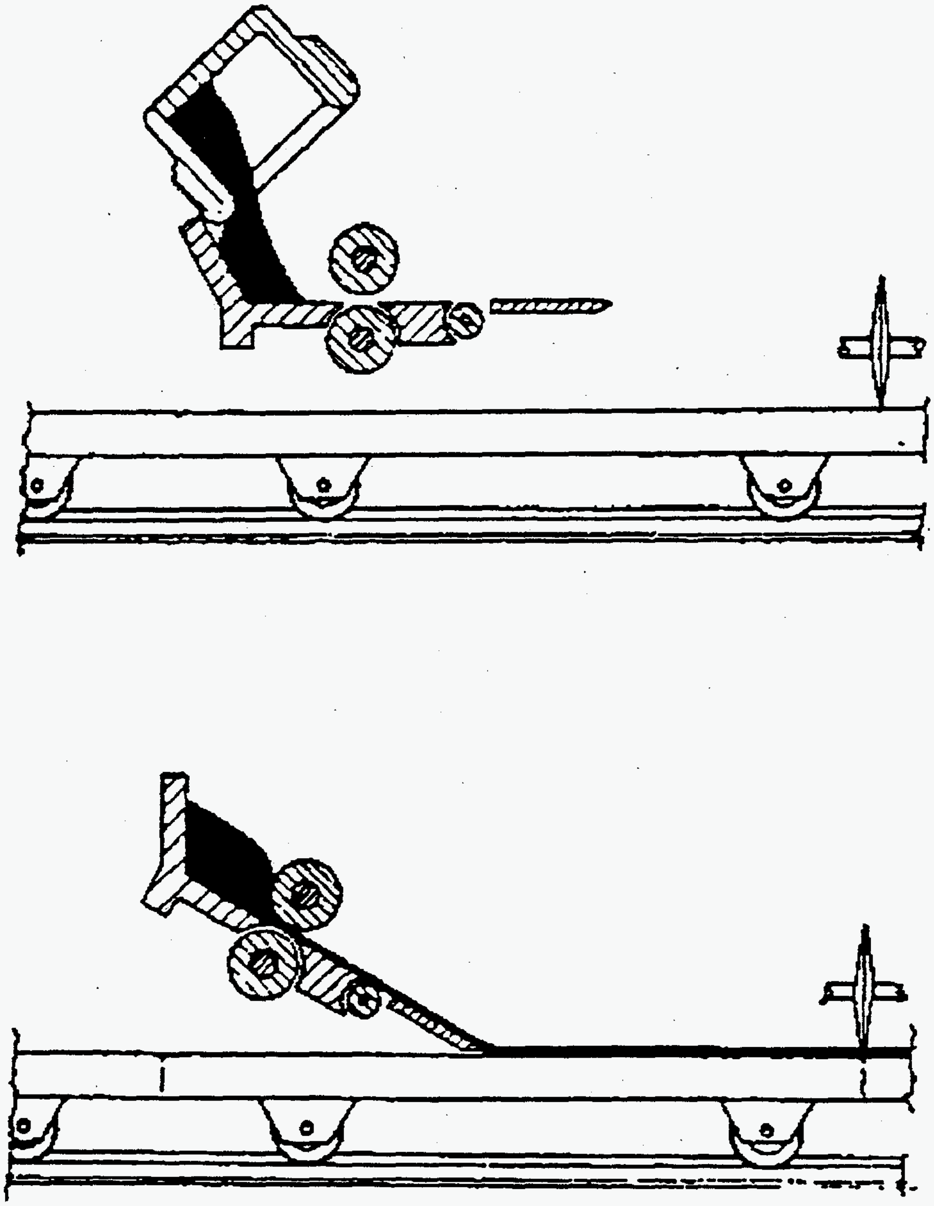

Figure 3.21. Rough Plate Rolling Machine (Engineered Materials Handbook 1991)

The production rate for all this machinery is sufficient as it is currently being used in industry and will easily meet the 100 MT/d requirement. Rates of well over 360 MT/d have been achieved, with normal operation at around 225 MT/d.

Routine maintenance will be required on the roll-forming machine and the crusher. The cutting machine and stacker will also require maintenance, although on a less regular schedule. Maintainability is expected to be moderate.

Float Glass

Production using the float glass process will begin with a rough ribbon coming out of the melter that drops onto a molten pool of tin approximately 160 ft long and 12 ft wide (Figures 3.22 and 3.23). A slightly reducing atmosphere is maintained with hydrogen gas to keep the tin from oxidizing. The glass will spread out flat on the tin and will be held at the proper thickness by edge rollers. As it exits the float bath, the ribbon will be picked up by rollers that carry it through the annealing Lehr and to the cutter. The glass pieces will proceed in the same way as they would with the roll-forming system. Ribbon dimensions would be similar to those for roll forming.

Float glass plants are very large facilities producing huge tonnages of high-quality glass. A single float line can produce 810 MT/d (Tooley 1974). A plant could easily be scaled down to meet the production requirements for a waste-processing application.

Necessary support systems for the tin float bath are unknown, so maintenance requirements cannot be estimated. However, there are no moving parts. Maintenance on the cutter, crusher, and stacker systems could be significant. Overall maintainability is expected to be moderate.

3.6.3 Quality Assurance

The plate-forming processes are less sensitive to glass changes than marble making, and more sensitive than pressing. The glass must spread out on the molten tin or the rollers must flatten it. Glasses such as a soda-lime glass would not present any difficulty, but glasses with a very steep temperature viscosity curve could cause problems. Annealing may not perform as well when glass conditions change from design.

Some loss of volatile components may occur in the float bath area. These would need to be collected and combined with the melter off-gas.

The glass can be tested at the melter and after it is cut. Optical inspection can verify plate dimension before each plate is stacked. Out-of-specification glass and misshapen glass can be conveyed to the crusher after it is cut. Samples for final product testing can be taken following the crushing step. The crushed glass will then be fed directly back to the melter.

3.6.4 Design Information Needed

Glass properties will determine amenability to roll and float forming. Necessary float bath and annealing temperatures and times will also need to be determined. Temperature limitations and the reducing atmosphere have so far limited commercial use to soda-lime-silica glass.

The possibility of fusing the plate edges once they are stacked will depend on the melting properties of the glass. The possibility that the fused edges can significantly decrease surface area will need to be investigated and tested.

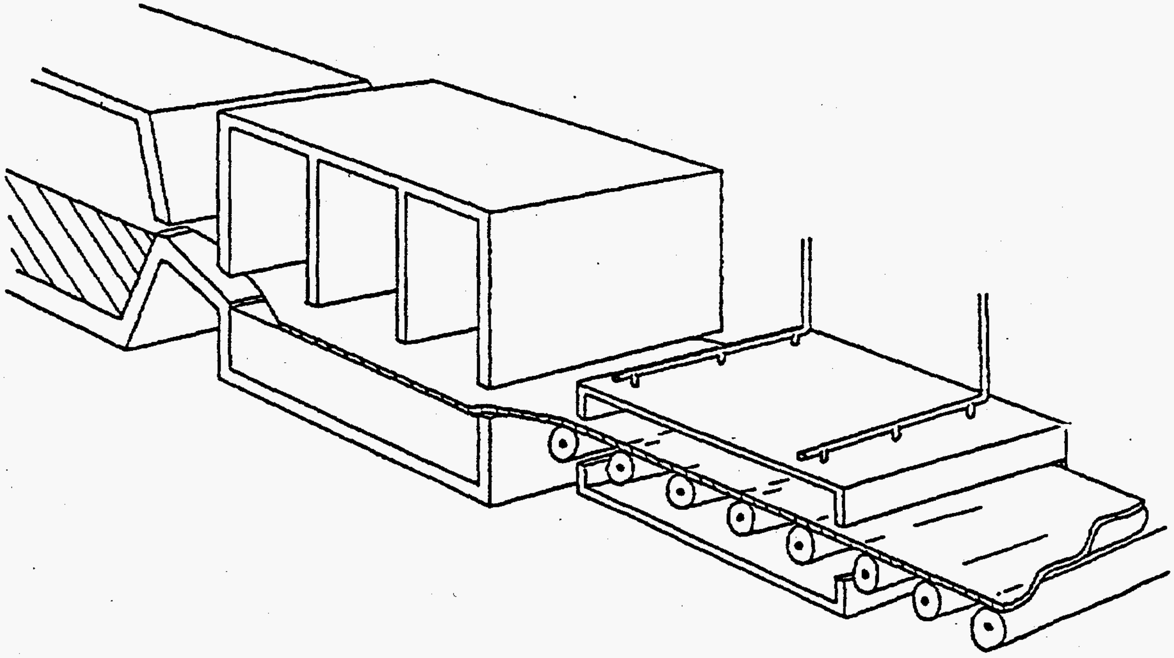

Figure 3.22. Float Glass (Perry 1984)

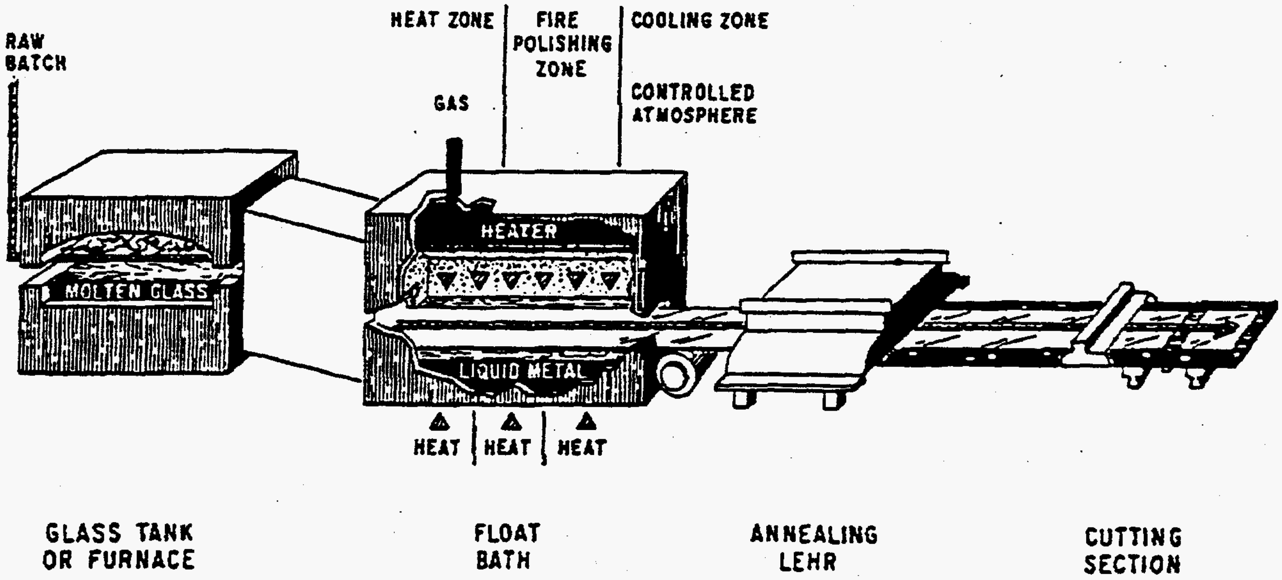

Figure 3.23. Float Glass Continuous Process (Engineered Materials Handbook 1991)

Flat glass cutting and stacking machinery currently in use will need to be investigated further.

3.7 Monoliths

3.7.1 Process Description

To form monoliths, the molten glass discharged from the melter is drained into containers that can be of varying configurations and/or sizes (Figure 3.24). This forming technique is a very versatile and flexible method for forming waste glass. It is one of the simplest, if not the simplest, method of forming glass. For high-level radioactive waste vitrification, it is the conventional approach. Container size has been limited and defined by the repository for handling a consistently sized package. In the United States, the container is limited to 0.61 m (24 in.) in diameter and 3.05 m (10 ft) tall (Figure 3.25). Periodic flow rates of about 200 kg/hr allow these containers to be filled completely. This has been routinely demonstrated. One melter experiment (Chapman et al. 1979) successfully filled 0.91-m-

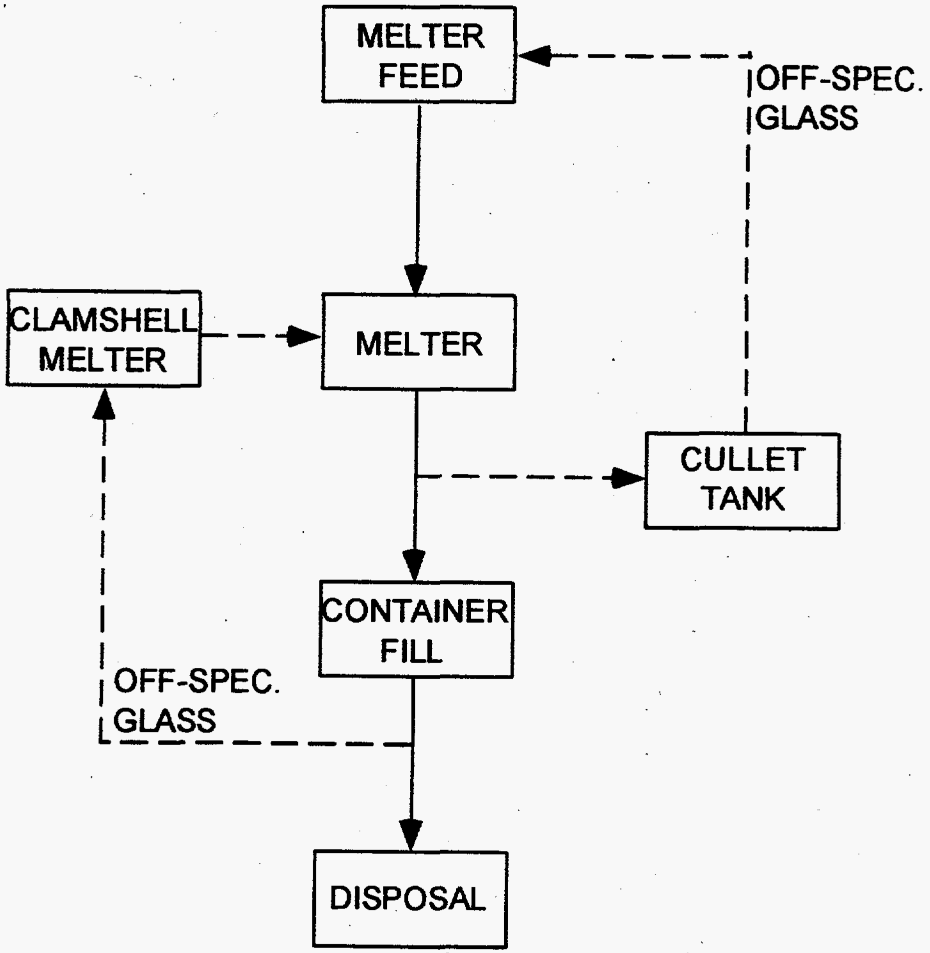

Figure 3.24. Monolith Process Flow

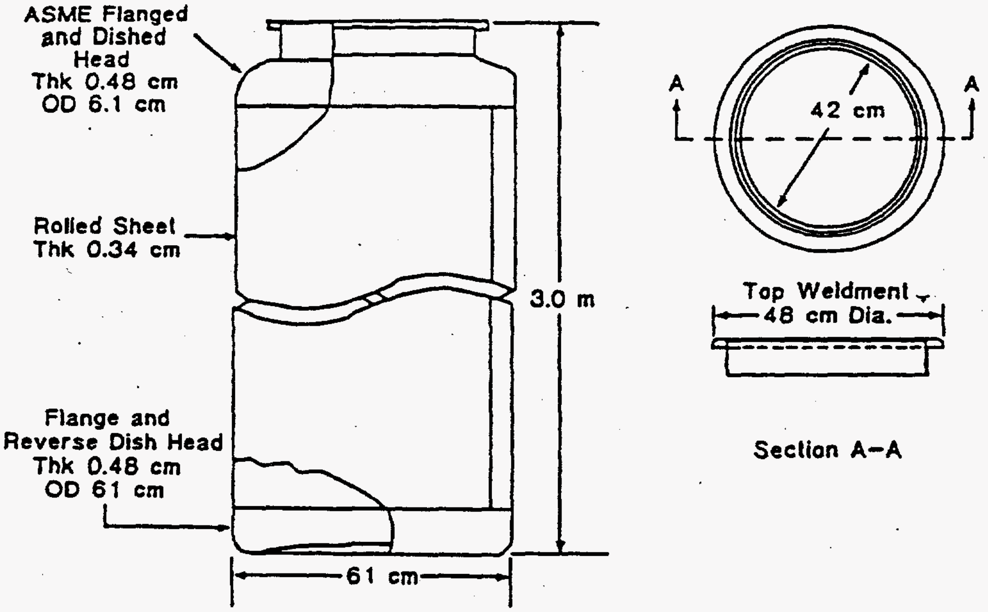

Figure 3.25. West Valley Canister Design (Whittington and Peters 1992)

