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Beneficial Reuse of Vitrified Dredged Estuarine Sediments - Phase III Final Report

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LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BNFL	British Nuclear Fuel, Ltd.
C/F	Coefficient of Friction
EPA	United States Environmental Protection Agency
FT/ES	Futuristic Tile / Environmental Stone, LLC (Allenton, WI)
LLC	Limited Liability Company
Mg	Metric tonne (1000 kg)
MO_x	Metal Oxides
MPRSA	Marine Protection Research and Sanctuaries Act
NY/NJ	New York / New Jersey
PAH	Polyaromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
RCRA	Resource Conservation and Recovery Act
SEM	Scanning Electron Microscopy
SRL	Savannah River Laboratory (Aiken, SC)
STD	(Westinghouse) Science and Technology Department
TCLP	Toxicity Characteristic Leaching Procedure
WEC	Westinghouse Electric Company, LLC (Pittsburgh, PA)
WPC	Westinghouse Plasma Corporation, LLC (Madison, PA)
WPTC	Westinghouse Plasma Test Center (Madison, PA)
WRDA	Water Resources Development Acts of 1992 and 1996
WSTC	Westinghouse Electric Corporation Science and Technology Center (Pittsburgh, PA)

ABSTRACT

Estuarine sediments are commonly contaminated with organics and heavy metals from industrial and urban wastes, which poses a difficult disposal problem for harbor dredging. One approach to decontamination of such sediments is vitrification using a non-transferred arc plasma torch. This process converts pretreated sediment to glass aggregate, which then may be used for a variety of beneficial purposes. The current report describes demonstration testing of 4 Mg of pretreated New York/New Jersey Harbor sediment, vitrifying the sediment into a coarse glassy aggregate, and then converting the aggregate into sintered architectural tile. The plasma vitrification process effectively decontaminates the sediment, destroying nearly quantitatively any organic species while immobilizing heavy metals in a low-leachability glass matrix, as tested by the EPA's TCLP procedure. Conversion to tile provides an economically attractive beneficial reuse, where sale of the finished product can partially or completely offset the cost of high-temperature thermal processing. Mechanical testing demonstrates that tile produced in this way is of high quality. Plans are now under development for installing a demonstration-scale facility at the New York/New Jersey Harbor to process sediment and produce tile for commercial sale.

EXECUTIVE SUMMARY

Contaminated harbor sediments pose a difficult environmental challenge. To maintain access to shipping ports, very large volumes of sediment must be dredged and subsequently disposed of. Historical disposal methods such as ocean disposal have become increasingly difficult in recent years as the result of environmental regulations related to the level of potentially bioaccumulative contaminants typically found in industrial and coastal harbors and estuaries. New York/New Jersey Harbor, for example, can no longer use the offshore Mud Dump Site for sediment disposal, largely due to the presence in the sediment (albeit at low concentrations) of such contaminants as polychlorinated biphenyls, dioxins, furans, pesticides, polycylic aromatic hydrocarbons, and heavy metals. Roughly four million cubic yards of sediment must be disposed of annually from the New York/New Jersey Harbor to maintain the shipping channels, and so identification of alternative means of sediment disposition represents an urgent need.

The United States Environmental Protection Agency (EPA) Region 2, and the U.S. Army Corps of Engineers (USACE) New York District, through an appropriation from the Water Resources Development Acts of 1992 and 1996 (WRDA), has supported a program to develop and demonstrate such technology, administered by the Department of Energy Brookhaven National Laboratory (BNL). The Westinghouse Electric Corporation Science and Technology Center (WSTC) proposed technology for converting contaminated sediment into environmentally benign glass, by exposure of the sediment to the extreme temperatures found in the plume of a plasma torch. In this process, organic contaminants are quantitatively destroyed, and the final glass effectively binds heavy metals into a highly leach-resistant matrix. The glass material may then be used for a variety of beneficial applications such as vitreous architectural tile, sandblasting grit, roofing granules, insulating fiber, and roadbed aggregate.

The EPA program proceeded through three phases. In Phase I, WSTC characterized the sediment, including contaminant loading, mineralogy, and particle size distribution. Additive compositions were then developed to prepare a glass having good processing properties and low leachability. A bench kilogram-scale test of sediment vitrification was also carried out in a melting furnace, demonstrating the potential effectiveness of the process. A preliminary heat and material balance was also prepared to estimate the processing cost.

In Phase II, seventeen metric tonnes (Mg) of contaminated New York/New Jersey (NY/NJ) Harbor sediment were converted into glass in several campaigns at the Westinghouse Plasma Test Center pilot facility in Madison, PA. The glass product was subjected to detailed chemical and leachability analyses for both organic and inorganic contaminants. Results indicated greater than 99.9999% destruction of target organic species, and production of a low leachability of the glass product which passed the EPA's TCLP test by several orders of magnitude. The pilot plant data were then used to refine the plant flowsheet, and to develop a preliminary plant design and cost analysis for a facility to process 100,000 yd^3/yr (92,200 Mg/yr) of NY/NJ Harbor sediment. The overall material balance for the process is shown in Figure A. Depending on the cost of electricity (rates between 3¢/kWh and 5¢/kWh were assumed in this study), a gross processing cost for converting as-dredged sediment into granulated glass was found to be \$85 to \$112/yd^3. Assuming a tipping fee of \$50/yd^3 currently paid for sediment disposal from the NY/NJ Harbor area,* the anticipated processing cost after credit for the tipping fee then becomes \$35 to \$62/yd^3.

Obviously, this cost is substantially higher than for competing low-temperature processes such as solid stabilization and synthetic soil. For that fraction of the Harbor sediment where the contaminant level is low, less aggressive and lower cost alternatives make sense. However, for more highly contaminated

* Note that current disposal costs may range from \$35 to \$50 per cubic yard.

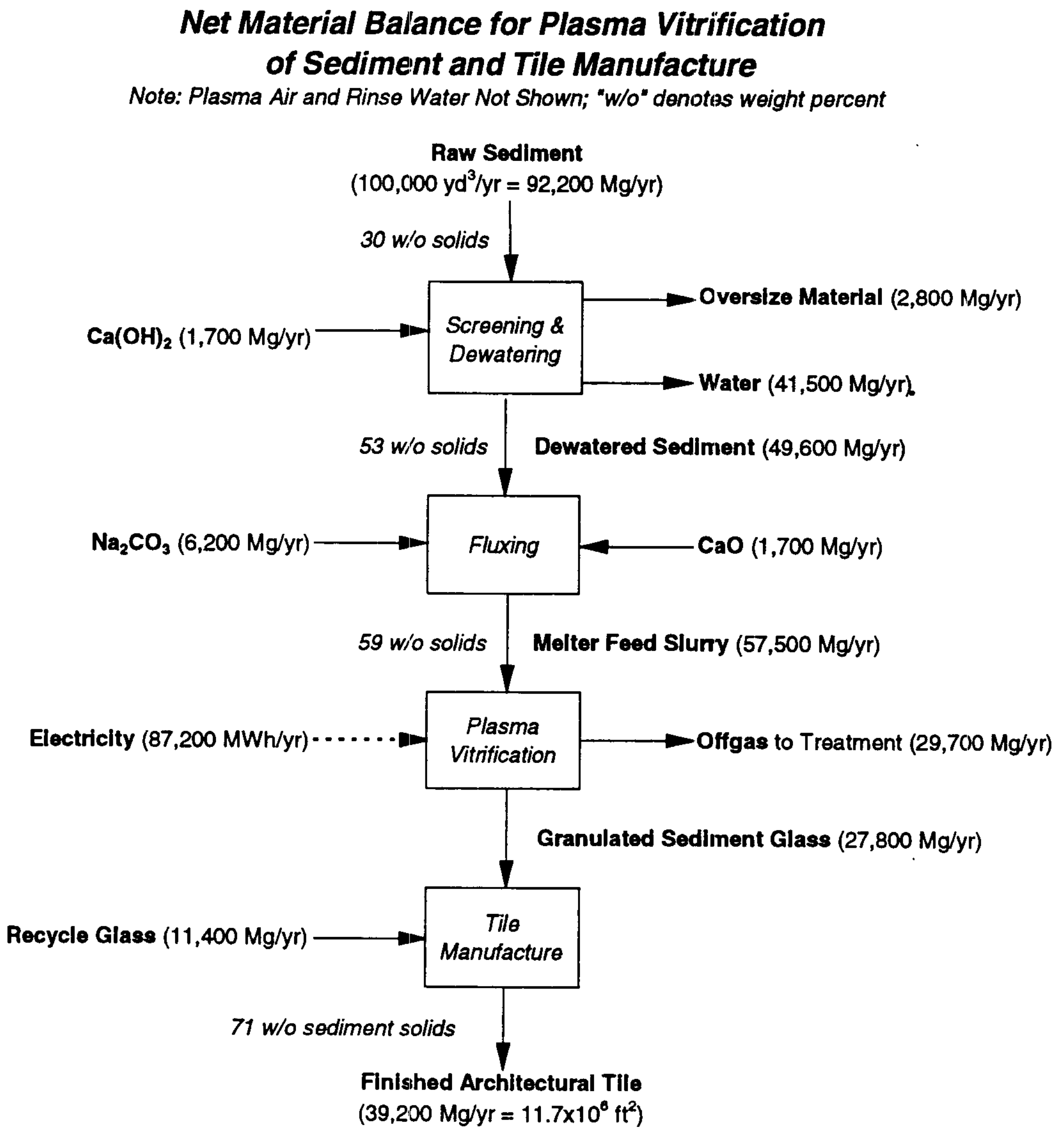

Figure A - Material Balance for a 100,000 yd^3/yr Sediment Vitrification Plant

material, these alternative processes may not be environmentally acceptable, and a highly effective but higher cost thermal process such as plasma vitrification becomes appropriate. In addition, lower-cost approaches such as stabilization generate a low-value product, which may be useful only for fill, landfill capping, or manufactured topsoil. The glass material produced by plasma vitrification can be inexpensively converted into high-value, resalable products such as architectural tile, which can partially or completely offset the higher treatment cost.

