Design, Operation, and Evaluation of the Transportable Vitrification System (U)

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DESIGN, OPERATION, AND EVALUATION OF THE TRANSPORTABLE VITRIFICATION SYSTEM

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ABSTRACT

The Transportable Vitrification System (TVS) is a transportable melter system designed to demonstrate the treatment of low-level and mixed hazardous and radioactive wastes such as wastewater treatment sludges, contaminated soils and incinerator ash. The stabilization and safe disposal of low-level and mixed wastes is a significant challenge facing the U. S. Department of Energy (DOE). The TVS is a large-scale, fully integrated vitrification system consisting of melter feed preparation, melter, offgas, service, and control modules. The TVS was designed and constructed by EnVitCo, Inc., with subcontract of the offgas system to Andersen 2000. A number of design parameters were not well defined as the TVS was designed and constructed. The melter is a new design, and characteristics of the offgas such as temperature and particulate loading were not known. The actual waste streams to be vitrified were not identified, making it difficult to design waste and feed handling systems; important physical properties that affect designs were not known.

Once selection of the initial waste stream was defined, it was determined that the design of the TVS needed improvement. The dry feed systems for glass-formers and dry waste did not operate correctly and the melter feed system was not sized correctly for the material and flowrates to be fed. A number of fixes were made to these systems, resulting in successful operation. The melter plenum was found to allow excessive air inleakage, resulting in very low operating vacuums, lower than desired offgas temperatures, and a lower than design maximum glass production rate. Modifications were made to the melter plenum that allowed the system to be operated at higher vacuums; plenum temperatures were increased, and the maximum glass production rate exceeded the design rate. However, the modifications made startup of the glass drain chamber of the melter more difficult. The addition of a variable frequency drive on one of the offgas fans is expected to alleviate this problem.

The TVS was tested with surrogate waste at the Clemson University Environmental Systems Engineering Department's (ESED) DOE/Industry Center for Vitrification Research prior to being shipped to the DOE Oak Ridge Reservation (ORR) K-25 site for treatment of mixed waste. This testing, along with additional testing at ORR, proved that the TVS would be able to successfully treat mixed waste. These surrogate tests consistently produced glass that met the EPA Toxicity Characteristic Leaching Procedure (TCLP). Performance of the system resulted in acceptable emissions of regulated metals from the offgas system. The TVS is scheduled to begin mixed waste operations at ORR in June 1997.

INTRODUCTION ^{1,2}

The Transportable Vitrification System (TVS) is a transportable melter system designed to demonstrate the treatment of low-level and mixed hazardous and radioactive wastes such as wastewater treatment sludges, contaminated soils and incinerator ash. The stabilization and safe disposal of low-level and mixed wastes is a significant challenge facing the U. S. Department of Energy (DOE). Many waste streams have been identified as suitable candidates for stabilization by vitrification. The Savannah River Technology Center (SRTC), operated by Westinghouse Savannah River Company (WSRC), was tasked by the DOE Office of Science and Technology, as part of its Mixed Waste Focus Area (MWFA), to develop a vitrification system to demonstrate vitrification technology on a "field" scale.

The TVS is a large-scale, fully integrated vitrification system consisting of melter feed preparation, melter, offgas, service, and control modules. These modules were designed to be easily decontaminated, disassembled, sealed,

transported, and reassembled. Transport of the disassembled modules is accomplished using standard flatbed tractor-trailer rigs. Disassembly, transport, and reassembly can be accomplished in about eight weeks.

The contract to construct the TVS was awarded to EnVitCo, Inc., and was constructed at their Erwin, TN facility. After initial functional testing of the TVS at Erwin in July 1995, the system was shipped to the Clemson University Environmental Systems Engineering Department's (ESED) DOE/Industry Center for Vitrification Research for more extensive testing with surrogate waste materials. Upon arrival at Clemson, SRTC made numerous upgrades and modifications to the TVS that were not possible to incorporate in the delivered system; these modifications were made to improve the reliability, safety, and environmental controls of the system. In December 1995, testing began with a surrogate waste for Oak Ridge K-25 B&C Pond Sludge, which was the first expected waste to be treated. A total of 23 surrogate waste batches were made and vitrified; this testing was completed in March 1996. In May 1996, the TVS was disassembled and moved to the K-25 site at the Oak Ridge Reservation (ORR) in Oak Ridge, TN. At this time, SRTC began working with Lockheed Martin Energy Systems (LMES) to start up the TVS, perform additional limited surrogate testing for system checkout, and then demonstrate treatment of a mixed waste stream. Surrogate testing at ORR was completed in November 1996. Startup with mixed waste is scheduled to begin in June 1997 with either B&C Pond Sludge or Central Neutralization Facility (CNF) sludge. Vitrification tests with actual CNF sludge will be conducted in an EnVitCo designed minimelter at Clemson ESED prior to operating the TVS with CNF sludge.