(36-in.-) diameter containers at a nearly constant flow rate of about 125 kg/hr. The upper size limit for poured glass depends upon the discharge rate from the melter, the temperature-viscosity relationship of the glass, and the degree of effective insulation around the container during the pouring operation. In addition, a requirement to control devitrification during cooling may impose an upper size limit by imposing a minimum cooling rate. Such a requirement would be specific to glass composition. For the reference LLW vitrification production rate of 1,000 to 4,000 kg/hr, the container's maximum dimension could apparently be 2.5 to 5.0 m (8.2 ft to 16.4 ft) based upon rough scaling from current experience, assuming similar glass properties. As nature has shown during volcanic flows, very large containers could be used if the flow rate is sufficiently high. Thus, it appears feasible to have readily fabricated containers or tanks and conventional materials-handling equipment to allow casting, cooling, and transportation of large, filled containers.

This glass-forming system can be readily automated to ensure complete filling and fulfillment of the desired functional requirements. The control system would provide replacement or movement of the filling or filled container based upon a fill height measurement. Active or passive flow diverters would be employed to span the gap between containers. Some of these concepts are described in the following section.

One of the most attractive features of this forming method is the ability to greatly limit radiation exposure to the operators. Because the containers are used only once and the transportation device does not contact the glass, contact maintenance is not required and only unplanned, extraordinary process upsets would introduce the potential of exposure to operators.

3.7.2 Equipment

The primary equipment in this forming system is the container. The container can take many different forms ranging from unpainted barrels, standard pipe with end caps, tanks, or even railroad box- sized containers. The canister turntable developed for processing HLW at the West Valley Demonstration Project, shown in Figure 3.26 and 3.27, illustrates one approach that could be pursued for forming the monoliths. This system is connected to the melter and enclosed in a vessel that controls the fumes from the draining glass so they can be directed to the off-gas system. The West Valley turntable also has a water-cooling jacket so temperatures within the vessel can be controlled to some extent. After the canister is full, as determined by the gamma level detector system, an empty canister is indexed under the fill position. While the newly positioned canister is filling, a full canister is removed from the turntable and replaced with an empty canister. These canisters are 0.61 m in diameter and 3.05 m tall. They each contain about 2,000 kg of glass. The West Valley design fill rate average of about 45 kg/hr translated to a canister being filled about every 44 hours. For a LLW glass melter with 25% of the entire plant production rate, or ~1,000 kg/hr, this turntable would require canister changes at 2-hour intervals. Using the same scheme but larger canister diameters would allow less frequent canister changes. Table 3.2 provides some general capacities and changeout rates as a function of canister diameter with a fixed height of 3.05 m.

With much larger containers, much slower operations are possible. For example, a package such as a "land and sea" container that is 2.1 m wide, 2.4 m tall, and 12.2 m long (7 ft x 8 ft x 40 ft) holds about 128,000 kg of glass, assuming an 87% fill fraction. Using a package of this size, conventional rail equipment and technology can be used to transport the packages from the LLW vitrification facility to the disposal site. At the disposal site, conventional ship unloading equipment can be used to unload the rail cars and place the packages into the disposal area. This processing and disposal option can be achieved without special design and development. This general arrangement or approach is illustrated in Figure 3.28.

A potentially simpler system may be possible not only for the forming operation, but for reliable processing and disposal of the LLW glass. This system would consolidate melting, forming, and disposal into a single step, as shown in Figure 3.29. This approach would have the minimum impact on operator exposure and could allow for compositional variations by remelting the mass within the disposal site (Figure 3.30). It would not, however, meet the retrieval requirements as they now stand.

To gauge the relevance of this approach, Table 3.3 lists a range of vessel diameters for a fixed depth of 18.3 m. For the largest tank listed in the table, 24.4 m in diameter by 18.3 m deep, the total number of tanks needed to vitrify the entire Hanford LLW inventory would be about 20. Because this tank size is nearly the same size as the tanks from which the waste would be extracted, using the existing underground storage tanks as the processing and disposal vessel could be considered. To avoid adversely impacting surrounding tanks, cooling wells could be installed around the periphery of the tank to block thermal effects.

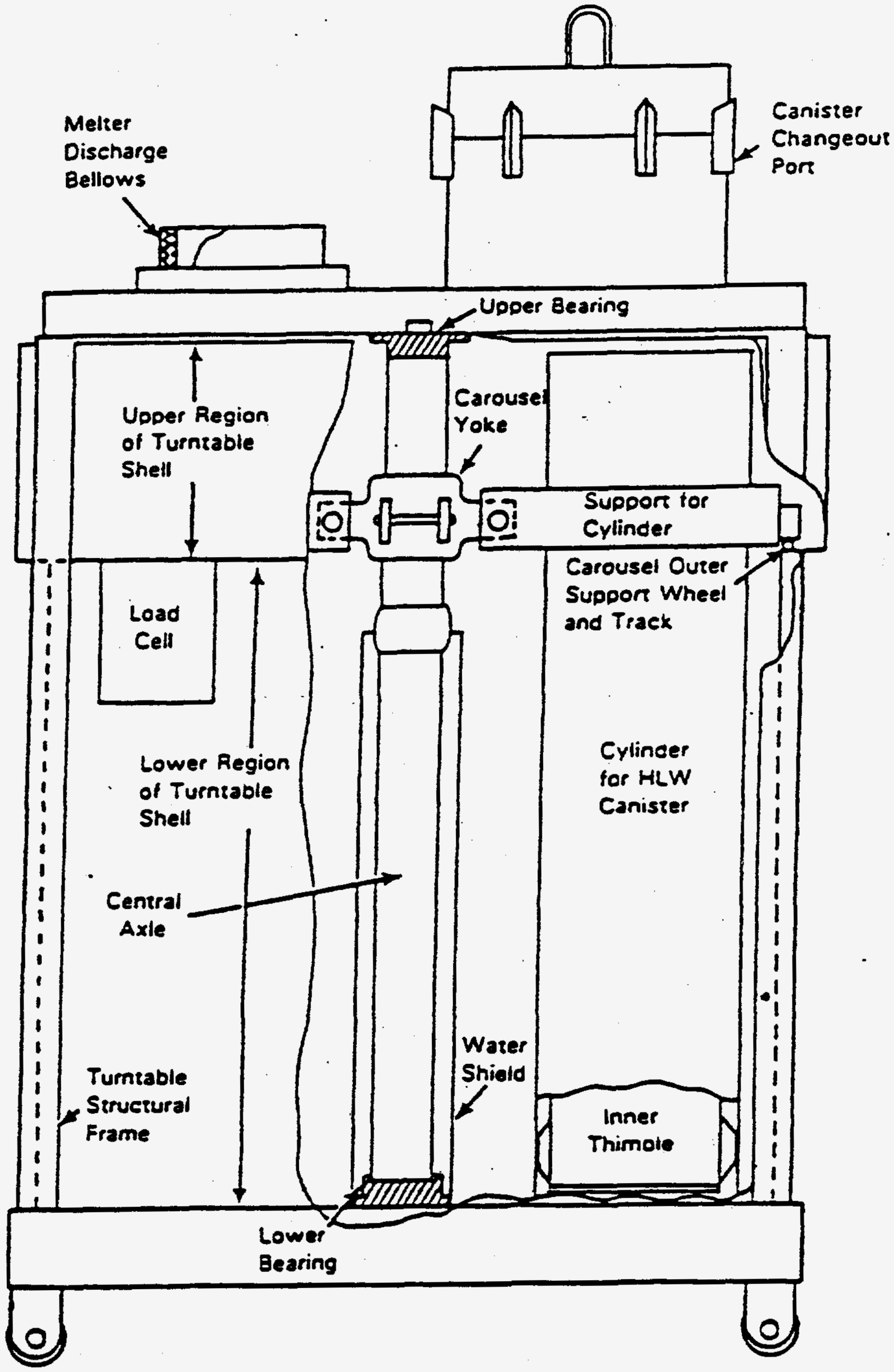

Figure 3.26. Glass Canister Turntable Assembly, View 1 (Whittington and Peters 1992)

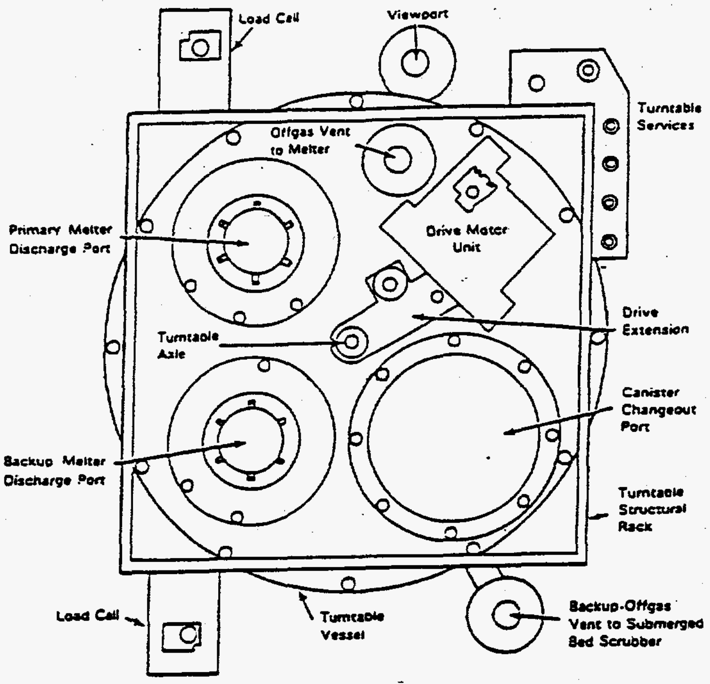

Figure 3.27. Glass Canister Turntable Assembly, View 2 (Whittington and Peters 1992)

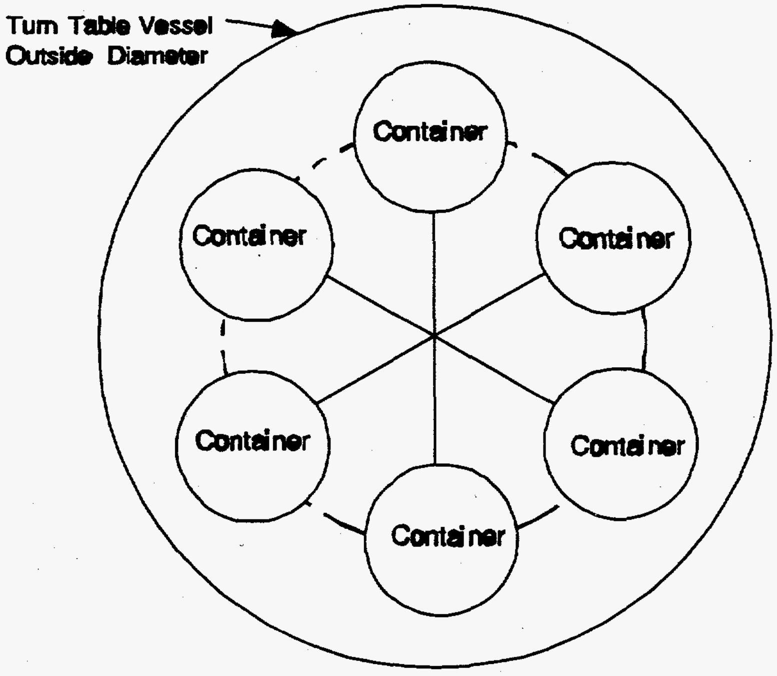

Figure 3.28. Rotary Canister Loading Table

Table 3.2. Capacities and Changeout Rates

Canister Diameter, m (ft)	Capacity, kg	Canister Fill Time, hr	Six-Position Turn Outside Diameter, m (ft)
0.61 (2.0)	2,047	0.5	2.75 (9.0)
0.76 (2.5)	3,199	0.8	3.19 (10.5)
0.91 (3.0)	4,607	1.2	3.63 (11.9)
1.22 (4.0)	8,190	2.0	4.52 (14.8)
1.52 (5.0)	12,796	3.2	5.41 (17.7)
1.83 (6.0)	18,427	4.6	6.29 (20.7)
2.13 (7.0)	25,081	6.3	7.18 (23.6)
2.44 (8.0)	32,759	8.2	8.07 (26.5)
(a) Canister height, 3.05 m (10 ft); fill height, 2.9 m; Rate of fill, 4,000 kg/hr; glass density, 2.4 g/cm^3.			

The simplicity of very large monoliths is intriguing. However, because large monoliths cannot meet the retrieval requirements, this particular monolith option is not evaluated further. Subsequent evaluations are based on monoliths that can be handled and retrieved. If monoliths are selected as the form of choice, the advantages and disadvantages of this extreme case should be addressed more completely.

3.7.3 Quality Assurance

This forming technique relies almost entirely upon the melter and its feed composition control system to achieve a desired glass composition. Although it is conceivable to recycle the out-of-specification solidified glass, it is not very practical. This is not a major disadvantage because this approach is the standard throughout all the HLW programs around the world. Compositional control is readily achieved and is being applied in operating plants with wastes that have much more stringent compositional control requirements and acceptance criteria.

Cooling rates may need to be controlled to achieve a tradeoff between excessive cracking (caused by rapid cooling) and devitrification (caused by slow cooling). The cooling rate may be determined largely by the monolith size, especially for larger monoliths.