Phase III of the program consisted of a large scale demonstration of architectural tile production from sediment-derived glass. In partnership with Futuristic Tile/Environmental Stone (FT/ES) of Allenton, WI, an additional 2.5 Mg of sediment were converted first to glass, and then the glass fabricated into finished floor tile. The sediment glass formed the structural base layer of the tile, while the top finish layer was produced from recycled bottle glass using proprietary Futuristic Tile technology. Testing of the tile using accepted ASTM procedures showed it to be equal or superior in all respects to the recycle-glass vitreous tile currently marketed commercially by Futuristic Tile.

The current market for vitreous tile is large, and revenues from sale of tile are predicted to more than offset both the cost of sediment treatment and tile manufacture. Typical wholesale prices for tile are $1.25/ft^2. On this basis, revenue from tile produced by treatment of 100,000 yd^3 of as-dredged sediment (see Figure A) would be $14,600,000, or $146/yd^3. This figure is greatly in excess of the estimated sediment vitrification costs ($35 to $62/yd^3). While the actual cost of tile manufacture by the FT/ES process is proprietary, the potential is clear for profitable operation of the integrated process.

The next phase of development will be commercialization of the process. The Westinghouse plasma business was divested in April 1999, to the Westinghouse Plasma Corporation (WPC). The Westinghouse Plasma Corporation plans to continue the effort to commercialize this technology, in collaboration with Futuristic Tile/Environmental Stone.

1. INTRODUCTION

Many of the major harbors in the United States have become contaminated with a wide variety of contaminant chemicals as the result of historical and present industrial discharge, sewage, and spills from commercial ship traffic. Since routine dredging of many of these harbors is required to allow access to modern deep-draft commercial shipping, large quantities of contaminated sediments must be removed from the harbor bottoms and subsequently dealt with. Disposal of dredged materials was once a technologically simple process of offshore hauling and disposal in deep coastal waters, although the process was controlled by a testing and regulatory process. This procedure has become increasingly complex due to more rigorous and stringent testing protocols governing ocean placement.

1.1 DREDGING ISSUES IN THE NEW YORK/NEW JERSEY HARBOR

In the specific case of the New York/New Jersey Harbor (see Figure 1.1), ocean disposal at a location southeast of the harbor (the Mud Dump Site) has been the primary alternative for sediment disposal since 1977. These sediments consist of a mixture of fine sand and silt, with some natural organic material. Contaminants (both organic and inorganic species) are ubiquitous, however. The U. S. Environmental Protection Agency (EPA) 1994 Contaminated Sediment Management Strategy has defined contaminated sediments as those materials "which contain chemical substances at concentrations which pose a known or suspected threat to aquatic life, wildlife, or human health." Much of the sediment quality in the Harbor is poor, due to pollutant inputs from the Hudson, Hackensack, and Passaic River watersheds, from atmospheric deposition, and from wastewater discharges (both industrial and domestic), and from combined sewer overflows.

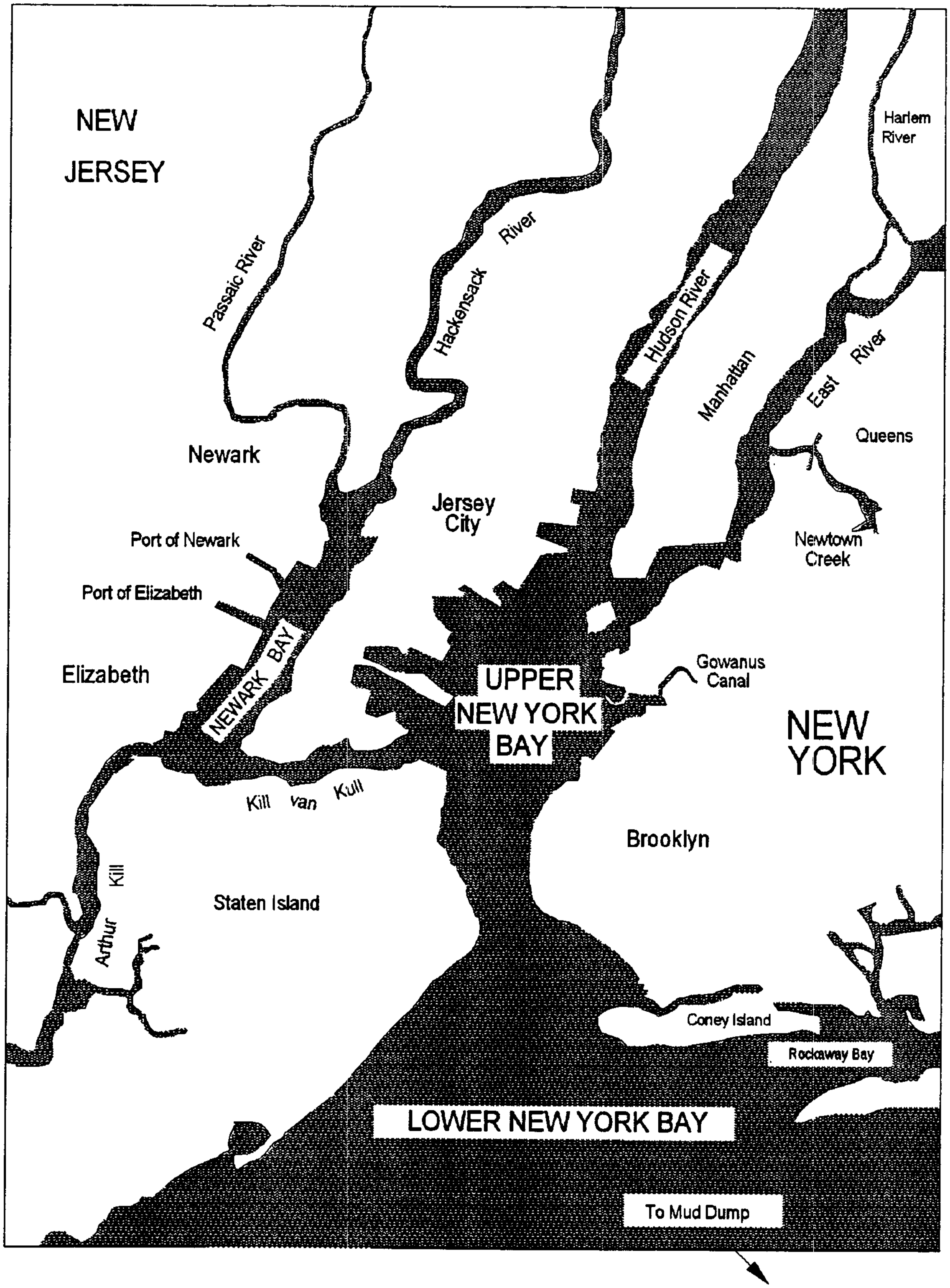

Figure 1.1 - New York/New Jersey Harbor

Although much progress has been made in the reduction of point sources of new pollutants, large inventories of industrial residues still exist as non-point sources which feed into the Harbor.

Sediments have been classified since 1977 by the Marine Protection Research and Sanctuaries Act (MPRSA) according to their degree of contamination. Preliminary estimates in 1977 indicated that up to 40 percent of New York/New Jersey sediments would classify as MPRSA Category III (the highest level of contamination), and would not be permissible for ocean dumping (although most if not all of the sediment does not qualify as EPA Hazardous Waste when considered for land disposal). The presence of dioxins and furans is especially difficult to deal with because of stringent bioaccumulation regulations. Since September of 1997, the Mud Dump Site has been closed to further disposal except for Category I or unrestricted dredged material.

Agencies responsible for Harbor management are therefore faced with rapidly escalating costs to maintain harbor access, since sediments must be disposed of by some alternative (and invariably more expensive) procedure. Options include:

- Disposal within the Harbor in subaqueous pits, which is allowed within environmental regulations, but is politically sensitive.
- Landfilling, with cost and containment appropriate to the level and type of contamination based on New Jersey and New York regulations. The large volume of material to be disposed of, the costs of landfill construction and maintenance, and the general unavailability of suitable land near urban New York City, all make this approach very expensive.
- Stabilization by addition of some additive such as cement to reduce contaminant leaching, followed by on-land surface disposal. This approach provides some degree of beneficial use, since stabilized sediment may be used for land development applications such as filling spent mines or capping of industrial "brownfield" sites.

- Disposition by some alternative technology, preferentially including use for some beneficial purpose to partially or completely defray the cost of decontamination, and to obviate the need for waste disposal.

Decontamination of harbor sediments is complicated by the *very* large volume of sediments involved (roughly four million cubic meters annually in the case of the New York/New Jersey Harbor), and the complex suite of organic and inorganic contaminants which may be present. Sediment from NY/NJ Harbor contains low concentrations of a wide variety of heavy metals (including Ag, Cd, Cr, Ni, Pb, Sb, Se, Tl, Be, As, Hg, and Zn). Any effort to decontaminate the sediment must therefore contend with removal of a diverse range of inorganic chemical species of widely varying oxidation state, chemical solubility, high-temperature volatility, and concentration.

Sediments also contain an even broader range of organic compounds including pesticides from farmland runoff, hydrocarbons from oil spills, industrial solvents, polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dioxins, and furans. These compounds range from easily extracted or thermally desorbed light hydrocarbons to very stable and essentially nonvolatile dioxins. The wide spectrum of physical-chemical properties of these organic species make both thermal and chemical extraction processing challenging. Pathogenic microbiological agents such as *pseudomonas*, *streptococcus*, *clostridium*, and fecal *coliform* may also be present, further complicating handling and treatment.