This paper will cover design, operation, and evaluation of the TVS in several sections:

- A description of the TVS Systems (Modules).
- Discussion of some of the initial designs, evaluations of these designs based on operational experience, and subsequent design modifications.
- Results from surrogate testing, including glass formulation, glass quality, and offgas system particulate characterization.

TRANSPORTABLE VITRIFICATION SYSTEM DESCRIPTION

Dry or slurry waste material is blended with dry glass formers such as sodium carbonate (soda), silica, and lithium carbonate in the feed preparation system mix tank to produce a feed slurry, as shown in the schematic drawing in Figure 1. Dry wastes are introduced into the mix tank from the Waste Hopper via an auger. Slurry or other aqueous wastes can be added via a liquid addition port using an external, customer supplied pumping system. The glass formers are also added by augers. Water for batch makeup is supplied from the offgas system blowdown. All additions to the mix tank, which sits on load cells, are performed by weight. After mixing of a feed batch, the melter feed is transferred to the feed tank. Both the mix and feed tanks are equipped with agitators and centrifugal recirculation pumps.

Introduction of the feed slurry into the melter is accomplished via a recirculation loop, with a side stream providing the melter feed. The design production rate for the TVS is 68 kg/hr [150 lb/hr] of glass produced when slurry fed. The slurry is fed into the main melt chamber of the melter and the flow is controlled by a control valve. Additional control of the feedrate is achieved by adjusting the back-pressure and flow of the feed recirculation loop. Melting of the slurry feed in the main chamber of the melter is accomplished by joule heating, with an operating temperature range of 1100-1400°C. A propane gas burner supplies additional energy input into the main melt chamber. The propane burner is used during cold startup of the melter to heat the solid glass in the melter to a temperature sufficient for joule heating to begin (ca. 700°C). The propane burner is also used during normal operation to maintain the melter plenum temperature; the TVS melter is a "cold top" melter, wherein the cold cap of feed slurry on top of the glass insulates the plenum from the heat of the glass, so additional energy input into the plenum is needed. The offgas line from the melter to the offgas quencher is constructed of refractory lined pipe that has limited resistance to attack by acidic offgases. The refractory lined pipe was chosen rather than a material such as Inconel 690 for economic reasons. Therefore, offgas temperature needs to be maintained so that condensation of offgases does not occur in this line.

Located adjacent to the main joule-heated melter chamber are two side chambers. Glass melted in the main chamber flows into the glass drain chamber, which contains the glass draining mechanism, and is both joule heated and heated by plenum resistance heaters. The salt drain chamber can be used to collect alkali salts (sulfates, fluorides, phosphates, etc.) that are not incorporated into the glass due to their limited solubility. This chamber also has a drain mechanism and is heated by plenum resistance heaters. Glass poured from the glass drain chamber is collected in stainless steel boxes or drums, which move on an automated conveyor system. The main melt chamber can also be drained from the bottom to remove metals that may accumulate. Metals may accumulate due limited solubility or because they do not readily form oxides that can be incorporated into the glass.

Because offgas can be generated from any of the three melter chambers, the melter has three offgas lines to the offgas system. The majority of the offgas is generated from evaporation of water in the main chamber, with much smaller amounts of offgas generated from the side chambers. The offgas travels through the refractory lined pipe to the offgas quencher. The quencher completely quenches the offgas to a temperature of about 50-70°C using recirculated scrub liquid. The quencher is equipped with an emergency quench system that uses process water. Makeup water for the offgas system is added to the packed bed cooler and also via pump seal flushes.

Exiting the quencher, the offgas passes to the packed bed cooler, which is designed to additionally cool the offgas prior to scrubbing in a variable throat venturi. The packed bed cooler is packed with polypropylene packing and has a chevron mist eliminator. The quencher and packed bed cooler also remove some of the larger particulate material from the offgas. The packed bed cooler has an overflow system that is used when the emergency quench is used; this system collects the overflow and pumps it to the wastewater tank.