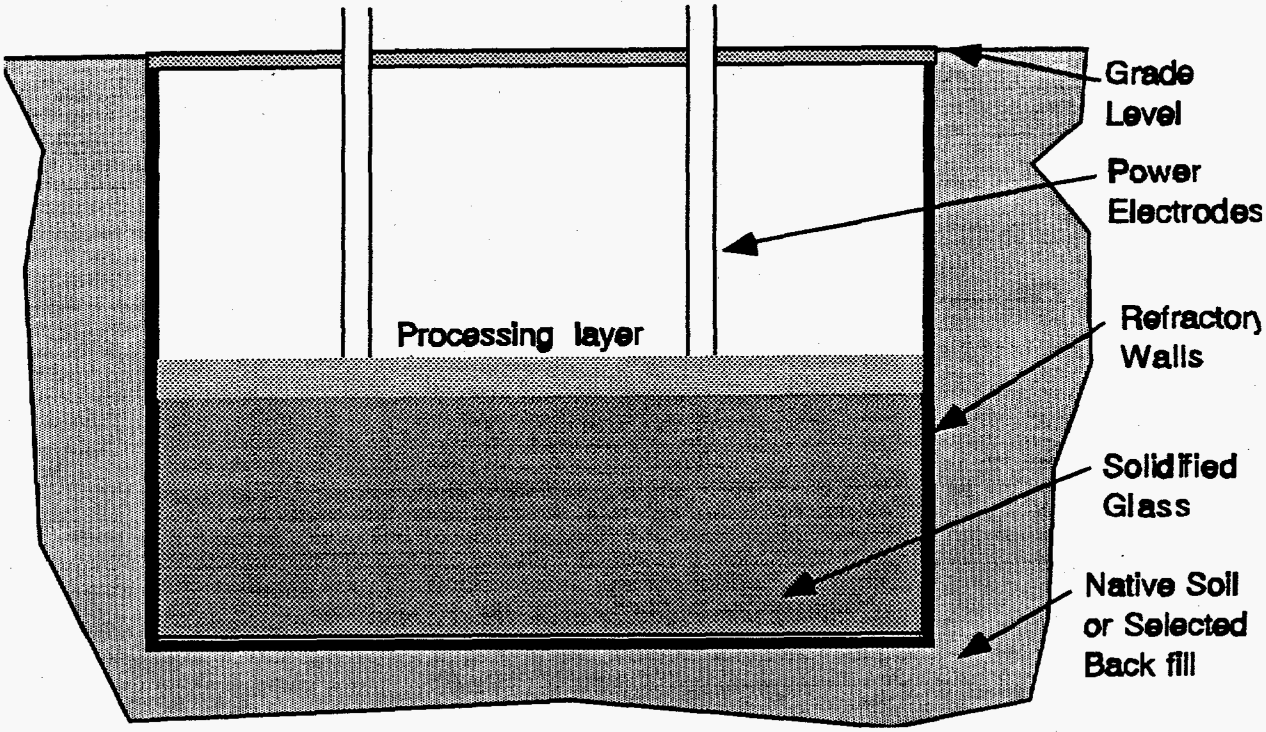

Figure 3.29. In-Ground Melter and Disposal Unit

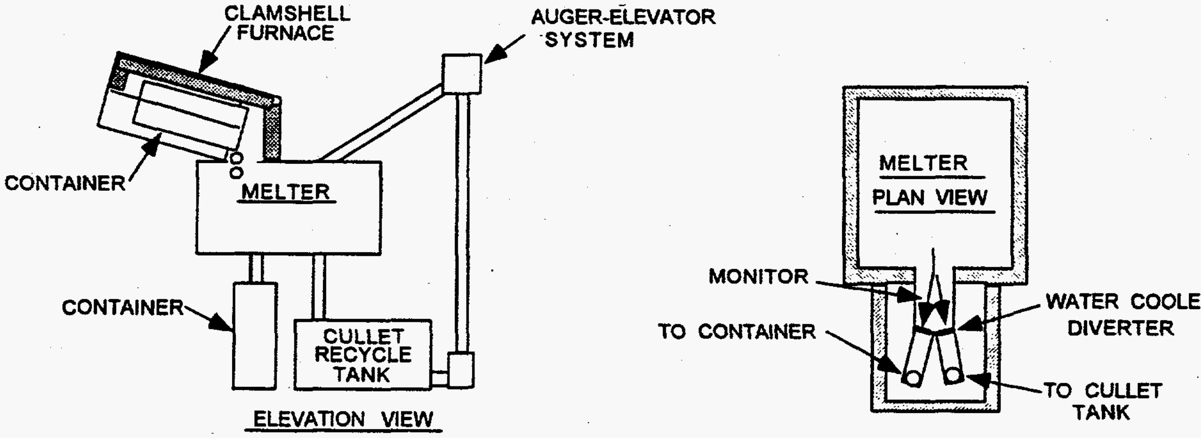

Figure 3.30. Monolith Recycle

3.7.4 Design Information Needed

Molten glass viscosity as a function of temperature needs to be determined. Experiments that validate the flow characteristics or ability to fill a large container are needed to validate the use of large containers or packages. This could be readily accomplished by coupling to a large commercial glass production furnace with different sized containers. The rate of cooling of large castings also needs to be determined.

Table 3.3. Vessel Diameters at the 18.3-m Depth

Depth: 18.3 m (60 ft)		
Diameter, m (ft)	**Glass Mass**	**Days of Operation**
15.2 (50)	7,043,469	70
18.3 (60)	10,142,595	101
21.3 (70)	13,805,199	138
24.4 (80)	18,031,281	180

Devitrification of the reference glass needs to be measured and its influence on the chemical durability of the glass determined. Although large castings are known to crack (Figure 3.31), the real significance of this phenomena on the potential system release rate has not been measured at or near full scale. Some speculate that the full surface area is the true measure of the release potential of large castings. Others speculate that the castings will behave essentially as a solid monolith, with the outside surface being the only relevant surface area. If the latter is true, large monoliths would not only be the simplest forming technique but could also represent, by far, the best form for long-term storage. Experimental studies are needed to establish the release behavior over time for the cracked monolith.

3.8 Annealing Lehr

3.8.1 Process Description

In glass making, the annealing step eliminates stress in formed glass. This step is not needed in all forming situations. First, the temperature of the formed glass is elevated to its annealing temperature for a sufficiently long time to allow the stresses to relieve (soak). Second, the temperature is slowly reduced to prevent new stresses from forming (Figure 3.32). The goal of this treatment is to prevent cracks from forming in the final product, although the treatment may cause some of the interior glass to devitrify.

Annealing requires a conveyance method to carry the glass and equipment to control the temperature around the glass. The conveyor could be a roller, a chain belt, or, for large pieces, an overhead rail. The oven is a long, insulated tunnel in which the temperature can be controlled along its length (Figures 3.33 and 3.34). It would probably be heated electrically, although some designs use hollow rollers in which the combustion gases are burned (Tooley 1974).

Figure 3.31. Monolith Canister Cross Section Showing Cracking (Peters and Slate 1981)

In a waste-processing application, the operating parameters will be determined by the glass properties and the final product dimensions. The annealing temperature will be determined by glass properties, but the most important factor will be the dimensions. The smallest dimension will determine annealing times and cooling times, and will effectively determine the size of the Lehr. Annealing times increase as the square of thickness increases. The time needed to anneal 3/4-in.-thick plate is about 45 minutes. Annealing a 6-in. plate would require 50 hours. Annealing also requires cooling. A 12-in.-thick piece would take over 200 hours to anneal and another 200 hours to cool (Tooley 1974).

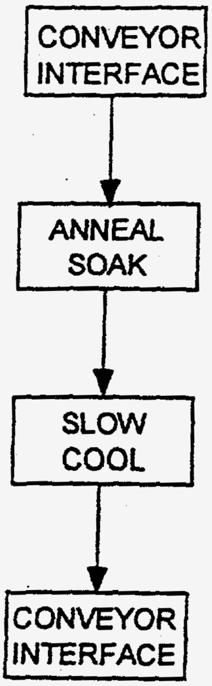

Figure 3.32. Annealing Process

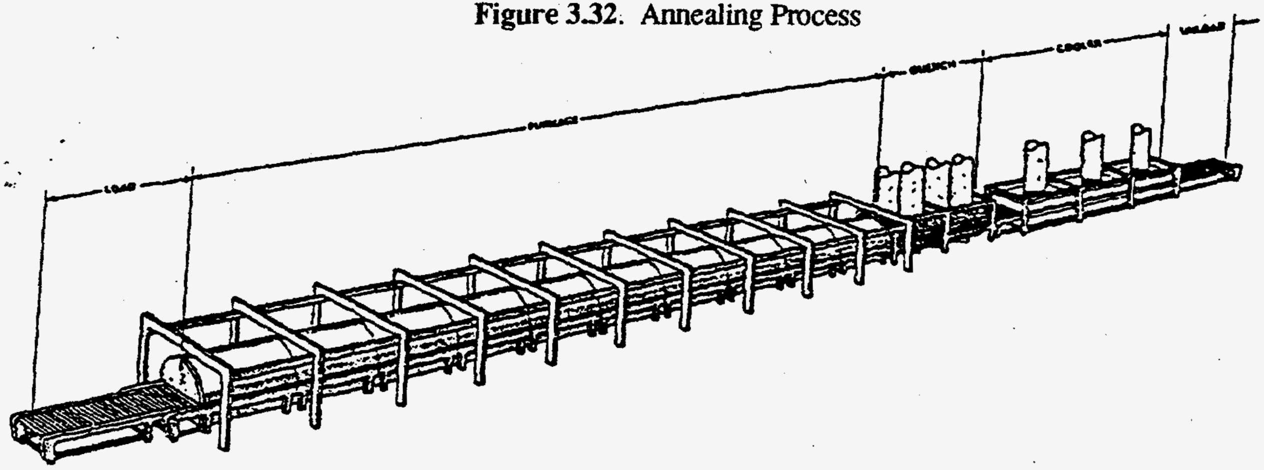

Figure 3.33. Tempering Lehr (Engineered Materials Handbook 1991)

Monoliths could be effectively annealed simply by insulating them to maintain their heat near the desired level. Annealing a monolith would not totally eliminate cracking and could cause significant devitrification. It would, however, significantly reduce the surface-area-to-mass ratio.

Completely automated annealing Lehr systems are currently being used in industry. The only moving parts are the belt and rollers in the conveyor system.

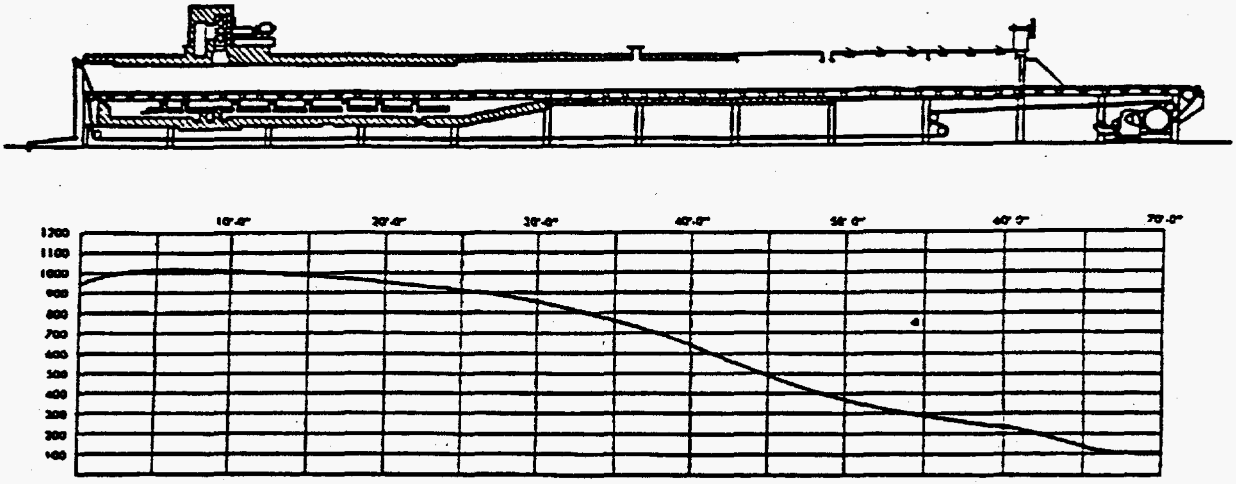

Figure 3.34. Continuous Lehr Annealing Curve (Tooley 1974)

3.8.2 Equipment

Conveyor

Annealing Lehr systems could be adapted for use in a radioactive environment. The conveyor normally consists of a steel chain belt supported by a roller conveyor. For handling plate glass, the belt would not be needed and the glass ribbon could be held by the rollers only. The belt would be powered by a variable-speed motor. The belt, rollers, and drive unit would require periodic maintenance, although significant problems with equipment breakdowns have been greatly reduced with the use of electronic load controls on the drive motors. The controls ensure that if something becomes stuck or jammed, the drive motor will stop before the system is damaged.

Larger pieces, like small monoliths or blocks, could hang from an overhead track, eliminating the need for the conveyor mechanism in the Lehr system. The trolleys would be pulled by a motor-driven cable or chain. The drive and trolleys would require some maintenance.

Lehr Oven

The Lehr oven would be built using high-temperature insulating materials that probably would not need any maintenance. Air temperature would be controlled by electric heating elements that wrap around the conveyor and by the amount of draft air pulled through by the off-gas system. Sections of elements are controlled separately to maintain the desired temperature gradient along the Lehr (Figure 3.34). Some of the heating elements will need to be replaced periodically. Replacing the elements could easily be delayed until the next planned outage, because some excess heating capacity would be built into each section.

3.8.3 Quality Assurance

Glass composition changes may significantly impact the required annealing temperature and cooling rates. If QA for the system requires a very good anneal, it may be necessary to incorporate a feedback system to control the temperature gradient. Glass composition could be sampled periodically at some point before the Lehr system. Equations to predict the optimum anneal conditions could be used to adjust the temperature curve and the conveyor speed.

3.8.4 Design Information Needed

The glass composition and variance will need to be known to design the optimum Lehr system. The effect of compositional changes will need to be determined. The benefits and drawbacks of annealing, especially for monoliths, will need to be weighed against the need for reduced surface area and/or easier handling.

4.0 Evaluation of Forms

This chapter provides qualitative rankings of the forming alternatives in a variety of areas. The glass forms considered include cullet, flake, cullet in sulfur, marbles, pressed shapes, plate, and monoliths. Each shape was evaluated on a scale of 1 to 10 (10 being best) in the areas of performance assessment, production capacity, retrievability, operability and maintenance, disposal volume, equipment cost, and quality assurance. No effort has been made to weight the various rankings to arrive at a final score. However, a qualitative evaluation of the results is used to arrive at a preferred form for the LLW glass. Chapter 5.0 summarizes the results of the qualitative rankings.

4.1 Performance Assessment

The form of the LLW glass can significantly affect the rate at which radioactivity is released to the environment because the form controls the total surface area available for leaching. Forms having a large available surface area per mass will release a proportionally higher amount of radioactivity (except in regimes where very little water is available and dissolved products approach saturation). Another potential impact on the ability of the final form to retain its radioactive components is through addition of a secondary barrier to keep water away from the glass surface and retard the transport of dissolved products to the environment; SPC is considered such a "secondary barrier."

Piepho et al. 1994 attempted to calculate the dosage an individual would receive by drinking water from a well 100 m from a storage site. The model used parameters for transport from the waste form to the well that were used in the grout performance assessment. Release from the glass waste form itself was modeled using differently sized spheres and assuming a variety of corrosion rates for the glass. Calculations were performed with and without an SPC matrix of assumed properties designed to reduce release.