1.2 THE WESTINGHOUSE PLASMA DECONTAMINATION PROCESS

Given the challenge of designing a process for physically or chemically separating all of these anthropogenic contaminants from the vastly larger body of natural mineral sediment, an alternative process for sediment decontamination was investigated and developed by Westinghouse Electric Corporation Science and Technology Center (WSTC). This process provides for near-quantitative destruction of organic and microbiological contaminants, immobilization of heavy metals, and conversion of the sediment into a high-quality glass material suitable for a variety of beneficial uses, specifically including production of architectural tile.

The process is based on Westinghouse non-transferred-arc plasma torch technology. Air is passed through the electrodes of the torch, superheating it to temperatures approaching 5000°C. Harbor sediment, screened and partially dewatered, is injected into the plume of the torch, heating it extremely rapidly. All organic species are combusted and destroyed, even refractory organics such as dioxins. The mineral phases in the sediment are heated to the melting point, and fuse into a homogenous glassy liquid. Fluxing agents such as lime and soda ash may be added to adjust the viscosity of the final melt. The molten glass is then quickly cooled (quenched) with air or water to maintain the vitreous characteristics, incorporating and trapping heavy metals in the glass matrix into a highly leach-resistant composite. The final quenched glass product is then suitable for a wide variety of applications, ranging from low-value products such as road aggregate and sandblasting grit, to high-value products such as glass fiber or sintered architectural tile.

1.3 THE ESTUARINE SEDIMENT DECONTAMINATION PROGRAM

This development effort was supported by the United States Environmental Protection Agency (EPA) Region 2, and the U. S. Army Corps of Engineers (USACE) New York District, through an appropriation from the Water Resources Development Acts (WRDA) of 1992 and 1996. The program was administered through the U. S. Department of Energy (DOE) Brookhaven National Laboratory (BNL).

The program proceeded through three phases. In Phase I, started in August of 1995, small samples of sediment from the Newtown Creek, NY site, located off the East River (see Figure 1.1) were provided to Westinghouse for evaluation. Assays were carried out for mineral composition, solids content, heating value, density, viscosity, particle size distribution, and contaminant analysis (both organic and heavy metal). A formulation was developed for flux addition to produce glass of the desired viscosity and thermal expansion coefficient.

Coupon testing was carried out by the Westinghouse Savannah River Laboratory (SRL) to verify the predictions of the theoretical models, whereby one formulation was selected based on glass properties and optimal economics (high sediment loading, minimization of higher-cost fluxes). Larger, kilogram-scale quantities of the glass were then fabricated by Ferro Corporation in Cleveland, OH. These larger samples were tested for environmental performance, and were found to pass the TCLP test by orders of magnitude for all RCRA heavy metals. A preliminary plant flowsheet was developed, and heat and material balances performed.

The final component of the Phase I program was a proposal for Phase II pilot scale testing at the Westinghouse Plasma Test Center (WPTC). These tests were carried out between July and December, 1996. A total of 15.9 metric tonnes (Mg) of Newtown Creek dredged sediment were delivered to WPTC. Westinghouse teamed with Sevenson Environmental of Niagara Falls, NY to develop a sediment pretreatment process, consisting of pumping, settling, salt removal, dewatering, and blending of flux into a viscous slurry suitable for transfer to the plasma melter. Pretreatment generated 13.6 Mg of melter feed, about one-third of which was converted to glass during the final Phase II test on December 5, 1996.

Based on results developed during Phase II testing, a preliminary plant design was generated, including utility requirements, specification of all major plant equipment, and capital and operating cost estimates. The resulting material balance indicated only two small waste streams leaving the plant which would require disposal, namely (1) oversize debris which could not be conveniently vitrified, but which would be washed and substantially decontaminated, and (2) a small calcium sulfate solid waste stream arising from sulfur control in the melter offgas. Allowing credit for a tipping fee of $\$50/yd^3$, the net processing cost for the sediment was estimated to be between \$35 and $\$62/yd^3$, with the principal variable being the cost of electricity.

Beneficial use options for the decontaminated sediment were also investigated during Phase II. A broad range of options were assessed, including:

- Sandblasting grit, similar to Black Beauty®, a registered trademark of Reed Minerals (a division of Harsco Corporation)
- Roadbed aggregate
- Roofing granules
- Replacement glass cullet for reformulation into glass products
- Filler material for artificial onyx bathtubs and similar fixtures
- Rock wool insulating fiber
- Vitreous architectural tile

The product having the most attractive preliminary market and economics was architectural tile. Three major types of ceramic tile are currently marketed, low-grade wall tile, high-grade wall tile, and floor tile; each grade has different requirements for abrasion resistance and water absorption. The least expensive tile is composed of talc ($3MgO \bullet 4SiO_2 \bullet H_2O$), ball clay, and wollastonite ($CaO \bullet SiO_2$); sediment glass could readily substitute for natural talc, yielding an estimated product credit of up to $\$156/yd^3$. Higher grade tiles use feldspar ($Al_2O_3 \bullet 6SiO_2 \bullet K_2O$) in place of talc for increased resistance to water absorption. Substitution of sediment glass for feldspar potentially increases the product credit to $\$230/yd^3$.

The tile market is also favorable, with approximately 75% of all ceramic tile being consumed by new construction. Demand should be high in the New York City urban area, providing a local market requiring minimal transportation costs. At current production figures, a 500,000 yd^3/yr sediment decontamination facility could generate 196,000 Mg/yr of glass product (see Figure 4.7), equivalent to as much as 5% of the current ceramic tile market. Sale of sediment-derived tile does not depend on expansion of current demand, however. Vitreous tile is viewed as a high-quality, low-cost substitute for current higher-cost tile products, so that impact on the total tile market demand would be minimized as vitreous tile replaced other lower-quality or higher-cost products.

Phase II marketing studies therefore concluded that conversion of vitrified Harbor sediment to vitreous architectural tile provided a vehicle for partially or completely offsetting the cost of sediment decontamination, and could almost completely eliminate the need for waste disposal of process residuals. A Phase III program was therefore proposed, to demonstrate production-scale conversion of vitrified sediment into tile product. For this purpose, Westinghouse partnered with Futuristic Tile/Environmental Stone (FT/ES) of Allenton, WI, who have proprietary technology for production of vitreous tile from recycled waste glass. The current report describes the results from this Phase III effort, including vitrification of the remaining WPTC sediment inventory, and tile production and qualification testing at FT/ES.

The next phase of development will be commercialization of the process, as summarized in the Executive Summary of the current document. Since completion of Phase III testing, the plasma technology business has been divested as the Westinghouse Plasma Corporation (WPC), formed in April, 1999. The Westinghouse Plasma Corporation plans to continue efforts to commercialize this technology, in collaboration with Futuristic Tile/Environmental Stone. Current scoping efforts by WPC and FT/ES are considering the design throughput capacity for this plant for optimum demonstration-scale economics. The schedule for implementation has not yet been defined, but is under consideration as well.

2. CONCLUSIONS AND RECOMMENDATIONS

2-1. Demonstration of Overall Process Technical Viability - Phase III testing has demonstrated the large-scale technical feasibility of converting vitrified harbor sediment (with organic contaminants nearly quantitatively destroyed and RCRA heavy metals immobilized) into commercial paving and wall tile. Phase III converted 4,980 kg of pretreated fluxed sediment (55% solids) into 1,810 kg of vitrified sediment aggregate at the Westinghouse Plasma Center. This material was then converted into approximately 4,200 kg of finished tile (average 43% sediment glass), using the commercial processing facilities of Futuristic Tile/Environmental Stone in Allenton, WI.

2-2. Tile Production Per Unit Sediment Processed: Phase III testing produced two-layer tile having a range of sediment glass content in the bottom layer, while the top layer and the balance of the bottom layer consisted of recycled bottle glass. Although the average sediment glass content in the average Phase III tile inventory was only 43%, test batches containing much higher sediment glass were successfully prepared. Based on these tests, commercial production with 71% sediment glass content is projected for Demonstration Plant operation.

2-3. Economic Tradeoffs with Respect to Flux Chemistry: Use of higher flux-to-sediment ratios will produce sediment glass having lower sintering temperatures, reducing both the residence time in the sintering furnace and the energy expenditure. The flux chemistry may also be altered to achieve the same effect, by increasing the sodium-to-calcium ratio in the flux. Both of these strategies increase chemical costs, but also allow tile to be prepared with higher sediment glass content. Optimization of the process economics for the integrated plasma-tile facility will be a task for the Demonstration Plant.

2-4. Scaling of the Process to Higher Throughputs: Both the plasma vitrification process and the tile manufacturing process are essentially modular, so that scaling to higher throughput involves installation of additional melting tuyeres or additional tile sintering furnace trains.

2-5. Evaluation of Tile Product Quality Made from Vitrified Sediment: A total of ten different product quality tests were run on samples of tile fabricated from vitrified New York/New Jersey Harbor sediment, including breaking strength, flexural strength, compressive strength, modulus of rupture, bonding strength, coefficient of friction, thermal shock resistance, freeze-thaw resistance, moisture absorption, and surface hardness.. Wherever appropriate, results from the Phase III tile testing were compared to ANSI standards for "Unglazed Paver's Tile". The sediment glass tile passed ANSI standards in all cases, and in most cases performed better than the recycled glass tile currently being manufactured and marketed successfully by Futuristic Tile/ Environmental Stone.