Removal of particulates is accomplished in the variable throat venturi scrubber, which has an adjustable throat that can be used to vary the pressure drop across the venturi. This adjustment is the primary mechanism for controlling the amount of vacuum in the melter. The venturi is designed to maintain 95% removal of particulates larger than 1 micrometer at any of its throat settings. Condensate transferred from the packed bed cooler is used to scrub the offgas. Blowdown from the entrainment separator is transferred to either the contaminated water tank, where it can be used for feed makeup or melter feed line flushing, or to the wastewater tank.

The offgas from the venturi is passed to the entrainment separator, which contains a chevron mist eliminator. Following the entrainment separator, a two-stage induced draft fan is used to maintain offgas flow and vacuum. The offgas is then heated, passed through a HEPA filter (two in parallel), a second induced draft fan, and then is emitted from the stack. The second fan is used to maintain vacuum at the inlet of the HEPA filters. The offgas system was designed and constructed by Andersen 2000.

The offgas system is also equipped with a gas chromatograph for measurement of hydrogen, carbon monoxide, and carbon dioxide evolution. A continuous extraction system for particulates, and ports for EPA method sampling and for stack gas analyzers are present. The service module contains the plant and instrument air systems, the contaminated water pump system, and the melter cooling water tank and pumps.

DESIGN, EVALUATION, AND MODIFICATIONS ³

The design of the TVS presented many challenges for EnVitCo and SRTC. The melter design chosen by the vendor was new, so many of the actual operational characteristics were not known. Moreover, the vendor was not experienced in the design of the support systems (slurry feed, solids handling, offgas). The performance requirements for each of these systems were also not well defined. Because the melter design was new, the characteristics of the offgas (temperature, particulate loading, water content) could only be estimated, making it difficult to be sure the offgas system designed would be adequate. The actual waste streams to be treated had not yet been identified, and even when identified, important physical characteristics were not available. The particle size distribution, tendency to agglomerate, and characteristics when slurried with glass formers (such as viscosity, non-Newtonian behavior) were also unknown. Even the physical characteristics of the glass forming materials to

be used were not known, as these had not yet been specified. All of these unknowns complicated the design of a reliable system.

It is important to define the design conditions as well as possible so that designs will be adequate; however, when designing a system to handle a wide variety of as yet undefined material, designers and customers need to realize that changes and modifications will be necessary so that the systems work properly and that some iteration will probably be required. The following sections highlight some of the initial design inadequacies of the TVS and modifications made to alleviate these problems. Some retrofits were successful and some are still in the process of being evaluated.

In the feed preparation system, augering of both the glass formers and surrogate waste from the hoppers to the mix tank presented many problems. Several different types of glass formers were used, ranging from very fine (precipitated silica) to very coarse (sodium carbonate). We found that moving the very fine solids was so difficult and that the feed slurry made was so viscous that coarser materials were eventually substituted. The particle size of the glass formers can affect the rate of melting in the melter and also the amount of waste that can be incorporated into a given glass composition. Smaller particle sizes for glass formers usually results in higher possible waste loadings; however, if it is almost impossible to get these materials to the melter, the overall production rate will suffer. Therefore, a compromise between waste loading and feed processibility was needed. Substantial improvement in the reliability of the glass former augers was made by inserting solid cores into the augers.

The waste hopper auger system presented different problems. The characteristics of the surrogate waste were not known until it was made. We found that the surrogate tended to clump and stick together, probably due to the moisture content. The waste auger typically became starved for surrogate waste either from funneling (waste in the center of the hopper was fed but most was left up against the sides) or from bridging (waste in the center was fed, but material above did not collapse down into the void). In an attempt to solve these problems, a vibrator was added to the hopper. The vibrator helped some when funneling occurred, but packed the waste solids more densely when bridging occurred. At Oak Ridge, "air blasters", which blast the solids with a short puff of air were added. These were found, during limited testing, to be very effective in moving the solids into the auger. Additional testing is planned. However, the physical characteristics of the first solid waste to be treated at Oak Ridge are not well known and may vary substantially.