Table 4.1 summarizes data indicating how the choice of glass form might affect the long-term environmental release that will be considered in a performance assessment. The left columns of the table list the type and size of glass form being considered. Entries are included for different assumptions concerning the quality of a sulfur cement matrix for cullet, a fused block for glass plate, and different assumptions regarding size and degree of cracking for the monolith. The right columns of the table list the estimated specific surface area per kilogram of glass, a surface area-to-volume ratio, and an estimate of total surface area for 100 metric tons of glass production. Based on glass corrosion occurring on this surface area, the relative release compared to an 8-cm sphere is estimated. Using preliminary results of calculations in Piepho et al. (1994), a corrosion rate is estimated that would meet a 4-mrem/yr drinking-water dose limit, and a "yes/no" determination is made regarding whether the system is likely to meet limits for each of two glass formulation corrosion rate estimates. It should be noted that the performance assessment calculations used to make these evaluations are preliminary and may not accurately reflect the eventual performance assessment calculations.

Table 4.1. Performance of Low-Level Waste Glass Alternatives

Alternative PA Model[a]	Size	Surface Area, m²/kg	Surface-to-Volume Ratio, 1/m	Total Surface Area, m²[b]	Radioactive Release Compared to 8-cm Sphere	Glass Corrosion Rate to Meet 4-mrem/yr g/cm²-s	Will "Typical" Glass Meet PA Requirements[c]	
							Soda-Lime Glass	Borosilicate Glass
Spheres	8 cm dia	0.03	75	3,000	1	3.2E-13	N	N
High permeability sulfur		0.03	75	3,000	0.08	3.8E-12	N	Y
Cullet (fines removed)	1504 micron (effective size)	1.6	3,990	160,000	53	6.0E-15	N	N
High permeability sulfur[d]	1504 micron (effective size)	1.6	3,990	160,000	4.4	7.2E-14	N	N
Low permeability sulfur[e]	1504 micron (effective size)	1.6	3,990	160,000	0.05	5.9E-12	N	Y
Marbles	1 in. dia	0.094	236	9,400	3	1.0E-13	N	N
Block	12 in. x 6 in. x 6 in.	0.013	33	1,312	0.44	7.3E-13	N	N
Plate (fused as block)	36 in. x 36 in. x 1 in. (thick)	0.033	83	3,325	1.11	2.9E-13	N	N
	36 in. x 36 in. x 36 in.	0.003	6.6	261	0.09	3.7E-12	N	Y
Monolith	24 in. dia x 10 ft	0.003	7.2	288	0.10	3.3E-12	N	Y
Cracked-2 x (area)		0.006	14	576	0.19	1.7E-12	N	Y
15 x (area)		0.043	108	4,320	1.44	2.2E-13	N	N
	48 in. dia x 10 ft	0.0016	3.9	157	0.05	6.1E-12	N	Y
Cracked-2 x (area)		0.003	7.9	314	0.10	3.1E-12	N	Y
15 x (area)		0.024	59	2,355	0.79	4.1E-13	N	N

(a) Piepho et al. (1994).

(b) For 100 MT production (1 day of production).

(c) Corrosion rates of typical glasses at 25° C (from memo prepared by Baskaran and McGrail, "Dissolution Rates of Glasses: Compilation of Data")

	g/cm² - S
Typical soda-lime glass	2.0E-11
Typical borosilicate glass	1.4E-12

(D) "high" permeability sulfur estimates mass transfer properties of degraded sulfur to be same as for new concrete

(e) "low" permeability sulfur estimates mass transfer porperties of degraded sulfur to be 1000x slower than new concrete

4.1.1 Cullet - Wet Process (Quenching)

Quenched cullet breaks into irregular shapes. For modeling purposes, these shapes have been estimated to be cubes (the actual surface-area-to-mass will be somewhat larger than that for cubes because true irregular shapes have points and crevices that add area). The size of most of the cullet mass is fractions of an inch. However, there are also many fines particles that add significant surface area without adding much weight. The size of the cubes is estimated from sieve analysis tests of two samples of quenched cullet. One sample from Oregon Steel in Portland was taken after a classifying step in the process where some unknown fraction of fines were removed. The second sample from Vortec in Pittsburgh, Pennsylvania was taken directly from a quench bath. The sieve analyses of these samples is shown in Table 4.2.

Fines contribute tremendously to the surface area. Fines removal can decrease the surface area per mass, but at the expense of reworking these fines through the melting process. For this estimate, we assumed the smallest 1% by mass of the particles was removed, as indicated in a preliminary TWRS mass balance for the quench process (Orme 1994). The size of the "theoretical particle" is that size that will possess the same surface area/kg as the sample distribution. Although 86% of the cullet pieces were larger than .16 cm (1/16 in.), the surface area contribution of the fines lowered the "theoretical particle" size to about .15 cm.

One day's worth of production (100 MT) represents more than 150,000 m^2 of surface area available for radioactive release (leaching). This is nearly two orders of magnitude greater than that for any of the other candidates.

The wet cullet process will also suffer from another performance-reducing mechanism unless additional process steps are performed. Without pH adjustment and subsequent washing, the quench water will become alkaline. When the cullet is dried, the residual caustic may greatly increase the corrosion rate of the glass when environmental moisture reaches it.

The surface area is so high that to meet requirements, a glass many times more resistant than a waste borosilicate glass would be required. If possible, the glass would also require a small acceptable quality region. This ranking applies to both cullet (wet process) and flake (dry process). **Ranking: 1**

4.1.2 Flake - Dry Process

Flake is a dry method of manufacturing a type of cullet. For this analysis, it is assumed to give a size distribution sufficiently similar to quenched cullet. It is also assumed to behave practically the same as quenched cullet. Samples of dry cullet were not examined to confirm or deny this assumption. However, considering the orders of magnitude difference between cullet and larger shapes, it wasn't considered likely that differences would be significant. **Ranking: 1**

Table 4.2. Particle Size of Quenched Cullet

Sample[a]	Particle Size, microns	Surface Area, m^2	Volume, m^3	Mass Fraction	Area/Mass, m^2/kg[b]	Area/Volume, m-1	Packing Factor[c]	100 MT	
								Volume	Surface
Frit Sample (Oregon Steel)[d]	3	5.4E-11	2.7E-17	0.00005	0.040				
	22	2.904E-09	1.1E-14	0.00023	0.025				
	60	2.16E-08	2.2E-13	0.00036	0.015				
	90	4.86E-08	7.3E-13	0.00016	0.0042				
	130	1.014E-07	2.2E-12	0.00013	0.0025				
	290	5.046E-07	2.4E-11	0.0065	0.053				
	700	0.00000294	3.4E-10	0.099	0.34				
	2500	0.0000375	1.6E-08	0.813	0.78				
	4000	0.000096	6.4E-08	0.080	0.048				
		Total surface area per kg frit (m^2)			**1.31**				
Theoretical particle size to have same surface area/kg	1833					3273	0.5	80	130,935
Frit Sample (Vortec)[e]	3	5.4E-11	2.7E-17	0.0002	0.16				
	22	2.904E-09	1.1E-14	0.00069	0.08				
	60	2.16E-08	2.2E-13	0.0017	0.07				
	115	7.935E-08	1.5E-12	0.0059	0.12				
	290	5.046E-07	2.4E-11	0.027	0.22				
	630	2.3814E-06	2.5E-10	0.064	0.24				
	915	5.02335E-06	7.7E-10	0.032	0.08				
	1680	1.69344E-05	4.7E-09	0.557	0.80				
	3000	0.000054	2.7E-08	0.312	0.25				
		Total surface area per kg frit (m^2)			**2.02**				

Table 4.2. (contd)

Sample[a]	Particle Size, microns	Surface Area, m^2	Volume, m^3	Mass Fraction	Area/Mass, m^2/kg[b]	Area/Volume, m-1	Packing Factor[c]	100 MT	
								Volume	Surface
Theoretical particle size to have same surface area/kg	1186					5057	0.5	80	202,291
					Area/kg of "Screened" Glass				
Screened Frit Sample (Vortec)[e]	3	5.4E-11	2.7E-17	Removed[f]					
	22	2.904E-09	1.1E-14	Removed					
	60	2.16E-08	2.2E-13	Removed					
	115	7.935E-08	1.5E-12	Removed					
	290	5.046E-07	2.4E-11	0.025	0.21				
	630	2.3814E-06	2.5E-10	0.064	0.25				
	915	5.02335E-06	7.7E-10	0.032	0.08				
	1680	1.69344E-05	4.7E-09	0.557	0.80				
	3000	0.000054	2.7E-08	0.312	0.25				
		Total surface area per kg frit (m^2)			**1.60**				
Theoretical particle size to have same surface area/kg	1504					3990	0.5	80	159,591

(a) Each frit sample had many large pieces that were highly fractured and barely holding together. To simulate further breakage caused by handling, exposure to pumps, etc., each sample was shaken in a vibrator for 5 minutes. The resulting distribution appeared to be more single pieces with only the large agglomerations broken.

(b) Assumed glass density of 2.5 g/cm^3.

(c) Packing factor is the measured bulk density (material poured into a graduate cylinder and tapped down) divided by an assumed glass density of 2.5 g/cm^3. The result is approximately 1 void space.

(d) An unknown amount of fines removal occurred in the Oregon Steel samples during processing before the sample collection point.

(e) Quench system operators indicated that particle size can be affected by water temperature, turbulence, etc. However, no information regarding the achievable sizes is available.

(f) Assume smallest 1% of fines removed. Removing smallest 1% of mass reduces area almost 20%.

4.1.3 Cullet in Sulfur Polymer Cement

The effect of a sulfur polymer matrix is to retard the flow of water (liquid or vapor) to the glass and retard the transport of released products from the glass surface to the surface of the matrix (then they pass to the environment like the non-matrix model). The transport depends greatly on diffusion and on hydraulic conductivity through the block. Qualitatively, the SPC matrix is described as "impermeable" (Mattus and Mattus 1994). Although this description may be qualitatively correct, the diffusion coefficient and hydraulic permeability are not quantitatively zero.

Leaching tests performed on SPC showed that when SPC was loaded directly with 25% wt of a radioactive ash (not glass), a 200-g sample of the SPC released between 0.003 and 0.5 of its original charge in 6 months (Mattus and Mattus 1994). Data for diffusion properties of SPC are difficult to determine. In one proposed model, Piepho et al. (1994) assumed that after some degradation the effective permeability may be like new concrete. When using this permeability, addition of an SPC matrix reduced the release by about a factor of twelve for a given surface area and glass corrosion rate holding all other variables constant. In Table 4.1, this is indicated as "high permeability sulfur."

It is possible that SPC may not degrade to be as permeable as concrete. The actual permeability drastically influences any estimates based on the Piepho model. To estimate an upper limit for quantifying the effect of SPC in reducing the release, the following model was conceived. Sulfur is assumed to completely fill the voids surrounding glass cullet in a container to form a uniform block containing 30 vol% sulfur and 70 vol% glass. A planar section taken through this block would expose an area consisting of 70% glass cullet and 30% sulfur. This type of surface was assumed for the outside of the block and the exposed area was taken as 70% of the geometric surface area of the block. Although the surface area of exposed cullet is only 70% that of a solid glass block, (1/0.7) more blocks would need to be produced because of the lower glass content of each block. Therefore, taking surface area values from Table 4.1, the extent of improvement from cullet alone to cullet with sulfur would be:

$$\text{Improvement} = A_1/(k_1)\,(A_2)\,(k_2) = 533$$

where A_1 = 1.6 m^2/kg cullet

k_1 = 0.7 fraction of sulfur block area as glass

A_2 = 0.003 m^2/kg in solid glass block 36" x 36" x 36"

k_2 = 1/0.7 = 1.43 increase in number of blocks over a solid block to dispose of same quantity of glass

Without any further justification other than simplicity and a desire to get a sense of reasonableness, it was assumed that the permeability of SPC might be sufficiently low to reduce release from the cullet by a factor of 1000 as an upper limit. This amount of release reduction was then used to calculate whether or not such an SPC matrix could be used in conjunction with a form that has a high surface area, such as a cullet, and meet release limits. In Table 4.1, this is indicated as "low permeability sulfur."

A later model by Rawlins et al.(a) predicted an upper limit release reduction of approximately 10,000. To achieve this, unrealistic transport parameters were used for the SPC matrix. Such a result would not be consistent with the experimental release form ash in SPC.

Table 4.1 indicates that without any matrix material, cullet has such a large surface area that only a very "super" glass could meet release limits. If effective permeabilities for SPC were only as low as concrete, then neither a typical soda-lime glass nor typical waste borosilicate glass would meet release 11 requirements. If SPC permeabilities are sufficiently low to reduce releases by a factor of 1000, then even relatively "poor" glasses may meet requirements.

CAUTION: This discussion does not suggest that a factor of 1000 reduction is possible to achieve in practice. It only indicates that if it can be achieved, even a form with a large surface area such as cullet could meet release requirements.

The effects of SPC on meeting release requirements are yet unknown, although SPC appears to offer significant promise that must be verified experimentally and with a rigorous model. There are also reservations about its long-term stability. Thiophillic bacteria are known to attack sulfur-containing materials. Whether or not SPC will retain its stability over long time periods is still a significant concern (Mattus and Mattus 1994). One observation indicating that sulfur will not be stable is that elemental sulfur is found in only a few special geologic deposits and only on the earth's surface where it is being renewed by volcanic or geothermal activity.

The descriptions about the impermeability of SPC are encouraging in that cullet with an SPC matrix could perform near the upper limit assumed in this estimate for reducing release. However, the leach tests indicate that the quality of "impermeable" isn't a good quantitative description of the product. Also, long-term durability of the form is questionable in a near-surface storage location. It may take lengthy tests to unequivocaly confirm or deny the long-term durability. The study time required will delay further progress toward implementation. **Ranking: 5**

4.1.4 Marbles

Marbles are assumed to be 1 in. in diameter based on information from a vendor that this size represents the largest standard marble made using conventional marble machines. The surface is assumed to be uncracked.

(a) Rawlins, J. A., et al. August 25, 1994. "Impacts of Disposal System Design: Options for Low-Level Glass Waste Disposal System Performance." Working Draft. Westinghouse Hanford Company.

Like cullet, the surface area is too high to meet release requirements with current glass products. However, it is much more likely that a glass good enough to meet requirements may be developed (perhaps sacrificing waste loading). Ranking: 3

4.1.5 Pressed Shapes

A block with dimensions 12 in. x 6 in. x 6 in. was selected. The practical limit for a "gobbing" operation is about 40 kg. The rectangular shape was selected for stacking purposes, although the shape slightly increases the surface area-to-mass ratio.

Blocks will meet the requirements if a glass twice as durable as the borosilicate glass baseline is readily made, but will not meet requirements if the durability of only a soda-lime glass can be achieved. Durability sufficient to meet PA requirements should be achievable. Ranking: 8

4.1.6 Plate

Commercial plate can be made to a thickness of about 1 in. Thicker plate is probably possible; however, the time required for annealing increases as the square of the thickness increases. The length and width dimensions are purely arbitrary; here, the stack size was selected to be approximately 1 m^3 and 2.5 MT. Obviously, as plate dimensions increase, handling becomes more difficult. Commercial plate glass may be made up to 11 ft wide (Tooley 1974). Handling systems for plate glass up to this size exist in industry.