2-6. Variability in Product Quality with Quenching Procedure: It was found that molten glass quenched rapidly formed a fully vitreous, brittle aggregate, while melt allowed to cool slowly formed a very hard slag containing precipitated calcium silicate crystals. The vitreous material was found to have a lower sintering temperature and be more readily fabricated into tile; although both vitreous and slaggy phases were chemically identical in overall composition. Controlled cooling of the molten product will therefore be required for optimum tile processing, and will be designed into the Demonstration Plant.

2-7. Future Development of the Plasma-Tile Sediment Decontamination Process: Since the divestiture of the plasma business as the newly-formed Westinghouse Plasma Corporation (WPC), WPC will be responsible for developing applications of plasma technology, including this process. WPC plans to continue the effort to commercialize this technology, in collaboration with Futuristic Tile/Environmental Stone.

3. SEDIMENT VITRIFICATION OPERATIONS

Vitrification of the remaining Phase II inventory of pretreated sediment stored at WPTC (Test #4) was carried out on November 12, 1998. The Phase II final test report contains detailed discussion of the Test #3 results, including feed inventory, utility (plasma torch electrical power and compressed air) consumption, melter temperature and pressure profiles, heat losses, offgas compositions, and product accumulation. Detailed melter performance evaluation was not the goal of Test #4. Only a few summary results are therefore presented in this section.

3.1 PROCESS FEED

The overall feed composition is shown in Figure 3.1. The average feed (sediment plus flux) mixture was 55% weight water, 29% mineral oxides, 5% organics, plus 11% fluxes (CaO, $Ca(OH)_2$, and Na_2CO_3) . The solids content was slightly higher than that of the Test #3 feed, as shown in Table 3.1. The feed rate was also greater during Test #4. As a result, the energy requirement for melting (kJ per kg of glass) was roughly 10% less for Test #4 as compared to Phase II, Test #3. At the same time, the feed for Test #4 had a slightly higher flux content to reduce melt viscosity (79.8% sediment mineral oxide loading in the final glass, as compared to 83.2% for Test #3). This permitted higher sediment throughput at the same plasma torch power, since the pour temperature could be reduced somewhat while still maintaining a fluid composition.

A plot of sediment-flux feed versus time is presented in Figure 3.2. The feed rate is seen to be very uniform and linear, despite some difficulties once again encountered with the Graco drum pumps (one failed half way through the test; the

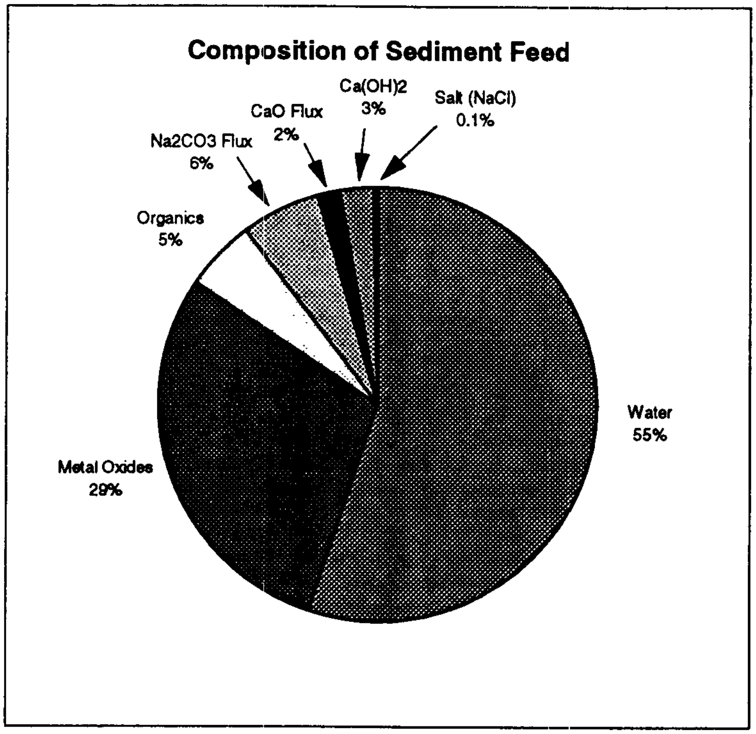

Figure 3.1 - Composition of Test #4 Sediment Feed Material

Table 3.1 - Summary of Operating Parameters for Tests #3 and #4

	Test #3 (Phase II)	Test #4 (Phase III)
Date of Test	December 5, 1997	November 12, 1998
Sediment Feed Processed (kg)	3,952	4,980
Feed Solids Content (%wt)	51.3 to 55.3	55.0
Glass Produced (kg)	1,604	1,810
Glass Sediment MO_x Loading (%wt)	83.2	79.8
Molten Glass Pour Temperature (°C)	1,396	1,331
Test Feed Duration (min)	445	447
Average Sediment Feed Rate (kg/hr)	533	668
Average Glass Production Rate (kg/hr)	216	243
Plasma Torch Power (kWe)	1,671	1,685
Plasma Torch Efficiency (kWt/kWe)	0.864	0.855
Energy Consumption (kJ/kg glass)	27,800	25,000
Air Feed Rate (slpm)	12,700	16,000

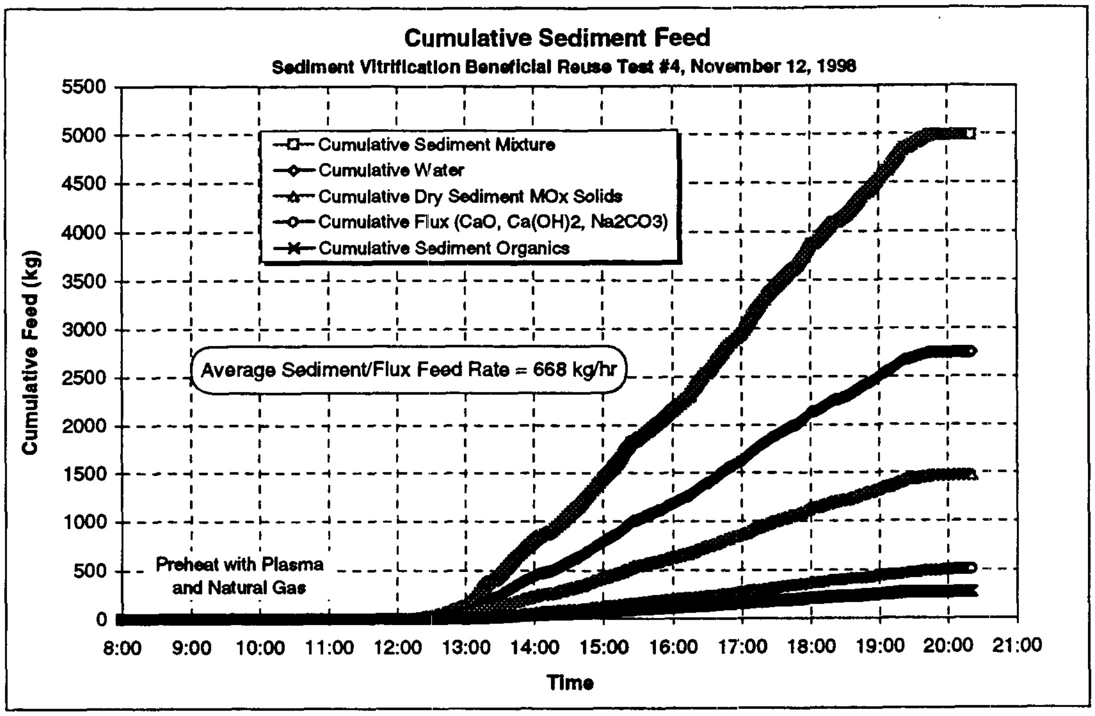

Figure 3.2 - Cumulative Feed Processed During Sediment Vitrification Test #4

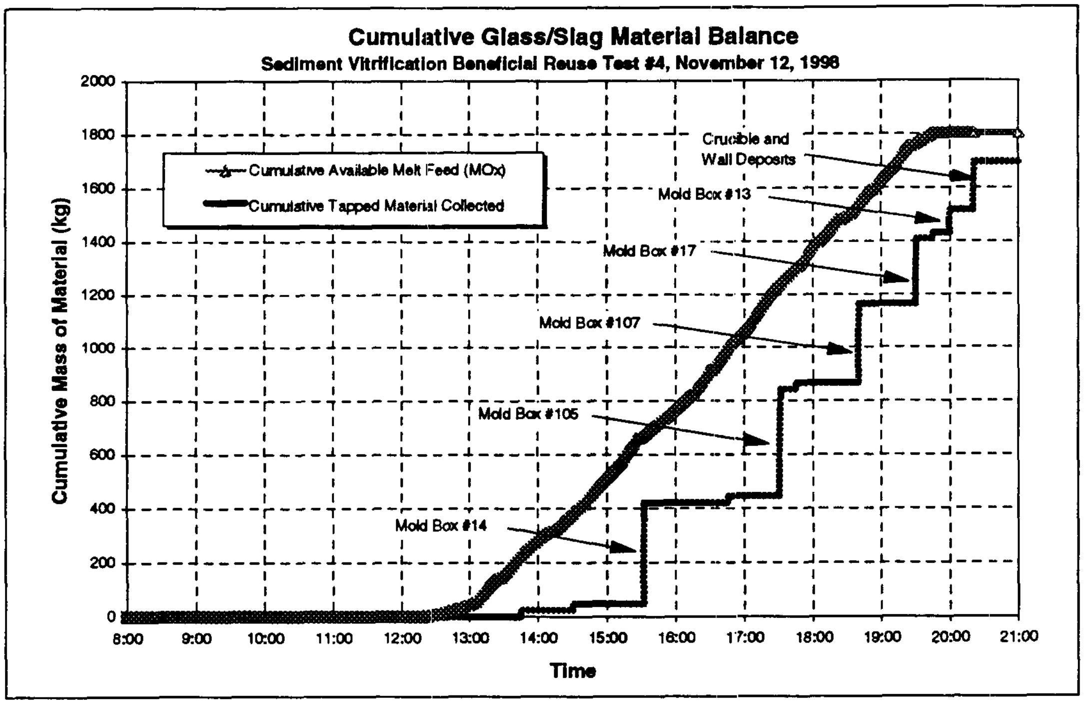

Figure 3.3 - Cumulative Product Collected During Sediment Vitrification Test #4

second failed with only 1½ drums of feed mix yet to be processed). Figure 3.3 presents the accumulation of molten product versus time. Five mold boxes were used, plus approximately 500 kg collected as water-quenched material throughout the test. Roughly 100 kg were left behind as glass coating on the melter walls.