The melter feed system relies on an automatic valve in the feed line from the recirculation loop to control the melter feed rate. The original valve was oversized, making it almost impossible to feed at the required rate of $0.150 \text{ m}^3/\text{hr}$ [0.66 gpm]. Replacement with a smaller valve solved these flow control problems. An automatic feed line flush system was also added that flushes the feed line with blowdown water if feed flow is lost. However, at Oak Ridge, the surrogate material used was found to contain a large amount of agglomerated material, with sizes ranging from 0.15 cm [1/16"] up to 1.25 cm [1/2"] in diameter. The surrogate material at Clemson was very homogeneous and rarely resulted in plugging. Some of these agglomerated solids were broken up in the mix and feed tanks, but many found their way to the feed valve, where they promptly plugged the valve. Currently, the feed system is again being modified to include a backflush through the feed control valve and to add in-line strainers in the feed recirculation loop. The system, as originally designed, had strainer baskets in the return line to each tank, but these strainers proved to be inadequate. When operations at Oak Ridge resume, these new modifications will be tested.

The melter offgas system was designed to operate the melter at a vacuum of up to 1250 Pa [5 inwc]. The design conditions and actual conditions are shown in Table I. In this table, the startup mode is the conditions expected during cold startup of the melter with the propane burner at the "high fire" setting. The vendor expected that the offgas would be at about 1100°C during startup, and that once joule heating was established, the burner would be turned down to the "low fire" setting with an offgas temperature of about 425°C. The actual performance seen is quite different from these conditions. During startup, the main chamber measured plenum temperature rises to about 800-900°C within about 32 hours, but the quencher inlet temperature only reaches about 200°C. All actual temperatures and flows (Table I) are less than the design values.

At Clemson, the typical operating vacuum in the melter was 25-75 Pa [0.1-0.3 inwc] compared to the design value of up to 1250 Pa [5 inwc]. The melter could have been operated at higher vacuums, but the variable throat venturi was always operated at the full closed position to avoid excessive heat losses from the melter via the offgas flow. When the melter vacuum was increased, it was difficult to maintain both the plenum temperature and the evaporation rate of water from the melter feed, even with the burner at the high fire setting. This heat loss problem was so substantial that during cold startup, inleakage at the packed bed cooler was increased (by opening a flange) to reduce the vacuum in the melter to about 5-12 Pa [0.02-0.05 inwc]. The melter air inleakage was reduced from about 680 m³/hr [400 scfm] to about 170 m³/hr [100 scfm] and resulted in an increased heatup rate in the melter plenum (Figure 2).

During normal operation (feeding or idling with joule heating), the quencher inlet temperature never exceeded 210°C even when the measured plenum temperature was as high as 1150°C. Figure 3 shows typical measured melter plenum and quencher inlet temperatures during operation at Clemson. The quencher inlet temperature does not track the measured melter plenum temperature. For these data, at low plenum temperatures, the melt pool had a covering of unmelted feed slurry or "cold cap"; at high temperatures, there was little or no cold cap, and the glass surface was at 1200°C or more. As is true in all melters, thermocouples in the plenum actually measure a combination of the actual gas temperature and a contribution from electromagnetic radiation "shine"; this effect results in the measured temperature being higher than the actual gas temperature. The data in Figure 3 indicate that the radiation contribution to the measured temperature may be as high as 600°C.

The design quencher inlet temperature was specified to be 426°C to prevent condensation of volatile salts in the offgas line prior to the quencher. However, it is not possible to maintain an offgas temperature this high with the current system. To maintain this temperature, an auxiliary burner or other heater would have to be added. The surrogate material used at Clemson did not have significant amounts of volatile salts, so we were unable to determine if salt deposition could be a problem.

At Clemson, the melter was typically operated at a vacuum of 5-12 Pa [0.02-0.05 inwc]; during surges in the melter feedrate or during feed line flushing, the melter occasionally became pressurized. For melters treating radioactive wastes, positive pressure excursions may result in the spread of contamination, so it was desirable to modify the melter to operate at a higher vacuum, thus giving more margin for pressure excursions. A number of simple modifications were made to the plenum of the melter main chamber, especially where the feed tube entered. The results of these changes were a decrease in the air inleakage into the main chamber plenum, an increase in the normal operating vacuum to 250-375 Pa [1.0-1.5 inwc], and an increase in the plenum temperature. Table II summarizes these improvements (including estimated air inleakage locations).

Prior to these improvements, the maximum glass production rate was limited by the maximum feedrate to 50 kg/hr [110 lb/hr], compared to the design rate of 68 kg/hr [150 lb/hr]. After these improvements, the glass production rate was increased to 86 kg/hr [190 lb/hr].