Because plate glass stacks quite tightly, it is expected that the surface area between the plates will be to some degree less available to water and subsequent release of radioactivity than the external surfaces. The degree of availability was not determined in this analysis. The release, however, would be greater than if the block were totally fused into one piece and less than if each sheet were exposed separately. The two extremes are easy to calculate and are presented as bounding conditions (the difference is about one order of magnitude).

Like with pressed shapes, plain soda-lime and borosilicate glasses will not be good enough for the full area of a single plate. If the available surface area is taken as the edges of a stack of plates, borosilicate durability glasses will meet requirements. The predicted performance is slightly better than pressed shapes. Ranking: 9

4.1.7 Monoliths

Two monolith sizes are indicated. The first is comparable to the canister size considered for HLW (24 in. dia. x 10 ft). The second size has twice the diameter, increasing the weight to about 5 MT, but still can be readily handled. The surface area of the monolith varies greatly because cracking from stresses were incurred during the cooling process. If a 24-in. canister is allowed to cool in the open air, it cools in about 25 hours and increases surface area 27 times (rounded to 30). If the canister is cooled over a period of about 100 hours, the internal cracking increases surface area only 7 times (Peters and Slate 1981).

The greatest fraction of the cracks in the monolith are tight and the monolith still maintains its integrity if the container is removed. How much of the extra surface area from the cracks is truly available for mass transfer is not readily determined. Experiments on leaching from cracks indicated that 0.38-mm-wide cracks released only about 40% of the material that would be released from a completely free surface. Tight cracks essentially did not contribute to release (Perez and Westsik 1981). More work needs to be done to verify the release from a cracked monolith. For the purposes of this evaluation, it is assumed the "real" release would be bounded by a release between 2x and 15x the release of an uncracked monolith. These bounding analyses are indicated in Table 4.1.

A second phenomenon also must be considered when assessing the radioactive release from monoliths. Cracking may be reduced by reducing the cooling rate so stresses can relax. During cooling there will be a tendency for the least soluble materials to separate from the amorphous glass and form crystals. When the glass is at room temperature, the driving forces exist but crystallization is kinetically limited. At elevated temperatures (550°C to 900°C), the molecules still have enough mobility to move. That is why the stresses can "relax." Simultaneously, the least soluble materials are nucleating and crystals are growing. This crystal formation, or devitrification, generally leads to increased leach rate of the matrix materials. The exact rates depend on the glass composition and the thermal history of the monolith. Devitrified glasses can display a leach between 2 and 5 times greater than the annealed glass (Mendel 1978). In extreme cases, devitrification may increase the release rate up to 10 times. On the other hand, it is possible to design a glass/glass-ceramic with a leach rate that may actually decrease with crystal formation.

The available surface area of monoliths for mass transport is a question just as it is for plate. As with plate, glass with durability as good as borosilicate will be good enough if the cracked surface area isn't readily available. However, there is a question about the resistance of devitrification products to leaching. They may be just as durable or may increase release. Plates are annealed so there isn't the question of devitrification. Due to the uncertainty, monoliths should be ranked slightly below plates.
Ranking: 8

4.2 Equipment Capacity

It has been specified that the waste vitrification plant will need to operate at approximately 100 MT per 24 hours (U.S. DOE/RL 1994). Some potential system candidates were therefore eliminated in the preview portion of this study. Though some fall short, most of the systems included can easily meet the desired rating.

4.2.1 Cullet

According to Whittington and Peters (1992), the RECOMP frit-making process had a 27 MT/d specified capacity, which could easily be designed to meet the desired 100 MT/d. The screw conveyor is already designed to handle up to 215 MT/d. The remaining system components would simply be enlarged (Whittington and Peters 1992). System designs have already been completed at size for the TWRS combined facility. Ranking: 9

4.2.2 Flake

Production rates of over 360 MT/d have been achieved on similar rolling machinery used to produce plate glass (Tooley 1974). Although the thinness of the glass restricts the production rate to some extent, equipment sized to handle the necessary rates should be easy to design. Ranking: 9

4.2.3 Cullet in Sulfur

Although the glass frit and sulfur mixing and casting operation is not a standard operation, it is assumed that this operation could be set up to handle 100 t/d of cullet. The ranking was not decreased because of the addition of sulfur. Ranking: 9

4.2.4 Marbles

Standard roller marble machines are reported to produce marbles at a rate of 54 MT/d. Two lines would therefore be necessary to meet the desired capacity. A third line would be desired to handle breakdown conditions. Ranking: 6

The PNL vibratory marble machine had a production rate of 1.4 MT/d (Whittington and Peters 1992). Other manufacturers have achieved better results using parallel molds and multiple streams, but a number of forming lines would still be needed. Further development may bring rates near needed levels, but at this time the vibratory machine cannot acceptably handle 100 MT/d. Selection of a vibratory marble machine would reduce the ranking to 3.

4.2.5 Pressed Shapes

As of 1974, double gob-pressing machinery had reached production rates of 35 to 45 MT/d (Tooley 1974). Current machinery can press pieces as large as 40 kg at a rate of 30-55 pieces/min (Howard 1985). Presses currently on the market would have no problem achieving 100 MT/d. However, two machines would still be desired to avoid unnecessary down time. Ranking: 7

4.2.6 Plate

Production rates of over 360 MT/d have been achieved for rolled glass (U.S. DOE/RL 1994). Rolled glass production plants are not being built today except for special applications. Equipment and plans for the desired size are probably available.

Single-line float glass plants run at rates as high as 810 MT/d. A wide range of sizes is being used today. Small float plants in the 80 to 210 MT/d range are being designed and built for use in developing countries. Equipment for float glass production is more readily available. **Ranking: 9**

4.2.7 Monoliths

Considerations for monolith production to meet 100 MT/d are simply that the container-handling equipment be able to handle the necessary number of containers per day. This requirement would apply equally to any of the other systems as well. The container-handling rate would be proportional to monolith size. For a 1.22-m (4.0-ft) by 3.05-m (10-ft) canister, 100 mT/d requires changing at 2-hour intervals. **Ranking: 9**

4.3 Retrievability

The final disposal system for the LLW glass has not yet been designed. For this study, it has been assumed that the waste form needs to be packaged for safe transportation to a temporary storage location on the Hanford Site and be stored to permit retrieval at a later date, if required. It can be argued that anything placed in storage could be retrieved again, even if mining were necessary. The authors feel that implicit in the requirement to be retrievable is a requirement for relative ease of retrieval. In the spirit of this requirement, forms that would require difficult reprocessing or "mining" were not considered. The options of casting a large vault full of molten glass (a single monolith) or molten matrix (SPC) were not considered "retrievable" options for this task.

Considering only final containerized forms of about 500 kg to 10 MT, there is not a significant advantage for any of the forms. Small shapes such as cullet, marbles, or cullet in SPC could be bulk loaded into the final container and sealed for transportation. Medium shapes such as pressed shapes or plate could be automatically stacked into a final container. The simplest operation for monoliths would involve casting the glass directly into the final container. The final container for any of these operations could be made readily transportable and retrievable from temporary storage. No single process has an advantage over the others for final forms in this size range.

Rating all the possibilities of the packaging size or packaging materials was not considered in the task. For analyzing performance of the shapes, packages of a size convenient to handle were established, but those dimensions are arbitrary. Any size picked for reasons associated with handling should compare similarly.

Glass is quite dense and much heavier final forms would still be small enough to handle, and may offer some handling or transportation advantages. Increasing the size of the final product decreases the number of pieces that have to be handled, decontaminated for transport, etc. Individual pieces approaching 25 MT could be individually loaded in containers and still be retrieved, shielded, and transported by truck to a permanent storage location. Rail transport would require building an individual spur line. Potentially, rail transport could facilitate individual containers approaching 80 MT and allow temporary shielding during transport within railroad weight limits.

Casting monoliths of this size raises a question about the devitrification and cooling rates that would be practical to minimize cracking. Cooling huge monoliths would take a long time. They probably would be transported to temporary storage while they are still quite hot. The effects of glass devitrification and resulting glass release rates is a concern for larger monoliths. The resistance to leaching of devitrification products is still unknown, so this would be considered less desirable than other processes for very large sizes.

For ranking purposes, monoliths are ranked only slightly below the other forms. The advantages of very large pieces for storage and transportation could still be achieved by casting smaller sizes and filling the transportation container using another processing step. Likewise, pressed shapes may need to be stabilized into smaller units before they are loaded into a very large container. This would require another simple process step.

Rankings

Cullet, cullet with sulfur, flake, marbles, plate - **Ranking: 10**

Monoliths and pressed shapes - **Ranking: 9**

4.4 Operability/Maintenance

4.4.1 Cullet

Operation and maintenance of a cullet production system as shown on the TWRS combined facility process flow sheet (Orme 1994) would be highly complex. Cullet is very abrasive. Equipment used to transfer the cullet from the cullet catch tank to the dryer and on to storage will probably require frequent maintenance and/or replacement. Once dried, the cullet will be very dusty. When the transfer piping and equipment are opened for maintenance, contamination control will be very difficult. Water used for quenching and air used for drying require recycle. Equipment used for these tasks will need to be located inside the cell. The rotating screen and cullet metering device will probably require considerable maintenance. Many of the process steps are interdependent to the point that if one piece of equipment fails to operate as required, major difficulties could occur upstream of the failure. For instance, if the outlet of the quench flume-roller crusher should plug, molten glass would back up into the glass separator and into the melter before the melter could be shut down. If the glass solidifies before the plug can be removed, the consequences would be significant.

- Amount of remote equipment required - HIGH

- Process complexity - MEDIUM

- Equipment maintainability (degree of difficulty) - HIGH
- Potential for equipment failure - MEDIUM

Overall Ranking: 3

4.4.2 Flake

Producing and packaging flakes could be simpler process if operated as a dry process and if product transfers, including canister filling, were made by vacuum. Dust control, especially during maintenance, would be difficult.

- Amount of remote equipment required - MEDIUM
- Process complexity - LOW
- Equipment maintainability (degree of difficulty) - MEDIUM
- Potential for equipment failure - MEDIUM

Overall Ranking: 6

4.4.3 Cullet in Sulfur Cement

Mixing cullet with sulfur cement would also be a highly complex process. The equipment requirements are essentially the same as those described above for cullet, with the added complexity of cullet/ sulfur cement mixing.

- Amount of remote equipment required - HIGH
- Process complexity - HIGH
- Equipment maintainability (degree of difficulty) - HIGH
- Potential for equipment failure - MEDIUM

Overall Ranking: 1

4.4.4 Marbles

From the standpoint of operation and maintenance, making a marble has about the same degree of difficulty as making a brick. However, because marbles are much smaller than bricks, handling before container loading can be done on a bulk basis.

- Amount of remote equipment required - HIGH

- Process complexity - MEDIUM

- Equipment maintainability (degree of difficulty) - HIGH

- Potential for equipment failure - HIGH

Overall Ranking: 1

4.4.5 Pressed Shapes

Producing and packaging bricks or spheres would be a highly complex operation. Close control of viscosity is required. With a continuously fed melter, such control may be difficult. The gob mechanism(s), moving molds, presses, annealing furnace transfer mechanisms, devices for removing shapes from molds, mechanisms for loading shapes into containers, grinder to condition broken shapes, and the mechanism for transferring the ground glass back to the melter all will require significant routine maintenance and frequent repair or replacement. All of the listed equipment will have to be inside of dust/ fume control enclosures to prevent gross contamination of the cell interior. This will further complicate maintenance.

- Amount of remote equipment required - HIGH

- Process complexity - MEDIUM

- Equipment maintainability (degree of difficulty) - HIGH

- Potential for equipment failure - MEDIUM

Overall Ranking: 3

4.4.6 Plates

The first method of making plate glass is to pour (float) molten glass onto the surface of a tank of hot tin. This process would probably create large quantities of contaminated metal that would require special processing and disposal. Other plate-making processes pour the glass stream between rollers that form and carry the glass through the Lehr system and on to the sizing (cutting) operation.

Commercial equipment is available to cut, sort, and stack plate glass made by either method. If the glass is to be stored without any covering (i.e., no container), there should not be a problem with loading and transporting. However, contamination control would be a major concern. If sealed containers are required, it will be very difficult to design an automatic welder that would reliably seal a container shaped to hold square/rectangular-shaped stacks of plate glass.

- Amount of remote equipment required - HIGH

- Process complexity - MEDIUM

- Equipment maintainability (degree of difficulty) - HIGH

- Potential for equipment failure - MEDIUM

Overall Ranking: 3

4.4.7 Monoliths

More experience exists with this process for radioactive service than with any other glass-forming method investigated. The process is relatively simple when compared to making brick, plates, etc. The forming process is operator friendly (easy to operate and has a large margin for error without significant consequence). The containers of glass are easy to transport and are readily retrievable. Containment during processing is good.

- Amount of remote equipment required - LOW, MEDIUM

- Process complexity - LOW

- Equipment maintainability (degree of difficulty) - MEDIUM

- Potential for equipment failure - LOW

Overall Ranking: 8

4.5 Product Volume

The total amount of waste glass that will be produced has been estimated at 400,000 MT (U.S. DOE/RL 1994). The packing densities of the candidate processes affect the volume and subsequent storage costs (both temporary and eventually permanent). Some of the volume left as voids between pieces is filled by matrix material if sulfur cement is used. Table 4.3 includes the packing factor of each form, the volume of one day's production (100 MT), and the estimated volume of the total LLW. In Table 4.3, cullet refers to both dry process (flake) and quench process (cullet). Both processes should produce a product with approximately the same bulk density.

The table assumes that each process uses containerized waste (see retrievability section) and that the total storage volume increases 30% over the glass volume to allow for container spacing and clearances from the roof and walls.

Table 4.3. Bulk Volume of LLW Glass Forms

				All LLW 400,000 MT Glass	
Alternative PA Model	**Size**	**Packing Factor[(a)]**	**Bulk Volume, m^3 (a)**	**m^3**	**Cost at $750/$m^3$, $MM**
Spheres	8 cm dia	0.74	54	2.8E+05	211
High permeability sulfur		0.66	61	3.2E+05	237
Cullet (fines removed)	1504 micron (effective size)	0.66	61	3.2E+05	237
High permeability sulfur	1504 micron (effective size)	0.66	61	3.2E+05	237
Low permeability sulfur	1504 micron (effective size)	0.66	61	3.2E+05	237
Marbles	1 in. (dia)	0.74	54	2.8E+05	211
Block	12 in. x 6 in. x 6 in.	1	40	2.1E+05	156
Plate	36 in. x 36 in. x 1 in. (thick)	1	40	2.1E+05	156
Plate fused as block	36 in. x 36 in. x 36 in. (thick)	1	40	2.1E+05	156
Monolith	24 in. dia x 10 ft	0.906	44	2.3E+05	172
Cracked-2 x (area)		0.906	44		
15 x (area)		0.906	44		
Monolith	48 in. dia x 10 ft	0.906	44	2.3E+05	172
Cracked-2 x (area)		0.906	44		
15 x (area)		0.906	44		

(a) For 100 MT production (1 day of production).

Basis: Assume all shapes except cullet are closely packed.

A base case for cullet in sulfur cement assumes the mixture is 70% cullet and 30% sulfur by weight. Glass and sulfur have approximately the same density and the mixture contains 6% void when mixed properly. The volume fraction of glass is therefore-0.7*.94-.66.