3.2 PRODUCT QUALITY

Several interesting observations were made when the glass product was examined. Of the 1,800 kg of glass produced, approximately 500 kg was quenched directly into water in the molten state. Immediate granulation took place forming a fine-grained, black, lustrous glass, and the glass appeared to be fully vitreous except for occasional small specks of refractory material. The balance of the product was collected by pouring into steel mold boxes. As soon as a box had been filled, it was suspended from a fork lift and quenched with a fire hose, both on top of the molten material and on the exterior of the hot steel.

When the mold box contents were examined and removed, it was observed that the material on top of the box was brown-black and glassy similar to the water quenched material. Similarly, material in contact with the sides and bottom of the box which had been rapidly cooled with the fire hose was also glassy. However, roughly 4" in from the walls a transition occurred in which the black shiny glass changed to a dull, gray, rock-like morphology, not unlike steel mill slag.

Subsequent analysis of the mold box product by scanning electron microscopy (SEM) indicated that even at the boundary between the vitreous and slaggy phases the overall chemical composition remained constant. However, in the slaggy phase distinct very small crystals could be seen, composed of calcium silicate. The resulting material around the crystals was high in alumina (Al_2O_3), and depleted in calcia (CaO) and silica (SiO_2).

These observations suggest that the composition being melted is close to the boundary of the glass-forming regime. Rapid cooling preserves the vitreous, amorphous nature of the molten glass, while slow cooling allows precipitation of crystals, producing a slaggy material, and increasing the melting point of the calcia- and silica-depleted matrix. For applications such as roadbed aggregate, the higher mechanical strength and lower brittleness of the slaggy phase would be advantageous. However, differences in sintering behavior of the two phases (see Section 4.3) make the vitreous material far more desirable for tile manufacture. These results suggest that a commercial melting operation producing feed for tile manufacture will require rapid quenching of the molten glass, either in water or by another technique such as dry chilling through water-cooled rollers, in order to maintain a vitreous product. The latter approach is preferred, since water quenching will leave the granulated material wet, so that a drying step would be required prior to tile manufacture.

4. DEMONSTRATION OF TILE MANUFACTURING

4.1 TILE MANUFACTURING PROCESS

In February of 1999, approximately 1500 kg of granulated or crushed vitrified sediment were transferred to Futuristic Tile for conversion into architectural tile. The crushed material consisted of both "slaggy" and "glassy" material (as discussed in Section 3.2), but the two phases were segregated to assess the impact of feed morphology on tile processing. The overall process used by Futuristic Tile is shown in Figure 4.1.

Glass is provided to the process in two streams, one forming the bottom structural layer, and the second forming the top decorative layer. The bottom layer is formed by first crushing the feed material (either recycled glass, vitrified sediment, or a mixture of the two) to a particle size 4 mm or less. The crushed material is screened, and oversize material returned for recrushing.

The commercial material currently in use by Futuristic Tile is "three-mix" glass. Modern technology for recycling of bottle glass has developed to the point that 90% of recycled glass can be automatically sorted into white (clear), green, and brown streams sufficiently pure for reuse as feed to those single-color glass manufacturing processes. The remaining 10% (typically material broken into too small a particle size for practical recycle) is blended, and is referred to as "three-mix."

For the Phase III testing carried out in February, sediment glass material was mixed with some "three-mix" in proper proportions to provide good sintering and melting temperatures for easy processability. The two streams were blended,

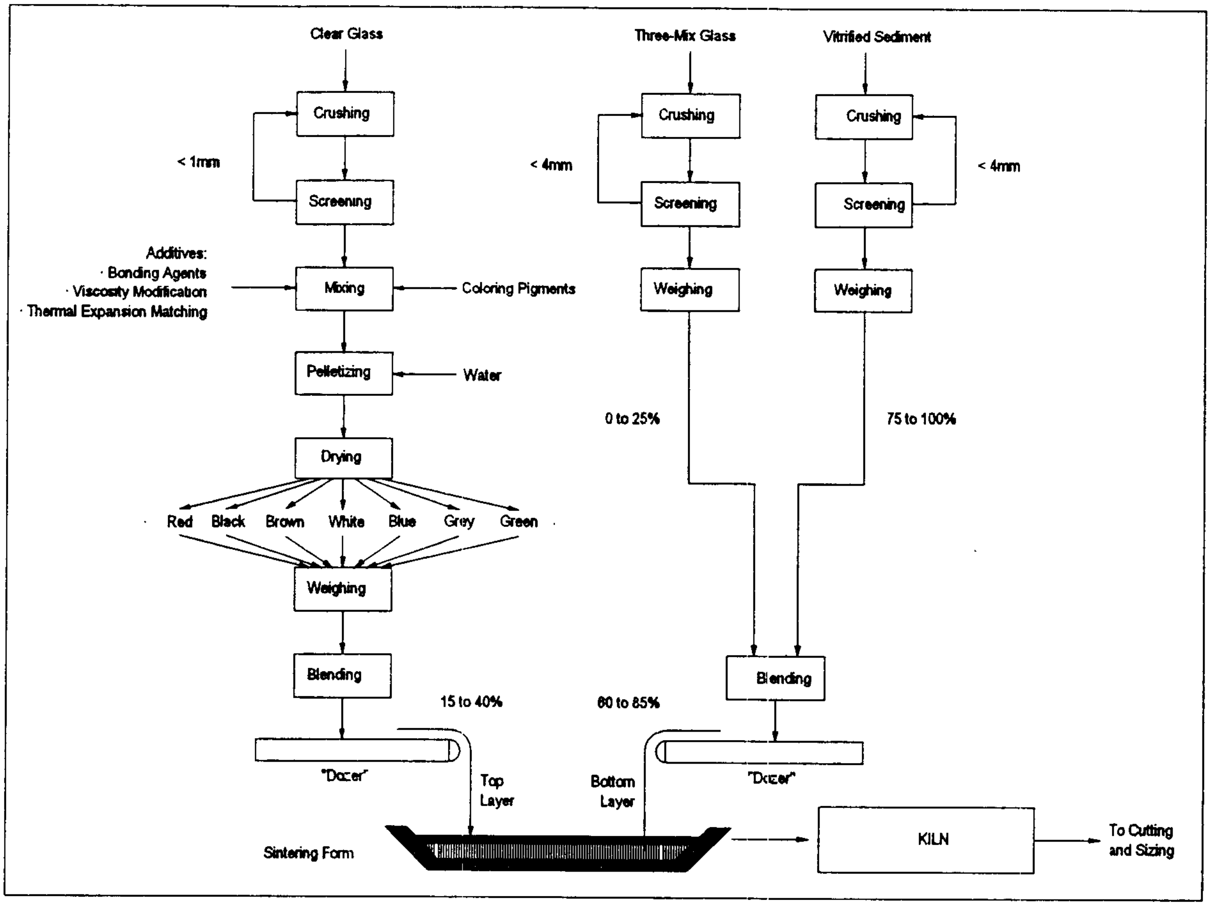

Figure 4.1 - The Futuristic Tile Manufacturing Process

and transferred to the "dozer," a mechanical distributor which places a uniform thickness layer of granular material into a cement form. (A thin layer of sand may be sprinkled on the mold first to facilitate release of the final tile).

The second, top layer consists primarily of crushed, pelletized, clear recycled glass. In this case the glass is crushed to less than 1 mm. Various additives are then incorporated, including bonding agents and chemicals such as soda (Na_2O) or boria (B_2O_3) to modify the viscosity of the molten glass or match the thermal expansion coefficient to that of the bottom layer. Colored pigments (glass enamel powders comprised of various metal oxides) are then added to produce the desired color. The mixture is then pelletized and dried. Depending on the appearance of the final tile, a distribution of white and colored granules may be used in forming the top layer. Futuristic Tile is skilled in the production of tile mimicking the appearance of a wide variety of natural stones, including granite, marble, and gneiss. The top layer is applied to a specified thickness by a second "dozer".

The filled mold is then sent to the kiln, in which it is exposed to a carefully controlled temperature profile as it travels along the length of the kiln. Heat is provided by combustion of natural gas, along with heat recovery to accomplish drying and gradual cooling. The finished tile exits the kiln, and is trimmed and cut to size by automated diamond saws. The original mold size is typically 30"× 37" (0.76 m × 0.84 m) or 32" × 42" (0.81 m × 1.07 m). Typical final product size is 12" × 12" (0.30 m × 0.30 m).

4.2 GLASS CHEMICAL COMPOSITION AND VISCOSITY MODELING

Vitrified sediment is a significantly different material from recycled bottle glass, both in its physical form and its chemical composition. As suggested above, initial screening tests were therefore performed at Futuristic Tile to determine its characteristics as a tile feed material. Testing consisted of viscosity modeling, coupon melt testing, and bench tile processability testing.