Sometimes, fixing one problem creates another. The air inleakage into the glass and salt drain chambers was increased when the air inleakage into the main chamber was decreased. This increase made it so difficult to heat up the glass drain chamber during startup that the offgas line from this chamber had to be blocked to reduce the heat losses. Once at normal operating temperature, the heat losses did not affect glass pouring from this chamber; however, the required energy input to maintain temperature was increased. This is because the induced draft fan operates in a region of the fan curve that maintains essentially constant flow at any inlet vacuum, so reducing the inleakage to the glass and salt drain chambers would only redistribute the inleakage back to the main chamber and increase the operating vacuum. Because of these problems, a variable frequency drive (VFD) has been installed on the two-stage induced draft fan to allow us to operate it at lower speeds. Limited initial testing has shown that the melter can be easily operated at a lower vacuums with less overall inleakage. Operation with the VFD may also result in an increase in the maximum glass production rate.

SURROGATE WASTE AND GLASS COMPOSITIONS

The glass system selected for the B&C Pond Sludge waste is the Soda-Lime-Silica (SLS) glass system. SLS is the glass system of choice for wastes that contain high levels of calcium (lime). Additionally, SLS glass is known to readily incorporate heavy metals. The target glass composition is formulated to attain the optimum glass product and processing characteristics. Important glass product characteristics include chemical durability, homogeneity and thermal stability. The processing characteristics include viscosity, liquidus, metals volatility, melting temperature, melt corrosivity and waste solubility. Chemical durability is critical since it is the parameter associated with controlling the release of the hazardous metals and radionuclides from the glass to the environment.⁴

To properly assess these characteristics, accurate compositional data is required, including information on the variation in composition of the waste. Compositional data must be complete; analyses must include all components for proper glass formulation. Minor components can have an adverse effect on glass properties or processing. Often overlooked are components that are not identified as hazardous by RCRA, but nonetheless have a significant effect on the glass. Example components are polymers, carbon, halides, sulfates, and phosphates. Also, analyses by standard EPA methods (such as SW-846)⁵ will not identify all components (such as silicon, which has a great effect on the glass as it is a major component of most glasses).

The surrogate waste was formulated to simulate Oak Ridge K-25 B&C Pond Sludge waste. The composition of the this surrogate waste is shown in Table III. The glass forming region for SLS glass is well known and is shown in Figure 4. SLS glass is well understood since it has long been used for consumer products (e.g., beverage bottles and windows). The extended glass forming region for glasses containing other alkali metals such as potassium and lithium is also shown in Figure 4. The composition of the surrogate waste, if melted by itself, would be on the edge of the extended glass forming region. To ensure an acceptable glass, the surrogate waste was blended with silica (SiO_2), lithium carbonate and sodium carbonate to move the composition closer to the center of the known SLS glass forming region. The target glass composition is shown in Table IV.

The durability of the glass product was measured with the EPA Toxicity Characteristic Leaching Procedure (TCLP)⁵ and was found to meet the EPA Universal Treatment Standards (UTS).^{6,7,8} Table V summarizes the TCLP results and compares them to the UTS limits.

The formation of crystalline compounds in glass may negatively impact glass durability as well as create compounds that have melting temperatures higher than the maximum melter temperature. Crystallization of the glass, often called devitrification, occurs if the glass passes through a region of thermal instability during cooling of the glass. The likelihood and extent of crystal formation is dependent on the glass composition and the crystallization kinetics. The temperature region conducive to crystal formation is below the liquidus temperature and well above ambient temperatures as shown in Figure 5. If the glass can be cooled quickly and the region of thermal instability avoided, devitrification will not be a problem.

The glass containers used are square stainless steel boxes that are divided into quadrants. One of the containers filled during surrogate testing was sectioned and examined for devitrification. This container was fitted with a series of thermocouples to monitor the glass temperatures throughout the container as the glass cooled. Examination indicated limited areas of devitrification. Small amounts of crystalline materials were found at the interface of glass and the metal box and larger amounts were found around the stainless steel thermocouples. Although some devitrification occurred, the crystalline material passed the TCLP test. In future operations, the boxes will be periodically rotated from one quadrant to the next to accelerate the cooling rate.