Bulk density of samples of glass cullet in Table 4.2 indicate only a 50% volume fraction of glass. For this table it is assumed that through compaction, the volume fraction of glass could be increased to be the same as that for cullet with sulfur.

Assume final bulk storage volume is 30% greater than material volume because of spacing between containers and roof and wall clearance.

The cost for storage space has not yet been determined. To roughly determine the magnitude of the storage cost and the value of more compact waste forms, estimates based on the 1992 cost for storage of Fernald LLW ($21/$ft^3$) (Whittington and Peters 1992) are included in Table 4.3.

Cullet requires the greatest storage volume, about 50% more volume than plate or pressed blocks. At the assumed value of storage volume, the difference is worth about $80 million. The next best option would be monoliths as cylinders. Monoliths could also be formed with hexagonal cross sections to achieve a maximum packing density. Keeping the straight sides of the shape could cause extra operational difficulties and require extra development. The corners would also localize stresses and probably would cause extra fracturing, increasing surface area. The value of the decreased storage volume is estimated at $16 million. However, cylindrical monoliths were assumed.

Close-packed marbles are the geometry with the next best storage volume following cylindrical monoliths. If spheres were considered as the preferred geometry for a pressed shape because of lower surface area or less tendency to fracture, then the volume ranking would be like that for marbles (closely packed).

Rankings

Cullet	Ranking: 5
Flake	Ranking: 5
Cullet with sulfur	Ranking: 5
Marbles	Ranking: 6
Pressed blocks	Ranking: 9
Pressed spheres	Ranking: 6
Plate	Ranking: 9
Monoliths	Ranking: 8

4.6 Process Equipment Cost

Rankings have been developed for initial plant costs. Costs are high if many complicated machines are required. Additionally, costs were considered to be higher for systems requiring greater plant space.

4.6.1 Cullet

Cullet is a fairly complex system that uses existing equipment. Equipment needed includes a quench tank, screen filter, conveyors, drying bins, holding bins, container-handling system, and water recycle system. **Ranking: 7**

4.6.2 Flake

Flake production is fairly simple using existing equipment. Required equipment includes pressing rollers, cracking rollers, conveyors, crusher (may not be needed), holding bins, and a container-handling system. **Ranking: 8**

4.6.3 Cullet with Sulfur

Adding the sulfur cement process to cullet production significantly increases the amount of equipment needed. There is also the added expense of the sulfur and other raw materials to be used. Most of the necessary equipment is available. This includes everything needed for the flake or cullet, a heated holding tank, a heated pumping system, mixing bins, a container preheater, a cullet preheater, and an additional off-gas system. **Ranking: 3**

4.6.4 Marbles

Marble making requires a complex system either way the marbles are made. Rolling is the best option for this application, so it will be assumed here. The equipment required is in use commercially. Required equipment is a forehearth, gob feeder, roll formers, conveyors, annealing Lehr system, holding bin, container-handling system, recycle quench tank, filter screen, and water recycle system. **Ranking: 6**

4.6.5 Pressed Shapes

A pressing system would be complex and expensive, but is commercially available. Equipment needed includes a forehearth, gob feeder, indexing press, conveyors, annealing Lehr system, robotic-handling system, container-handling system, recycle quench tank, filter screen, and water recycle system. **Ranking: 4**

4.6.6 Plate

Plate making should be moderately expensive. The equipment uses technology in use around the world. Necessary equipment is a forehearth, forming rollers or tin bath, conveyors, Lehr system, automatic cutter, robotic stacker, container-handling system, and recycle crusher. **Ranking: 6**

4.6.7 Monoliths

Monolith forming is the simplest of the systems. The equipment is not commercially available, but is already in use in other nuclear waste operations. Equipment needed includes a container-handling system, recycle quench tank, filter screen, water recycle system, and conveyors. The quench tank and associated equipment listed will not be needed at all if a redundant recycle system is not necessary for this forming method. **Ranking: 10**

4.7 Quality Assurance Evaluation

4.7.1 Quenched Cullet

The process used to form quenched cullet should be simple to control. The most significant potential problem would be plugging in the bulk conveyors and storage bins. Incomplete drying could contribute to this process difficulty. The presence of moisture is also unique for this candidate process and could hurt the PA. This is only a minor difficulty that can be easily monitored and corrected by rework in the process. This process will be very tolerant of changes in the melted glass. **Ranking: 8**

4.7.2 Flake (Dry Cullet)

Compared to the process to produce quenched cullet, the process to produce flake will be more sensitive to changes in the melted glass properties. Potentially, if the viscosity of the glass changes rapidly, unwanted breakage could occur. The sheet may break too soon or may be too soft to break, causing a process failure. This probably will not be a problem and other processes will be vastly more sensitive to these changes. In-process testing for flake production will be less stringent than for quenched cullet production. **Ranking: 8**

4.7.3 Cullet with Sulfur

The process used to form cullet is straightforward; QA will be relatively easy. However, the sulfur addition step adds significant control requirements for the final product to meet PA requirements and operate trouble free. The most significant of these requirements is that the sulfur temperature must be maintained in a 6°C band around 135°C (Mattus and Mattus 1994), where it has low viscosity and minimum off-gasing. Temperatures above or below this band can cause viscosity increases and plugging problems. The molten sulfur must be mixed in accurate proportions with the cullet and the glass must be preheated so the components mix properly. The container must be preheated so the mixture completely fills it. The temperature control requirements of the mixture are quite tight; if not maintained, the SPC can contain excessive voids, which can dramatically hurt its performance in retaining the radioactive materials. The process is considered to have controls as difficult to maintain as the most difficult glass forming method. **Ranking: 4**

4.7.4 Marbles

Commercially, marbles are produced rapidly using the roller marble maker. The process is a delicate balance of heat and mass transfer to form the glass and mold it using only the small forces of the weight of the individual piece. Hence, the process is very sensitive to the viscosity of the glass and its viscosity vs. temperature relationship. In industry this is carefully controlled through the batch make-up. Latitude to change the composition of the glass will be very limited for processing LLW. It is possible that the viscosity vs. temperature will be ideal. This should not be considered likely. In addition, the viscosity may change as the feed composition changes. Some adjustment may be possible by adjusting the temperature through forehearth control. These adjustments also will be limited because cooling the glob is also affected. The marble-forming cooling process using rolling wheels will be a very delicate balance of viscosity and heat transfer. It may not even be operable.

The marble-making process using moving molds is somewhat more tolerant of viscosity changes because perfect spheres aren't necessary. Nevertheless, good separation of the marble from the pour, and release of the marble from the mold, depend on the viscosity of the glass and its heat transfer to the mold. The suitability of either of these processes for use with LLW glass cannot yet be determined. They may be satisfactory or totally unsuitable. The uncertainty requires it be given a low ranking. **Ranking: 2**

4.7.5 Pressed Shapes

Pressed shapes will also be sensitive to viscosity changes of the glass. However, presses can employ many tons of force to the glass to shape it, making the process much more tolerant of even significant changes in viscosity.

After the article is pressed it needs to be annealed in a Lehr oven to prevent it from breaking. The Lehr oven will be operated with automatic controls. The aspect of breakage and recycle of broken pieces introduces a quality control point regarding shape integrity. This can be quite a significant concern in industry, where annealing requirements change significantly as different shapes (or thicknesses of glass) are processed. The major difficulties occur with product (grade) changes. This should be of only slight concern for processing LLW because the shape and size will remain constant. Changes in glass temperature or viscosity won't significantly change the annealing requirements.

After annealing, the pressed shapes will be stacked and put in containers. A quality control (QC) issue of shape and size uniformity could be a concern. In this case, however, there shouldn't be a problem. Presses are capable of a thirtyfold tolerance improvement over system needs. Commercial presses produce shapes with tolerances +/- .002" (5×10^{-5}). For stacking, tolerances of +/- 1/16" (1.6×10^{-3}) should be adequate.

If composition testing of the final product is occasionally needed, the discrete pressed shapes should prove as convenient for testing as the cullet processes. This isn't a strong positive because this feature probably will not be needed. **Ranking: 8**

4.7.6 Plate Glass

This process, like the marble-rolling process, will be sensitive to the viscosity of the glass from the forehearth. Plate forming uses much higher pressures than marble forming, so the roller process can accommodate higher viscosities. It is similar to the pressing operation. The plate process will also have a sensitivity to the thermal expansion characteristics of the glass, and a sensitivity to inhomogeneities (e.g., bubbles or particles). When making plate glass, the whole processing line is one sheet of glass 200 to 1000 ft long. As the glass cools, it contracts. A stable processing line draws and advances the glass at progressively slower rates to accommodate the shrinkage. If the glass properties change fairly rapidly, greater stresses can develop in the glass, causing fractures. In the process described here, the greater possibility of property changes is mitigated by operating at slower than normal speeds (0.45 m/min) and making heavy-gauge glass.

Similar quality issues about annealing exist as in the pressing operation. They should not be difficult to address.

Overall, QC for glass plate will be similar to that for pressed shapes, with a slightly larger probability of process difficulties from breaks in the continuous drawn plate. **Ranking: 7**

4.7.7 Monoliths

For operability, pouring glass into a container will be most tolerant of changes in the glass composition. The QC issues to address would be how to accommodate changing densities of the product while trying to completely fill the container. Similar to the packing density concerns of the cullet products, this isn't a process failure but rather a process at less than optimum conditions.

Having large individual blocks means that sampling a finished product or reworking those blocks will be difficult. However, this is not considered a significant negative because it is very unlikely to be needed. The compositional changes can be monitored in the melt. If a bad composition occurs, the pour could easily be stopped. There is no process to start up and stabilize. If the glass flow could not be stopped, a side stream water quench could be used for recycle.

Maintaining optimum conditions for product performance will require balancing a long cooling time with its inherent devitrification vs. a shorter cooling time with greater cracking and surface area. How much the block cracks and how much devitrification occurred may be important issues to determine whether or not the process is operating as designed to meet performance requirements. This will be very difficult when making monoliths. It could be done by cutting through a selected monolith and examining the surface for extent of cracking and crystallization. The sampling process could require more hardware than the basic fill process.

Except for the cracking and devitrification uncertainties, monoliths would be ranked very high for ease of QC. However, those questions may become issues and the uncertainty leads to a lower ranking. **Ranking: 6**

5.0 Conclusions and Recommendations

Glass produced in Hanford's LLW vitrification plant needs to be formed into some shape. The preferred form needs to be consistent with the overall integrated system. Many factors about the system's design criteria are still to be determined. Thus, different forming systems cannot be evaluated against quantitative requirements. However, good qualitative comparisons can be made that can indicate which forms should be pursued in greater detail as the quantitative values emerge. Three general categories for the solidified glass form that capture most of the potential forms were identified: small, medium, and large pieces. Within the categories, several different forms can be made. The different forms were qualitatively evaluated against general criteria; selected examples are shown in Table 5.1. The indicated forms are believed to be representative of potentially viable forms.

Generally, the larger the final form the better its qualitative score. This characteristic is due to the inherently higher surface area present with small pieces, the apparent vulnerability of the operations to higher exposure, and the greater manufacturing challenge to make many more pieces. The major advantage of small pieces is the ability to retrieve the waste from disposal and recycle the glass during processing to reprocess a poor quality product. Small pieces provide no advantage in decreasing the disposal volume and appear to complicate the steps involved in materials handling when transferring the forms from the vitrification facility to the disposal site. Intermediate-sized pieces (i.e., greater than 20 mm) suffer from the complication of the equipment needed to create the pieces. Pieces in this range are prevalent in the glass industry but the equipment used to produce them is more complicated and requires more maintenance. These factors introduce a higher probability for operator exposure and are the major reason for its secondary ranking.

The preferred form for the LLW glass, based on this qualitative assessment, is the large casting, or "monolith." Large castings of many different sizes and configurations can be made. This form provides the greatest flexibility in minimizing system costs because the system can be readily modified, even after completion of the facility design or even after facility construction. The flexibility of this forming approach extends beyond the narrow range of the forming system. The melter upstream need not be as carefully controlled as is necessary for other product forms. During packaging, transportation, and disposal, large castings also fall within the capabilities of widely used materials-handling systems. This feature should have a positive influence on the risk reduction and cost factors outside the forming system. The primary disadvantage of large castings is the difficulty in implementing corrective steps if the glass composition were found to be unacceptable. However, this concern also exists with a HLW process where the activities to recover and recycle out-of-specification glass are much more complex. In spite of this concern and a more variable waste stream, process control methods have been developed and demonstrated in high-level radioactive operating plants without major problems. Thus, this apparent weakness has been successfully addressed in other programs.

Table 5.1. Process Evaluation for Selected Glass Forms

Evaluations of Processes	Performance	Capacity	Retrievability	Operability Maintenance	Volume Cost	Equipment Cost	Quality Assurance
Small Pieces:							
Cullet	1	9	10	3	5	7	8
Flake (dry cullet)	1	9	10	6	5	8	8
Cullet in Sulfur	5	9	10	1	5	3	4
Marbles	3	6	10	1	6	6	2
Medium Pieces:							
Pressed Shapes	8	7	9	3	9	4	8
Plate	9	9	10	3	9	6	7
Large Pieces:							
Monoliths	8	9	9	8	8	10	6

Based on this qualitative comparison and the current understanding of the LLW requirements, it is recommended that large castings be optimized for forming the LLW glass. Many additional opportunities for optimization remain and should be exploited as the design criteria for the facility are further defined.

The option of using SPC as a secondary barrier is only attractive if simpler processes and forms cannot meet performance requirements. If a sufficiently durable glass cannot be developed, the secondary barriers would need to be considered; SPC is one option.

6.0 Open Technical Issues

Based on this study, the following open technical issues need to be resolved. Of primary importance is determining the glass waste form properties so design and testing of the forming system can proceed. These properties must be identified to design the forming equipment. In the case of large castings, these characteristics would include the following:

- *Viscosity as a function of temperature from the melting temperature to about 10,000 poise.*
  To design the casting system, the flow of glass depends most upon viscosity.

- *Effective thermal conductivity for the glass as a function of temperature from the melting temperature to room temperature.*
  Because viscosity is exponentially dependent upon temperature, the effective heat transfer must be determined to determine the extent of glass flow into the container. The rate of cooling is determined by the heat transfer characteristics of the glass, and package handling depends upon materials temperatures. With the heat transfer properties of the glass known, all of the design values can be calculated.

- *Devitrification of the glass as a function of widely different cooling times and its influence on chemical durability.*
  This study indicated that the larger the casting, the easier and better the package can be operated. This is limited conceptually by the chemical durability of the glass, which presumably is dependent upon devitrification. For very large castings, the rate of cooling could lead to ample opportunity for a large fraction of the glass to be devitrified. Thus, the time-temperature-transformation of the LLW glass family is needed so the packages avoid the unacceptable cooling range.

- *Distortion of container during glass pouring and cooling.*
  To achieve a high waste loading, glasses of a fairly high temperature are needed. Glasses at high temperature have been cast into large containers of steel and stainless steel metals without melting, but the distortion of the material during filling is not fully understood. Container filling needs to be completed at production rates to determine the limits of process.

- *The effective leaching surface area of large glass castings needs to be determined experimentally.*
  Large glass castings fracture thermally during cooling. Most assessments assume that the entire surface area is available for leaching. However, some experimental studies have been completed that show this assumption is too conservative. Even natural glasses that have cracked do not leach at this rate. It is speculated that an order of magnitude or more in performance may be achieved through experimental verification that large, constrained, cracked glass does not leach as assumed. Large castings need to be fabricated and leached to determine the validity of the assumptions.