Figure 4.2 presents the overall chemical composition of Test #4 feed material, after loss of water, combustion of organics, and calcination of sodium carbonate and calcium hydroxide fluxing agents. With the exception of aluminum and iron, this composition resembles typical soda-lime-silica glass used for commercial bottle glass (typically 72% SiO_2, 14% Na_2O, and 10% CaO). If only soda, lime, and silica were present in the same ratios as exist in the sediment glass, the composition would be 70.5% SiO_2, 13.2% Na_2O, 16.3% CaO , and would be expected to behave similarly in a melting or sintering process. The impacts of iron and aluminum oxides are quite different, and modify the properties of the glass. Aluminum generally raises both the melting point and the melt viscosity, while iron (III) oxide has the opposite effect, fluidizing the melt.

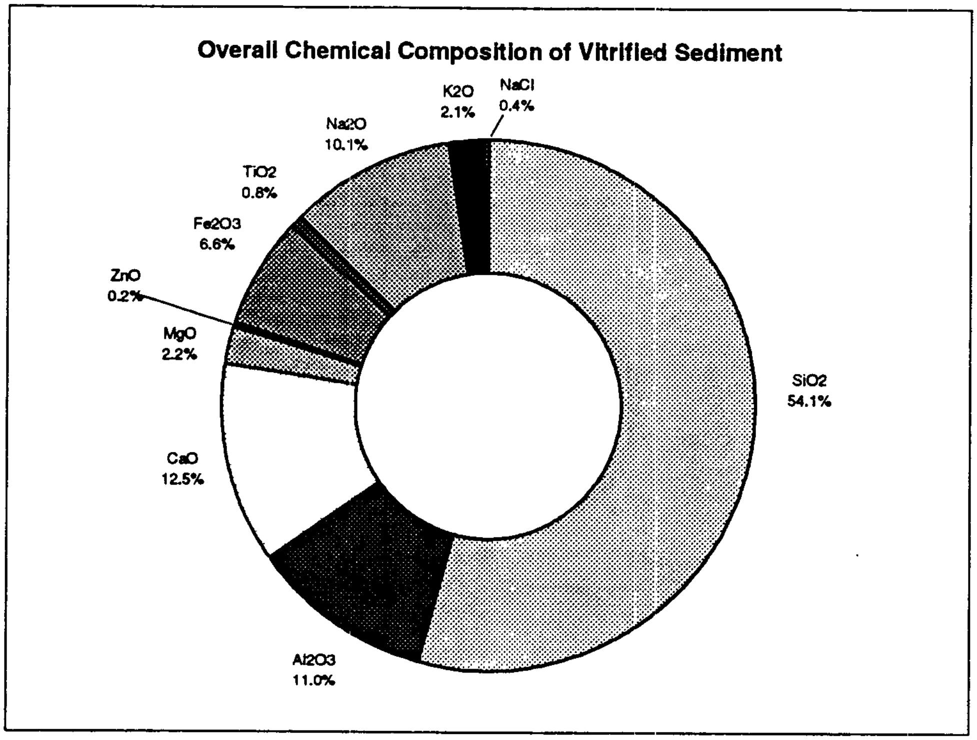

Figure 4.2 - Chemical Composition of Vitrified Harbor Sediment

Viscosity modeling was carried out to estimate the properties of the final sediment glass, with the results as shown in Figure 4.3. With the added fluxes, the target pour temperature (200 Pa-sec viscosity) is approximately 1330°C, which is in excellent agreement with measured molten glass temperature of 1331°C (see Table 3.1). Note that for the purposes of the Futuristic Tile/Environmental Stone process, the sintering temperature is of greater interest that the pour temperature, since the glass is never brought to a fully molten condition during the tilemaking process. Indeed, if the glass were to melt fully, it would adhere to the mold, and would also form a brittle product. The sintering or softening point (defined as that temperature where the glass exhibits a viscosity of 10^4 Pa-sec), is calculated to be 1002°C; this value was used to define the maximum temperature in the kiln profile.

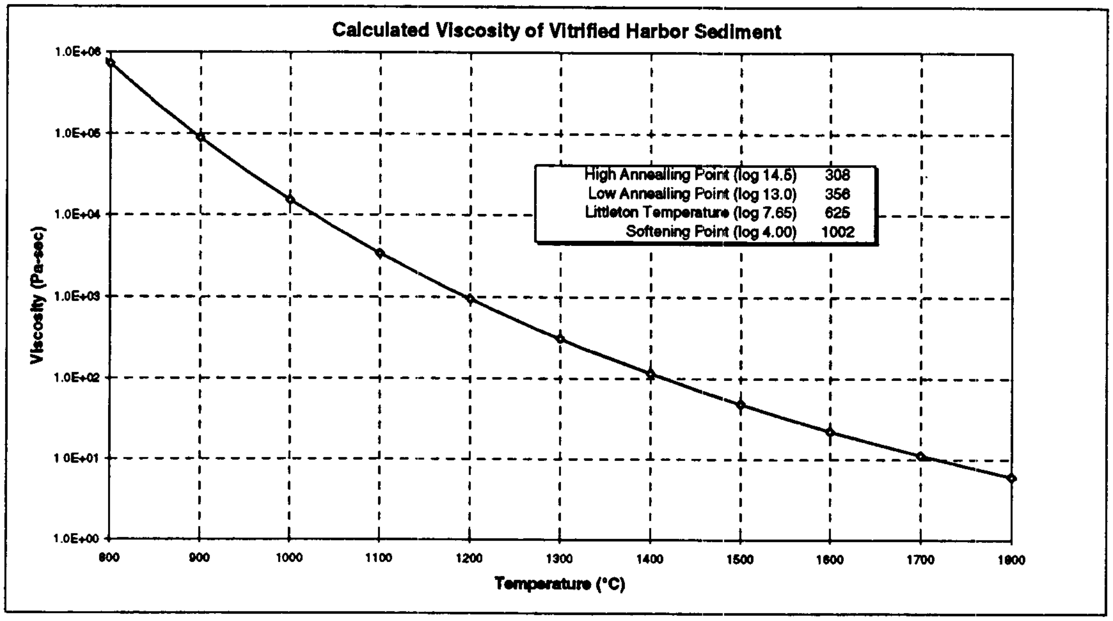

Figure 4.3 - Computed Viscosity of Molten Harbor Sediment Glass

4.3 TILE FORMULATION

To improve the rate of sintering and produce a better quality bottom layer (stronger, less brittle, and less porous), Futuristic Tile experimented with addition of some quantity of "three-mix" glass to the sediment material. Testing was carried out with the compositions as shown in Table 4.1. Although it was possible to produce good quality tile with 100% vitrified sediment feed, it was necessary to raise the temperature to 1100°C. While not excessive in terms of processing energy, at this temperature the sintered tile tended to stick to the mold. In addition, some of the pigment metal oxides change valence at this temperature and lose their color, so that tiles containing (for example) red pigment could not be made at this high a temperature.

The average sediment glass/"three-mix" composition, when combined with the decorative top layer, produced a total of 4,200 kg of finished tile having an average sediment glass composition of 43%. As shown in the table, because of the higher melting point of the sediment glass, it proved difficult to produce tile by the

Table 4.1 - Process Testing with Sediment-"Three-Mix" Compositions

% wt Sediment Glass	% wt Three-Mix	Comments
100	0	Required temperatures >1100°C to sinter; loss of pigment coloration; adhesion to cement mold
90	10	Bottom layer was crumbly when processed at 1050°C
80	20	Satisfactory composition with 1050°C sintering temperature; extended kiln residence time required; base layer strong but more porous than desired
70	30	Excellent quality base layer if "glassy" sediment fraction was used; poorer quality if "slaggy" fraction was used
50	50	Excellent quality base layer using either fraction of sediment material ("glassy" or "slaggy")

Futuristic Tile/Environmental Stone process using 100% sediment material. Compositions containing up to 80% sediment material produced good quality tile, although with slightly higher porosity (moisture uptake) than desired. Excellent product could be produced from mixtures containing 50% weight sediment glass, while good quality 70 to 80% sediment glass tile could be produced if exclusively "glassy" phase vitrified sediment material was used as the feed.

As discussed in Section 3.2, two distinct types of melted sediment were produced during plasma operations, depending on the rate in which the material was cooled. Rapid quenching produced a fully vitrified material, brown-black and glassy, which was entirely amorphous and homogeneous, and exhibited a conchoidal fracture. Slow cooling produced quite a different product, which was dull and gray, very hard, and which exhibited a brittle rock-like fracture similar to blast-furnace slag. Chemical analysis of the two types were macroscopically identical. However, upon electron microscope examination, the "slaggy" phase exhibited two distinct microscopic phases, an amorphous background with embedded calcium silicate crystals. Apparently, the composition was close enough to the boundary of the glassforming regime of the phase diagram that, given time, the high calcium content would yield precipitated calcium silicate crystals and prevent formation of glass.

This second phase sintered quite differently from the vitreous phase in Futuristic Tile's investigations, requiring either longer time at higher temperature, or else dilution with more "three-mix" glass to produce the same quality tile product. These observations indicate that rapid cooling of the molten product must be provided in commercial operation in order to generate a fully vitreous product. Rapid quenching could be accomplished by direct injection of the molten material into water; however, the granulated product would then be wet, and would require drying before it could be used in the tilemaking process. A preferred approach is cooling by pouring the molten material into a pair of water-cooled rollers. As the glass cools, it is also pressed into a thin sheet which can easily be broken into small fragments. This approach is used by the Futuristic Tile's supplier of the pigment glass enamel powder.