Devitrification was also a concern during shutdown of the melter. If the glass devitrified during cooldown, the crystals formed could have a higher melting point than the maximum melter temperature; if enough crystallization occurred, it could be possible that the melter could not be restarted unless the devitrified material was removed. At the time of shutdown, three melter volumes of surrogate had been processed. Simulated cooldown tests with glass samples taken during surrogate processing indicated that devitrification may occur at three melter volumes of surrogate. These tests indicated that devitrification would be less likely at a lower content of surrogate, so the melter was flushed with 1.5 melter volumes of SLS bottle glass. Addition of this amount of

SLS glass brought the melter glass composition back to near the concentrations that existed prior to the previous startup. The crystalline phase seen in these tests is suspected to be Wollastonite (calcium silicate).

PARTICULATE AND METALS EMISSIONS

Particulate and metals emissions were measured during the testing using EPA Method 29. The metals of interest included six toxic metals (Cr, Cu, Pb, Ni, P, Mn) and seven additional metals (Al, Ce, Fe, Li, Mg, K, Na, Ti). Although these additional metals are not part of Method 29, the method does provide a way to semi-quantitatively monitor their emission. The other toxic metals covered by Method 29 were not present in the surrogate waste. The mass average retention of the metals in the glass was 99.96 wt%. The metals, listed from lowest to highest percent retention in the glass are shown in Table VI. The retention in the glass combined with the removal in the offgas system is also given. The retention in the glass of toxic metals ranged from a high of 99.978 wt% for Mn to a low of 99.761 wt% for Cr. 99.3 wt% of the metals were collected on the front end (on filter and upstream of the filter) of the Method 29 sample train.

Total particulates were also measured as part of Method 29. The particulates exiting the melter and entering the offgas system, as a fraction of all solids fed to the melter, was 0.036 wt% (percent retention of 99.964 wt%).

CONCLUSIONS

Although the TVS had a number of initial design flaws, the system has been modified and upgraded to meet most of the original design parameters. Most major feed and offgas system problems have been alleviated. The system was successfully demonstrated with surrogate waste at both Clemson ESED and at ORR. Glass production rates, glass quality, as measured by the TCLP test, and offgas emissions were all better than the acceptance criteria.

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Table I
TVS Offgas System Design and Typical Actual Conditions

Startup Mode	Melter*	Quencher Inlet	Venturi Inlet	Entrainment Separator Outlet	Stack
Flow (std. m ³ /hr)	-	1041	1920	1925	1925
Flow (m ³ /hr)	-	5272	2552	2983	2781
Vacuum (Pa)	1250	1250	2700	17000	0
Water Content (vol%)	-	10	51	51	51
Temperature (°C)	1100	1093	82	78	122
Normal Mode					
Flow (std. m ³ /hr)	-	1041	1325	1329	1329
Flow (m ³ /hr)	-	2700	1702	1983	1918
Vacuum (Pa)	1250	1250	2700	17000	0
Water Content (vol%)	-	10	29	29	29
Temperature (°C)	-	426	68	65	122
Clemson					
Flow (std. m ³ /hr)	680	930-1020	1100-1190	1100-1190	1100-1190
Flow (m ³ /hr)	-	1530-1610	-	1340-1440	1440-1530
Vacuum (Pa)	25-75	250-500	750-1250	20000-22400	0
Water Content (vol%)	-	5	-	18	18
Temperature (°C)	400-600	140-210	-	55-60	90-100
Oak Ridge					
Flow (std. m ³ /hr)	680	930-1020	1100-1190	1100-1190	1100-1190
Flow (m ³ /hr)	-	1530-1610	-	1340-1440	1440-1530
Vacuum (Pa)	250-375	500-750	1000-1500	20000-22400	0
Water Content (vol%)	-	5	-	20	20
Temperature (°C)	650-800	100-200	-	55-65	90-100
* Flow is air inleakage std. conditions = 1.01325 kPa, 273.16 K					

Table II
Improvements in Melter Operation

	Clemson	Oak Ridge
Measured Melter Plenum Temp. (°C)	400-600	650-800
Measured Melter Plenum Temp. (°C)	<1000 ^a	>1150 ^b
Main Chamber Air Inleakage (std. m ³ /hr)	475	135
Salt + Glass Chamber Air Inleakage (std. m ³ /hr)	205	545
Glass Production Rate (kg/hr)	50	86
Melter Feedrate @ 50 wt% solids (m ³ /hr)	0.086	0.150
	^a burner at high fire	
	^b burner at low fire	