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Appendix A

Water Retention by Cullet

Appendix A

Water Retention by Cullet

Glass cullet (same sample used for sieve analysis test) was mixed with water and then filtered through a 325 mesh screen. After all the water had dropped through, the screen was tapped gently until water no longer dripped. The glass was then scooped off the screen into a tared beaker and dried overnight at 105°C to 110°C.

Weight--wet glass and beaker	72.664 g
Weight--dry glass and beaker	63.395
Weight--beaker	50.519
Water weight	4.269
Dry glass weight	17.876
Water retention (% of dry glass)	23.88%
Reference: LRB 55332, pg. 41.	

Appendix B

Listing of Glass Production Companies

Appendix B

Listing of Glass Production Companies

Following is a database of companies related to the glass industry. Some companies manufacture machinery, some make glass products, and some provide design engineering services.

Company Name	Address	City,St Zip	Fax #	Phone #	Contact	Call	Lt	Information
Forming Equipment Manufactures								
Corning Glass	Houghton Park	Corning, NY 14831		609-974-9000	Andy Jackson	g		
Emhart Glass	P.O. Box 700	Windsor, CT 06095		203-688-8551	Dick Robinson	k	•	Bottle making equip.
Kelley Industries, Inc.	Route 519 S.	Eighty Four, PA 15330	412-222-6985	412-222-6980		r		Molding and Pressing equip.
Lancaster Glass Corp.	232 W. Main St.	Lancaster, OH 43130-0070	614-653-9501	614-653-0311	Larry Figgens?	g		
Lynch Machinery-Miller Hydro	P.O. Box 767	Bainbridge, GA 31717-0767	912-243-0987	912-248-2300	Ron Howard	k	•	Forming/Pressing equip.
M & S Engineering, Inc.	204 S. River St.	Dundee, IL 60118	708-428-5631	708-428-5631		g		Casting equip.
Maul Technology	300 W. Martin St.	Winchester, IN 47394	317-584-1452	317-584-2101		r	•	Complete processing lines.
Sigri Great Lakes Carbon Corp.	550 Rte 206	Bedminster, NJ 07921		908-851-0060	Lee Young	k	•	Formed Graphite for molds, feeders, cutoffs.
Teichmann, Henry F, Inc.	3009 Washington Rd.	McMurray, PA 15317	412-941-3479	412-941-9550		g		Design of equip. for glass industry.
Related Equipment Manufactures								
A-I-T Industries, Inc.	2020-T Hammond Dr.	Schaumburg, IL 60195		708-397-1770				Optical Glass Machinery
Ashur, Inc.	1117 W. Elm Tree Rd.	Rossfor, OH 43460	419-666-0357	419-666-0357		k		Glass tempering ovens/forming molds
Bickley Furnaces, Inc.	Box 369	Bensalem, PA 19020	215-638-4334	215-638-4500		g		forming & melting. kilns and furnaces.
Burns Engineering						r		
Burns Machinery, Inc.	Route 1, Box 69-C	Dothan, AL 36301	205-671-0310	205-793-7086		r	O	Automated Handling equip.
Delkic & Associates	Box 1726	Ponte Vedra Beach,FL 32004	904-273-1616	904-285-0200		k		glass molds
Dura Temp Corp.	1750 Eber Rd. Box 368	Holland, OH 43528	419-866-4656	419-866-4348		g		Materials for Forming equip.
Eagle Machinery Corp.	Box 98	Taylor, MI 48280-0098	313-941-9082	313-941-8444		r		Sintering equip
Eldred International Corp.	2491-T Fairwood Ave.	Columbus, OH		614-491-4848		k	•	Molded glass finishing equip.
Envirite	620 W. Germantown Pike	Plymouth Meeting, PA 19462	215-828-8406	215-828-8655		k	•	Dust reclaimation system.
Frazier-Simplex, Inc.	P.O. Box 493	Washington, PA 15301	412-225-3114	412-225-1100		k	O	Batch Handling equip.
Glass Equip. Development Inc.	1943-T Midway Dr.	Twinsburg, OH 44087		216-425-3876	Mark Mallowski	k		Float Glass Processing equip.
Industrial Furnace Designers Inc				314-423-7775				
Industrial Furnace Supply	2125 S. Hellman Ave.	Ontario, CA 91761	714-947-6200	714-947-2449		r		glass forming & melting
Kercher Industries, Inc.	920 Mechanic St.	Lebanon, PA 17042	717-273-2967	717-273-2111	Mr. Kercher	k		Crushing and Mixing equip. (cullet and recycling)
KTG Systems	3471 Babcock Blvd	Pittsburg, PA 15237	412-366-8083	412-366-0330	Larry McCloski	k	•	Furnaces
Laclede Christy Clay Products	405 E. Peach St.	Owensville, MO 65066	314-437-3146	314-437-2132		k		glass forming & melting
Poco Graphite, Inc.	1601 S. State St.	Decatur, TX 76234	910-890-5724	800-626-5227		k	•	Materials for Forming & Melting equip.
PTX - Pentronix, Inc.	1737 Cicotte	Lincoln Park, MI 48146	313-388-9171	313-388-3100		k	•	Robotic Handling equip (from molds)
RAM Products, Inc.	1091 Stimmel Rd.	Columbus, OH 43223	614-443-4813	614-443-4634		k		Hydralics and Presses.
Selas Corp. of America	Box 200	Dresher, PA 19025	215-646-3536	215-283-8202	Peter Weber	r		Bending and Tempering equip for Flat glass.
Specialty Products Co.	Box 306	Jersey City, NJ 07303	201-434-6052	201-434-4700	Raul Hernandez	k	O	Mold Lubricating equip.
Superior Machine & Engineering	887-T Chartier Rd.	Marine City, MI 48039		313-765-8813	Tony Skudirna	k	0	Custom equip for Plate glass.
Swanson - Erie Corp.	810 E. 8th St.	Erie, PA 16512		814-453-5841		k		Automated Assembly machines
Toledo Engineering	3400 Executive Pkwy	Toledo, OH 43606	419-537-1369	419-537-9711		g		Engineering/Contracting for glass plants
Zircar Products, Inc.	110 N. Main St., Box 458	Florida, NY 10921	914-651-3192	914-651-4181		k	•	Fiberous Insulation and Refractory Materials.

Company Name	Address	City,St Zip	Fax #	Phone #	Contact	Call	Li	Information
Glass Producers/Retailers								
Aaron Equipment Co.	735 E. Green St.	Bensenville, IL 60106	708-595-3993	708-350-2200		k		Chem Processing equip.
Acme Vial & Glass Co., Inc.	1601 Commerce Way	Paso Robles, CA 93446	805-239-9406	800-394-2745		k	•	Containers (vials, tubeware, etc)
Andrews Glass Co.	410 S. 4th St.	Vineland, NJ 08360	609-692-5357	609-692-4435		r		glass forming & melting
Atlantic Optical Moulding Co.	103-T Ellis Ave	Dudley, MA 01570		508-943-1746	Joseph Krysiak	g		High-Precision Optical Parts
Avant Industries, Ltd.	Box 2156	Newark, NJ 07114		800-394-1039		k		glass containers
Carr-Lowrey Glass Co.	2201 Kloman St.	Baltimore, MD 21230	410-347-8868	410-347-8800		k		glass containers (design and manuf.)
Cataphote, Inc.	1001 Underwood Dr.	Jackson, MS 39225	601-932-5339	800-221-2574		r		glass beads
Continental Glass & Plastic Inc	817 W. Cermak Rd.	Chicago, IL 60608		312-666-2050		r		Glassware Retailer
Dawson Industries	13265 E. Eight Mile Rd.	Warren, MI 48089	313-771-4890	313-771-5200		k		Job Shop
Detector Technology, Inc.	Box K-300	Brookfield, MA 01506	508-867-4030	508-867-5411		g	•	Fab, Finishing, and Forming
Ferro Corp.	4150 E. 56th St.	Cleveland, OH 44101	216-641-2049	216-641-8580		k		glass frit
Ford Motor Co.	300 Renaissance Center	Detroit, MI 48243	313-446-8926	313-446-5915		r		Structural glass.
General Glass Equipment Co.	General Glass Bldg.	Absecon, NJ 08201	609-646-2960	609-345-7500		r		Models (also marbles)
Gray Glass Co.	139-24 Queens Blvd.	Jamacia, NY 11435	718-297-4742	718-297-4444		k		glass beads
HGP Industries, Inc.	3811 Turtle Creek Blvd.	Dallas, TX 75219		214-528-5022		g		glass fab & finishing
Holophane Co., Inc.	214 Oakwood Ave.	Newark, OH 43055	614-349-4486	614-345-9631		k		glass (reflectors, refractors)
Houde Glass Co.	1177-T McCarther Hwy.	Newark, NJ 07104	201-481-1524	800-526-1275		g		Distributer
Libby-Owens-Ford (LOF)	1701 E. Broadway	Toledo, OH 43605	419-247-4224	419-247-3731	Mr. Barry	g	•	Plate glass.
Meteor Glass Corp.	538 N. E. Ave. and N. St.	Vineland, NJ 08360		609-691-8251		k	•	Pharmaceudical glassware
MO-SCI Corp.	Twitty Industrial Park	Rolla, MO 65401	314-364-9589	314-364-2338		k		glass beads (microspheres)
Naugatuck Glass Co., Inc.	Church & Bridge Sts.	Naugatuck, CT 06770		203-729-5227		k	•	Custom Mirrors, Lenses, etc.
Pittsburgh Corning Corp.	800 Presque Isle Dr.	Pittsburg, PA 15239	412-733-4815	412-327-6100		r		glass beads (cellular, and blocks)
Potters Industries, Inc.	20 Waterview Blvd.	Parsippany, NJ 07054	201-335-9350	201-299-2900		g		glass beads(spheres)
PPG Industrial, Inc.	Box 11472	Pittsburg, PA 15238	412-665-8512	412-434-3131		r		plate and fiber glass manuf.
Shott Glass Technology, Inc.	400 York Ave.	Duryea, PA 18642		717-457-7485		k	•	Optical Glass Blanks.
Specialty Glass, Inc.	305 Marlborough St.	Oldsmar, FL 34677	813-855-1584	813-855-5779		k	•	Beads, Frits, Powders, Rods, Tubing
Stillmeadow Glass Works Inc.	PO Box 234 Dept T	Hampton Falls, NH 03842		603-474-2272		k		Pressed and Blown glass Job Shop
Stoneware Tile Co.	1650 Progress Dr.	Richmond, IN 47374	317-935-3971	317-935-4760		g		glass tile

B.4

Company Name	Address	City,St Zip	Fax #	Phone #	Contact	Call	Lt	Information
International								
ACI New Zealand Glass Manuf's Co.	752 Great South Rd/Penrose	Auckland, New Zealand	64-9-5795117	64-9-5799959				glass containers
BA-Fabrica do Vidros Barbosa & Alm	Apt. 27, Avintes	VN de Gaia Codex 4402, Portug	2-7826910	2-7820972				glass (bottles, vases)
Boulton, William, Vibro Energy, Ltd	Venturi House, Edensor Rd/	Stoke-on-Trent STE 2QB, UK	0782-599009	0782-599800				glass fab & finishing
Consol, Ltd.	Box 562	Germiston 1400, S. Africa		8274311-011				glass containers (& tableware)
Cristaleria de Cuyo	Cordoba 1345, Piso 13	Buenos Aires, Argentina		42-8430				glass containers
Electroglass, Ltd.	4 Brunel Rd/Manor Trading	Benfleet Essex/SS7 4PS, UK	268-565594	044-268-565577				glass forming & melting
Engis of Canada, Ltd.	4190 Fairview St., B-4	Burlington, ON L7L4Y8, Canad	416-632-4250	416-632-3016				glass fab & finishing
Fidenza Vetraria	Via Gran San Bernardo/Pal.	Rozzano/Milanofiori 20089, Ital	02-57500627	02-57575-1				glass beads
Glass Training Ltd.	Northumberland Rd.	Sheffield S10 2UA	0742-660738	0742-661494		k	•	Videos and Taining guides
Glassworks Equip, Ltd.	Park Ln./Halesowen	West Midlands B63 2QS, UK	0384-61363	0384-60666				
Hindusthan Nat. Glass & Ind's Ltd.	Two Red Cross Place	Calcutta 700 001, India	91-33-284191	033-280101				glass containers
Irish Glass Bottle Co., Ltd.	S. Bank Rd., Ringsend	Dublin 4, Ireland	01-683416	01-68-35-71				glass containers
Kuala Lumpur Glass Mfgrs. Co.	Box 25, 46700 Petaling Jaya	Selangor, Malaysia	03-7913613	03-7912277				glass containers
P&H Glasstechnology B.V.	Rekvelden 5	5503 NZ Veldhoven, Netherland	40-530970	040-530700				
Redfearn National Glass plc	Box 7, Monk Bretton/Barnsl	South Yorks S71 2Q9, UK		0226-710211				glass containers
Rurex - Stahl GMBH	Steinhof 37 / Box 1264	Erkrath D-40672 Germany	211-24-34-00	211-24-30-1415				
San Miguel Corp.	*109 Alvarada St., Legaspi Vl*	Makati, M.M., Philippines	632-8174434	632-854921-29				glass tile(containers and glassware)
Seraikella Glass Works, Ltd.	PO KANDRA/Bihar	Jamshedpur 832402, India		0657-87163-87386				glass forming & melting
Sovitec S.A.	Avenue du Marquis/Zoning I	B-6220 Fleurus, Belgium	71-81-76-73	71-81-50-11				glass beads
Taiwan Union Glass Industrial Co.	11th Fl., 26 Jen-Ai Rd., Sec.	Taipei 106, Taiwan, R.O.C.	02-708-8678	02-7027126				glass/glass beads
Teknik Cam Sanayii A.S.	Davutpasa Cad., Topkapi	Istanbul, Turkey	577-99-78-1	5760479-1				glass beads & BoroSi. glassware
Toyo Glass Co, Ltd.	3-1, Uchisaiwaicho, 1-chome	Chiyoda-ku, Tokyo 100, Japan	03-508-0048	03-508-2198				glass forming & melting, containers
VICASA	Paseo de la Cestellana, 77	28046 Madrid, Spain	91-397-24-29	91-397-20-00				glass containers & brick
Vidrala	Bo. Munegazo No. 22	Llodio Alava, Spain	4-6724791	94-6721600				glass containers
Welko Industriale S.P.A.	Via Milano 18/20	I-26016 Spino D'Adda Italy	373-966696	39-373-9891				
Yamamura Glass Co., Ltd.	2-21 Hamamatsubara-cho/H	Nishinomiya 662, Japan	798-32-2394	798-32-2356				glass containers and equip.
Zignago Vetro	30025 Fassalta di Portogruar	Venezia, Italy	0421-762-401	0421-762-1				glass
Equipment and Company Directories and Associations								
European Glass Dir.								"Buyer's Guide"
Glass Age						g	O	
Glass Industry						g	O	"Directory Issue"
Glass Production Tech. Internat.	86-88 Edgeware Rd.	London, W2YW		800-367-9692?				Published by Sterling Publications Ltd?
Machinery Dealers Nat. Assoc.	1110 Spring St.	Silver Springs, MD 20910	301-585-9460	301-585-9494	Sam Feidenburg	k	•	Used equipment directory.
Materials Tech. Assoc.	Box 11	Los Alamos, NM 87544		505-672-9001				R+D, and Engineering, for glass industry
Mohr Corp.	PO Box 1148	Dearborn, MI 48121	313-846-3766	800-223-mohr		r		Used Ceramic equipment
Pacific Ceramic Mach. & Equip.	PO Box 7842	Stockton, CA 95207	209-462-5142	209-462-3405	Ron	k	•	New and Used Ceramic equipment