An alternative approach to ensuring a fully vitreous product would be to adjust the composition of the sediment glass with more Na_2CO_3 flux. In this way, the resulting composition is further from the boundary of the glassforming regime, and crystallization will not occur even if the glass is cooled slowly. Sodium carbonate is relatively expensive, however, so that this approach is likely to be more expensive that mechanical cooling. Higher soda content will also allow good quality tile to be produced with a higher ratio of sediment glass to "three-mix", however, improving the throughput of the plant as a decontamination facility. The optimum process economics will be developed during operation of the Demonstration Plant.

Photographs of the various materials are presented in Figure 4.4 through Figure 4.6. The first figure shows the bottom layer, composed of pulverized sediment glass from Test #4 plus crushed recycled "three-mix" glass. The second figures illustrates the raw materials which make up the top layer, comprised of white (clear) recycle glass and color granules (themselves fabricated from white glass, plus glass enamel powder pigments).

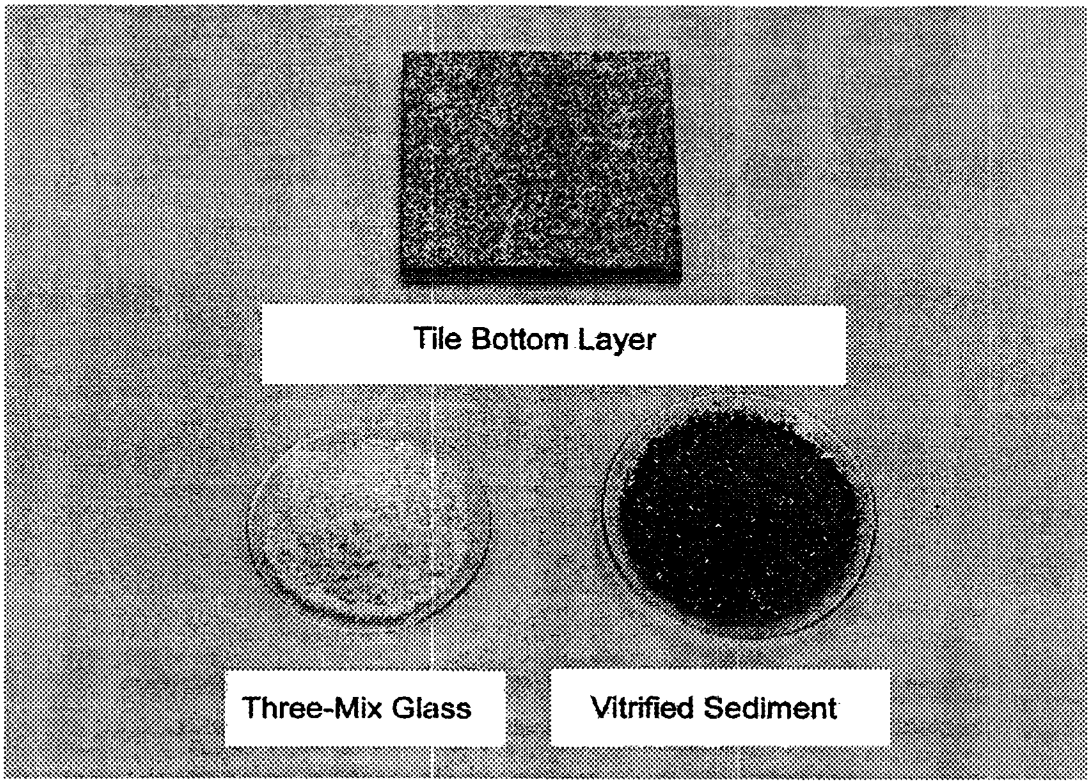

Figure 4.4 - Components of Finished Tile Base Layer

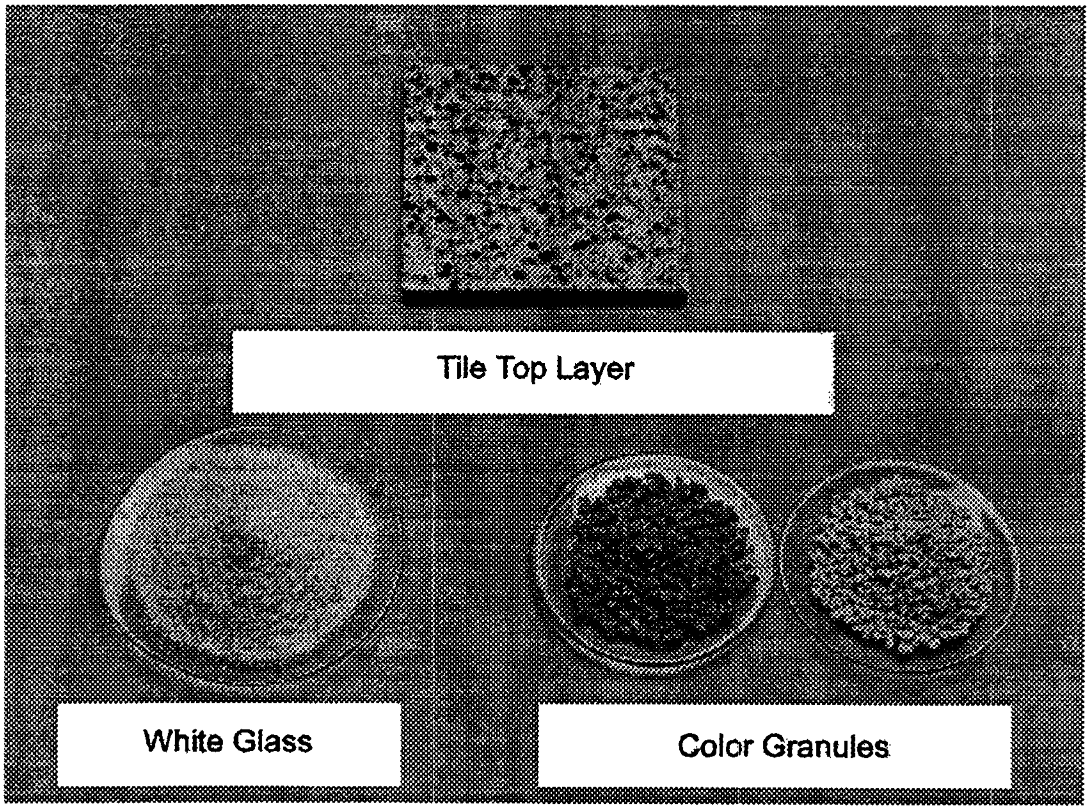

Figure 4.5 - Components of Finished Tile Top Layer

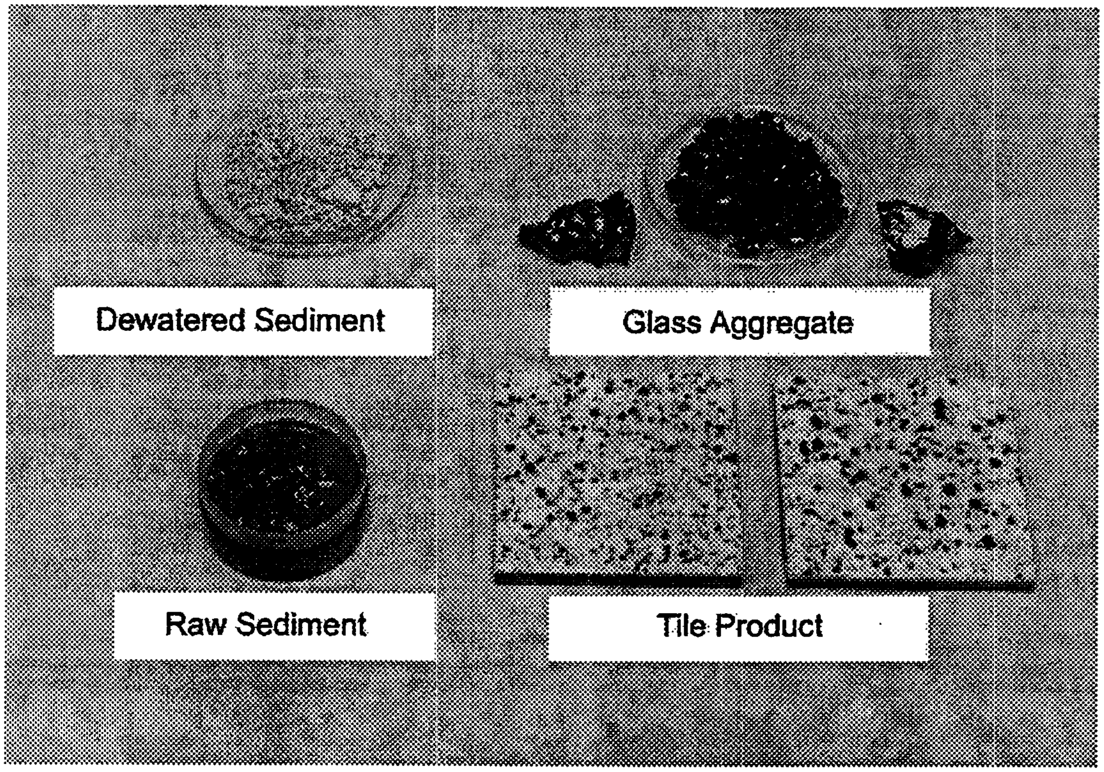

Figure 4.6 - Stages in Conversion of Raw Sediment to Finished Tile

The final figure illustrates the various stages of production of the sediment glass, from raw wet (as-dredged) sediment, to dewatered sediment containing $Ca(OH)_2$ flux, to the final vitrified glass product. Two tile samples from Test #4 are also illustrated, one with a top layer containing blue pigment and the second with black.