Table III
Composition of Surrogate B&C Pond Sludge Waste

Reagent	Weight Percent (dry basis)	Element	Weight Percent (dry basis)	Oxide	Weight Percent (dry basis)
Al ₂ O ₃	4.74	Al	2.51	Al ₂ O ₃	5.63
		C	10.9		
CaCO ₃	32.8	Ca	13.2	CaO	21.9
CaO	0.0596				
CeCl ₃ •7H ₂ O	0.241	Ce	0.0907	Ce ₂ O ₃	0.126
Cr(NO ₃) ₃ •9H ₂ O	0.215	Cr	0.0279	Cr ₂ O ₃	0.0485
Cu(C ₂ H ₃ O ₂) ₂ •2H ₂ O	0.0940	Cu	0.0256	CuO	0.0381
Fe ₂ O ₃	6.74	Fe	4.72	Fe ₂ O ₃	8.02
KOH	0.950	K	1.38	K ₂ O	1.98
K ₂ O	0.870				
MgO	0.718	Mg	0.433	MgO	0.853
MnO ₂	0.617	Mn	0.390	MnO ₂	0.367
(NaPO ₃) ₆	1.08	Na	0.260	Na ₂ O	0.417
Na ₂ O	0.0215				
Ni(NO ₃) ₃ •6H ₂ O	0.854	Ni	0.172	NiO	0.261
		O	42.1		
P ₂ O ₅	0.0119	P	0.334	P ₂ O ₅	0.910
Pb(C ₂ H ₃ O ₂) ₂ •3H ₂ O	0.0382	Pb	0.0209	PbO	0.0267
SiO ₂	49.4	Si	23.1	SiO ₂	58.7
TiO ₂	0.584	Ti	0.350	TiO ₂	0.695

Table IV
Glass Composition

Element	Wt %	Oxide	Wt %
Al	1.532	Al ₂ O ₃	2.89
Ca	8.04	CaO	11.2
Ce	0.0554	Ce ₂ O ₃	0.0648
Cr	0.0171	Cr ₂ O ₃	0.0249
Cu	0.0156	CuO	0.0196
Fe	2.88	Fe ₂ O ₃	4.12
K	0.845	K ₂ O	1.02
Li	3.35	Li ₂ O	7.21
Mg	0.264	MgO	0.438
Mn	0.238	MnO ₂	0.188
Na	5.40	Na ₂ O	7.28
Ni	0.105	NiO	0.134
O	46.7		
P	0.204	P ₂ O ₅	0.468
Pb	0.0127	PbO	0.0137
Si	30.2	SiO ₂	64.5
Ti	0.213	TiO ₂	0.357

Table V
TCLP Results for Glasses Produced
(mg/L)

Metal	Measured Values		UTS Limits
	Minimum	Maximum	
Ba	<0.01	0.08	7.6
Cd	<0.01	<0.01	0.19
Cr	<0.02	0.85	0.86
Ni	<0.01	1.02	5.0
Pb	<0.10	0.10	0.37

Table VI
Metals and Particulate Carryover to the Offgas System

Metal	Retention in Glass (wt %)	Feed Offgas Mass Ratio	Retention in Glass + Offgas System (wt%)	Feed Stack Mass Ratio
Cr	99.761	419	99.940	1680
Pb	99.857	701	99.991	11292
K	99.893	932	99.973	3757
Al	99.901	1007	99.965	2872
Na	99.926	1354	99.987	7792
Cu	99.943	1763	99.971	3467
P	99.952	2100	99.998	49379
Ce	99.960	2496	99.998	55220
Ni	99.961	2567	99.987	7563
Ca	99.965	2860	99.998	50734
Mg	99.967	3051	99.993	14062
Fe	99.974	3908	99.998	42951
Ti	99.975	4077	99.997	36829
Mn	99.978	4607	99.999	105564
Li	99.979	4808	>99.999	703304

Particulate Mass Flow Rate (g/hr)	23.5
Carryover as Percentage of Feed Solids	0.036
Percent of Feed Solids Retained in Glass	99.964

Figure 1. Transportable Vitrification System

Figure 2. Temperatures During Startup

Figure 3. Melter Plenum and Quencher Temperatures

Figure 4. Ternary Phase Diagram for Soda-Lime-Silica Glasses

Figure 5. Typical Glass Time-Temperature-Transition Diagram