Company Name	Address	City,St Zip	Fax #	Phone #	Contact	Call	Ld	Information
Perry Machinery Corp.	Mt. Laurel Rd	Hainsport, NJ 08036	609-267-4499	609-267-1600	Pete DeAngelo	k	O	Used Ceramic equip.
Surplus Record				800-622-5449	Martha Schneider	k	•	Association of equipment dealers.
TradeCo Equip. Corp.	PO Box 342	Trenton, MI 48183	313-946-5572	313-946-5570		r		new and used ceramic equip.
Used Equipment Directory				800-526-6052	Rosemary	k	O	
World Industrial Reporter								"International Buyer's Guide"

Company Name	Address	City,St Zip	Fax #	Phone #	Contact	Call	Lit	Information
Marbles and Balls								
Acra-Ball Mfg. Co.	2860 Gretta Ln	Anaheim, CA	714-632-9066	714-632-3801				
Alceram Technologies	PO Box 293	Great Neck, NY 11021	516-627-2361	800-876-5708				Precision glass components
American Toy Marble Museum	453.5 E Exchange St	Acron, OH 44304		216-374-0499	Michael Cohill	k		Sending samples/drawings
Bal-Tec	1550 E. Slauson	Los Angeles, CA 90011		800-883-1190				precision glass balls
Bird Precision	PO Box 569	Waltham, MA 02254		800-370-6308				glass bearings
Brody			516-676-6430	516-487-3377				
Cataphote, Inc.	PO Box 2369	Jackson, MS 39225		601-939-4612				glass spheres
Champion Agate Co., Inc.	PO Box 516	Pennsboro, WV 26415		304-659-2861	Dan Christians			marbles & glass balls
Epworth Mfg. Co., Inc.	1402 Kalamazoo St.	South Haven, MI 49090	616-637-3421	616-637-2128				balls
GBC Materials Corp.	581 Monistery Dr.	Latrabe, PA 15650		800-959-0839				components of glass/ceramics
Glebar Co. Inc.	PO Box 623	Franklin Lakes, NJ 07417	201-337-3848	800-235-5122				precision grinding
Glen Mills Inc.	395 Allwood Rd.	Clifton, NJ 07012		201-777-0777				.1 - 10mm balls
Gwilliam Co.	566-3 DanBury Rd.	New Milford, CT		203-354-2884				balls/bearings
Hartford Ball Co.	1033 Elm St.	Rocky Hill, CT 06067	203-529-9299	800-839-9007				balls
Hoover Precision Products Inc	PO Box 899	Cumming, GA 30130		404-899-9223				precision glass balls
Industrial Tectonics, Inc.	PO Box 1128	Ann Arbor, MI 48106		800-482-BALL				glass balls for all kinds of things
JABO Inc. (Vitro Agate)	PO Box 242	Parkersburg, WV	614-374-2601	800-338-9578	JoAnn Albright	k	0	Industrial marbles. Used machines ($10k - $20k)
Jilson Corp., The	20-22 Industrial Rd.	Lodi, NJ 07644		201-471-2400				glass bearings
Johnson/Peltier Glass Co.	518 De Leon St.	Ottowa, IL 61350	815-433-5787	815-433-0102		k		Marble machines for in-house use
Lucky Dog Enterprises	PO Box 87	Chesaning, MI		517-845-2632	Charlie Hall	k	•	Marbles. Contacts. Lots of info.
Marble King, Inc.	PO Box 195, Dept 10	Paden City, WV 26159	304-337-2264	800-672-5564	Berri Fox	k		Marble machines for own use.
Norca	185-J Great Neck Rd.	Great Neck, NY 11022		516-466-9500				quartz, glass, window glass
Potters Industries Inc.	20 Waterview Blvd	Parsippany, NJ	201-335-9350	201-299-2900				Spheres
Precomp, Inc.	17 Barstow Rd.	Great Neck, NY		516-466-8275				Ceramic products
Sigma Engineering Corp.	39 Westmoreland Ave	White Plains, NY		914-682-1820				Grinding media
Specialty Products Int.	18 Wildwood Td.	Keene, NH 03431		603-347-0122				Precision balls
Stern, Walter, Inc.	68 Sintsink Dr, E	Pt Washington, NY 11050	516-767-0400	516-883-9100		k		Balls. No machinery.
Sun Brokers Inc.	PO Box 2230	Wilmington, NC		800-522-8425				Beads and balls for labs
Viking Rope Corp.	1012 Second St.	Anacortes, WA 98221	206-293-8480	206-293-8489	Dick Ryan ?			formerly owned Vitro Agate
Winsted Precision Ball Co.	249 Rockwell St.	Winsted, CT 06098		800-462-3075		k		Finishing of glass balls up to 1".

Appendix C

Glass Form Evaluations

Appendix C

Glass Form Evaluations

Lynch Machinery - Miller Hydro is a machinery manufacturing company that designs and sells pressing machinery worldwide. They have a long history as a leader in glass-forming equipment.

They were contracted to evaluate pressing and monolith production for use in LLW glass forming. Their work has been incroporated into the body of the report and is included here for reference.

LYNCH MACHINERY—MILLER HYDRO

Lynch Fax

PRESIDENT'S AWARD FOR EXPORT

601 INDEPENDENT ST. • BAINBRIDGE, GEORGIA 31717 USA • PHONE (912) 248-2345 • TELEFAX 912-243-0987

DATE: August 24, 1994

TO: Mr. Gary Josephson
Battelle Memorial Institute
Pacific Northwest Laboratories

FROM: Robert Pando

FAX NUMBER: 509-376-1867

TOTAL PAGES TRANSMITTED: 11

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Dear Mr. Josephson:

Lynch has examined three different methods of vitrification of low-level nuclear wastes. Two of these methods draw on our extensive experience in rotary indexing glassforming machines. After scrutiny by senior Lynch personnel, we have concluded that the rotary indexing concept may not be the best way to proceed. We are including drawings and text describing both of these proposals.

Summary Description of the Three Concepts

1. Block Concept with Rotary Indexing Glass Press

The first concept is based on our experience in pressing molten glass into many forms. In this case, we considered forming the mixture into 6" x 6" x 12" glass blocks.

Vitrification of nuclear waste produces air contamination as an unavoidable by-product of the glass melting process. We reasoned that an objective of this project is to avoid additional contamination of the ambient air in the machine room. Glass that is formed under pressure must be annealed to avoid shattering as it cools. The annealing process involves reheating and cooling, which we believe will result in significant additional air contamination.

Further, the glass-waste mixture is a waste product and the only benefit of forming it is to make it easier to cool and to handle. It is true that blocks or other formed shapes will cool more quickly than monoliths, but we can find no serious disadvantage to an attenuated cooling period. Accelerating the cooling period, on the other hand, may not be useful and may cause more problems (in the form of air contamination) than it corrects.

2. <u>Monolith Concept with Rotary Indexing Loader</u>

After analysis, we concluded that the monolith is more practical than blocks or other formed shapes. Marbles, granules, and frit had already been considered and discarded. Because of our knowledge of rotary indexing machines, we attempted to combine the monolith concept with the rotary machine principle. We believe these can be successfully combined; however, several disadvantages are quickly apparent:

Number of Wear Parts
Frequency of Required Maintenance
Excessive Motions

At this point, we turned away from rotary equipment. The monolith, however, remained the most attractive shape and form for handling the vitrified wastes.

3. <u>Monolith Concept Utilizing Tilting Feeder</u>

We recommend the monolith concept utilizing a tilting feeder which fills a container cube. As detailed in the description, this concept is simpler and requires less complex equipment than either of the others. While we have no experience in handling radioactive contamination, this concept clearly involves less machine contamination and air contamination than do the other methods.

Each of the three concepts has advantages and disadvantages. If you are interested in pursuing either of the rotary indexing machines, we will be glad to study them more thoroughly and construct budget parameters. It is apparent to us, however, that because the third concept uses such readily available equipment as cranes and simple hydraulic systems, costs will be much lower than the other, more complex, systems.

After you have had an opportunity to review our thoughts, we are sure you will have some questions; please do not hesitate to contact Ron Howard, Ken Hileman, or me.

Regards,

Rbt T Pando

Robert T. Pando
President

cc: Ron Howard
Ken Hileman

PROPOSAL FOR BATTELLE INDUSTRIES

BLOCKS FROM ROTARY INDEXING GLASS PRESS

AUGUST 24, 1994

Project:	Encapsulation of Low-Level Nuclear Waste into Glass Blocks Stored in Steel Containers
Requirements:	100 Metric Tons of Vitrified Low-Level Nuclear Waste Per Day
Proposal:	Use Molten Glass to Capture the Low-Level Nuclear Wastes

<u>The Furnace</u> The low-level nuclear waste material is blended into molten glass in the furnace. The mixture flows from the main chamber of the furnace through the forehearth and into a feeder where it is fed through a shearing mechanism which cuts the stream of molten mixture into discrete gobs of uniform weight.

<u>Rotary Indexing Machine</u> The glass press is a rotary indexing machine with a large table which rotates around a center column. The table indexes (rotates) then stops at each of twelve stations spaced around the table. Different functions are performed at each station:

Station 1:	The mold is loaded.
Station 2:	The gob is pressed or patted.
Station 3:	First cooling station
Station 4:	Cooling
Station 5:	Cooling
Station 6:	Cooling
Station 7:	Cooling
Station 8:	Cooling
Station 9:	Cooling
Station 10:	Cooling
Station 11:	Take-out - The gob is removed from the mold.
Station 12:	Available for cooling, re-heating, lubrication, or other mold conditioning.

<u>The Mold</u> The glass is fed into a mold approximately 6" x 6" x 12". One mold is installed in each of the twelve stations on the rotary indexing press. The gob may require pressing or "patting" to level the top surface of the glass. The machine indexes and, while another mold is being loaded, cooling wind begins to lower the temperature of the glass block. Eight of the twelve stations provide cooling wind, and by the time the machine has indexed to station 11, the take-out position, the glass is cool enough to remove from the mold.

<u>Annealing Lehr</u> The glass block is transported by conveyor into position where a transfer cylinder is used to push the block off the take-away conveyor onto a cross conveyor. A lehr loader or push-bar stacker pushes the block into an annealing lehr, where the glass is tempered to prevent shattering as it cools.

<u>Container</u> At the end of the lehr, a conveyor and stacking device transfers the blocks into a steel container similar to the one described in the monolith proposal. A cube measuring 4' on each side would weight slightly less than 10,000 lbs. Once again, a steel lid is welded in place on top of the cube.

PROPOSAL FOR BATTELLE INDUSTRIES

MONOLITH WITH ROTARY INDEXING LOADER

AUGUST 24, 1994

Project:	Encapsulation of Low-Level Nuclear Waste into Monoliths Stored in Steel Containers
Requirements:	100 Metric Tons of Vitrified Low-Level Nuclear Waste Per Day
Proposal:	Use Molten Glass to Capture the Low-Level Nuclear Wastes

The Furnace The low-level nuclear waste material is blended into molten glass in a furnace. The mixture flows from the main chamber of the furnace to a feeder where it is fed in a continuous stream.

The Container The glass is fed into a "monolith" type of container made of 1/2" steel plates and measuring approximately 4' x 4' x 4'. Depending on the constituents, sixty-four cubic feet of glass-waste mixture should weigh slightly less than 10,000 lbs.

Rotary Indexing Machine The steel container is loaded into a rotary indexing machine with four arms. The arms index, or rotate, under the feeder, where the containers are filled with the molten mixture. The center column of the indexing apparatus extends through the floor, permitting the drive mechanism to be controlled, maintained, and repaired without exposure to the radioactive atmosphere.

Station 1:	The container is filled.
Station 2:	Cooling.
Station 3:	After filling, the container indexes to the next station, where a plate steel lid is placed on it. One side of the lid is welded to the container, then the arm swivels the container 90 degrees for welding a second side; the container is swiveled and welded two more times.
Station 4:	The container is released from the indexing machine and is ready for transfer.

Duplication of Equipment The welding equipment, lid-loading equipment, and transfer device are duplicated for security purposes. In the event that a system needs maintenance or repairs, the stand-by equipment moves into position to continue loading and welding. The faulty equipment is removed through an airlock into a decontamination room. The equipment is then decontaminated and taken to a maintenance and repair area.

PROPOSAL FOR BATTELLE INDUSTRIES

MONOLITH CONCEPT UTILIZING TILTING FEEDER

AUGUST 24, 1994

Project:	Encapsulation of Low-Level Nuclear Waste into Monoliths Stored in Steel Containers
Requirements:	100 Metric Tons of Vitrified Low-Level Nuclear Waste Per Day
Proposal:	Use Molten Glass to Capture the Low-Level Nuclear Wastes

<u>The Furnace</u> The low-level nuclear waste material is blended into molten glass in the furnace. The mixture flows from the main chamber of the furnace to a tilting feeder where it is fed in a continuous stream into steel containers.

<u>The Container</u> The glass is fed into a "monolith" type of container made of 1/2" steel plates and measuring approximately 4' x 4' x 4'. Depending on the constituents, sixty-four cubic feet of glass-waste mixture should weigh slightly less than 10,000 lbs.

<u>The Tilting Feeder</u> Two loading stations are used alternately. Once a container is filled, the feeder toggles and the mixture begins filling the next container.

<u>Hydraulic Slide</u> A hydraulic slide mechanism shuttles the container under the feeder. After the container is filled and the lid is fitted, it is transported from under the feeder for pick-up by the crane.

<u>Lidding the Container</u> A robotic arm places a steel lid on the container after it is filled, prior to transporting it for pick-up.

<u>Overhead Cranes</u> Two cranes are used to move empty containers onto the hydraulic slide and filled containers from the hydraulic slide to the lid weldment area.

<u>Lid Welding</u> A robotic welding machine welds the lid to the container.

<u>Decontamination Area</u> The outside surface of the container is cleaned to permit it to be transported through an air lock to the uncontaminated area outside. There, a lift truck transports it for storage and further cooling.

VENDORS OF VARIOUS EQUIPMENT

Rotary Indexing Machinery Lynch Machinery

Since incorporation in 1918, Lynch has manufactured more glass forming machines than any other equipment supplier in the glass industry. Lynch's knowledge of the requirements of the glassmaking industry have resulted in the company's reputation for designing equipment that is highly reliable, even under the harsh conditions of glass production.

Feeder and Shear Mechanisms British Hartford-Fairmont

For more than 70 years, this U.K. company and its American affiliates have furnished hot glass handling systems and equipment. They understand the nature of this vitrification project and have indicated their willingness to develop equipment that is technically suitable.

Annealing Lehrs E.W. Bowman Company

Bowman is the largest U.S. manufacturer of lehrs (glass annealing ovens). The company's experience in the glass and ceramics industries results in a wide range of engineering experience. Again, this company understands the nature of this project and is willing to work with Lynch and with Battelle.