4.4 MATERIAL BALANCES

To calculate the flowrates of sediment and recycled glass, projections were made by Futuristic Tile concerning probable improvements in the process; results are shown in Table 4.2. The top layer (equivalent to about 40% of the total tile weight for the Phase III tile inventory) could be thinned and reduced to between 15 and 20% of the total, improving the fraction of the total tile composed of vitrified sediment without sacrificing tile quality in any way. Similarly, with proper melt cooling to ensure a fully vitreous product, the fraction of sediment glass in the base layer could be improved to between 80 and 85%. The projected net loading of

Table 4.2 - Tile to Sediment Ratio for Projected Commercial Operation

Parameter	Phase III	Commercial Operation
Base layer thickness (mm)	9.5 to 12.5	9.5 to 12.5
Base layer sediment fraction (%wt)	50 to 75	80 to 85
Top layer thickness (mm)	4.5 to 5.5	1.5 to 3.0
Top layer sediment fraction (%wt)	0	0
Fraction sediment in tile (%wt)	33 to 58	71 to 82
Mg of tile / Mg sediment glass	1.7 to 3.0	1.2 to 1.4
Mg of recycle glass / Mg sediment glass	0.7 to 2.0	0.2 to 0.4

sediment glass in the overall tile product is then calculated to be between 71 and 82%, yielding 1.2 to 1.4 Mg of tile per tonne of sediment glass, and consuming an additional 0.2 to 0.4 Mg of recycled glass per tonne of sediment glass (distributed between "three-mix" as flux for the bottom layer, and clear glass for the top layer).

The overall material balance for a Demonstration Plant processing 100,000 yd^3/yr of raw as-dredged sediment is shown in Figure 4.7, assuming production of tile having a (conservative) net sediment content of 71%. The initial sediment (92,000 Mg/yr) is combined with 1,700 Mg/yr of $Ca(OH)_2$, 1,700 Mg/yr of CaO, and 6,200 Mg/yr of Na_2CO_3 and then melted, to generate 27,800 Mg/yr of sediment glass aggregate. An additional 11,400 Mg/yr of recycle glass is then added in the tile manufacturing process (along with small quantities of pigments and additives) to produce a final product stream of 39,200 Mg/yr of finished tile, approximately equivalent to 11.7 million square feet.

Previous estimates of the processing cost for contaminated sediment by plasma vitrification have shown a predicted gross decontamination cost of \$85 to \$112/yd^3, depending on the cost of electricity. Assuming a tipping fee of \$50/yr^3 (disposal costs currently being paid for low-cost stabilization and mine disposition

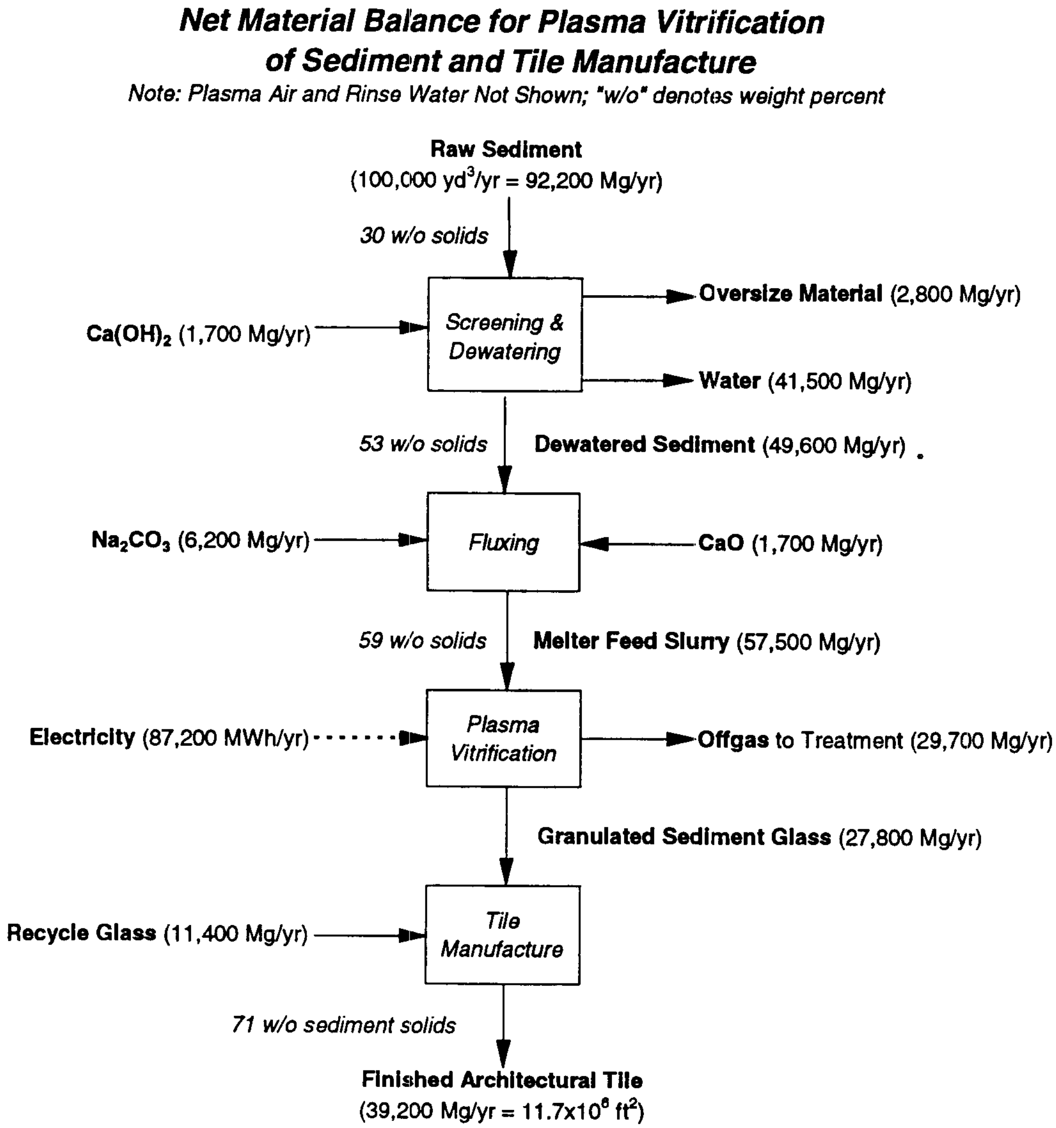

Figure 4.7 - Material Balance for a 100,000 yd^3/yr Sediment Decontamination Plant

range from \$35 to \$50/yd^3), the net cost to produce clean sediment glass would be \$35 to \$62/yd^3, or between \$3.5 and \$6.5 million per year for a 100,000 yd^3/yr facility. Typical wholesale prices for vitreous tile are \$1.25/ft^2, so that the revenue stream from this facility would be approximately \$14.6 million per year, more than twice the treatment cost. The actual cost of tile manufacture by the Futuristic Tile/Environmental Stone process is proprietary. However, with such a large margin to work against, the potential for profitable operation is clear.

It should be noted that based on the results of tile quality testing (see Section 5), use of sediment glass as a replacement for "three-mix" offers significant processing advantages, so that use of this feed material would be desirable even in the absence of other economic incentives. Tile produced from sediment glass is stronger than that produced from recycle glass material, and exhibits better freeze-thaw resistance. Variability in the chemical composition (and therefore sintering temperature) of sediment glass is expected to be less than that experienced with recycle glass, due to a high degree of large-scale homogeneity in the mineral composition of NY/NJ Harbor sediment. In addition, recycle glass requires use of a multi-step sorting process to remove paper, metal, plastic, and other debris before processing. Despite this sorting process, some non-metallic debris such as porcelain fragments becomes incorporated into the tile, and may cause defects. This problem would not be expected with vitrified sediment feed.

5. TILE PRODUCT QUALITY TESTING

Tile manufactured during Phase III was submitted to an independent testing laboratory (SGS U. S. Testing Company, Inc. in Tulsa OK) for evaluation of the physical and mechanical properties of the final tile product. Results are summarized in this section. Results of tile quality were compared to "*American National Standard Specifications for Ceramic Tile*," ANSI A137.1-1988. This standard provides quality specifications for a variety of tile materials; the sediment glass tiles were compared to standards for "Paver Tile (Unglazed)."

5.1 BREAKING STRENGTH

The breaking strength of the tile is measured in accordance with ASTM C-648, and is measured in comparison to the standard for unglazed ceramic paver tile as stated in ANSI A173.1, Section 5.2.1.3.3. Results are shown Table 5.1. The average breaking strength of the ten 12"×12" Westinghouse tile specimens was 448 ± 62 lb_f , which substantially exceeds the ANSI standard of 250 lb_f. It is also significant that typical Futuristic Tile commercial product made solely from recycle glass was also tested at the same time, and averaged 397 lb_f. While both tiles exhibited excellent breaking strength, the sediment glass tile actually outperformed tile made from recycle glass, which is already being widely sold for commercial and home applications.

5.2 FLEXURAL STRENGTH

Flexural strength of the sediment tile was also tested, using the methodology described in ASTM C880, using a perpendicular load. Table 5.2 indicates results for

Table 5.1 -Breaking Strength Test Results

Specimen	Breaking Strength (lb_f)
Test #4 Sample #1	391
Test #4 Sample #2	363
Test #4 Sample #3	437
Test #4 Sample #4	490
Test #4 Sample #5	475
Test #4 Sample #6	458
Test #4 Sample #7	503
Test #4 Sample #8	358
Test #4 Sample #9	548
Test #4 Sample #10	456
Average	448 ± 62
Typical FT Tile Specimen	397 ± 64
ANSI A137.1-1988 Standard	≥250

Table 5.2 - Flexural Strength Testing

Sample	Width (in)	Thickness (in)	Ultimate Load (lb_f)	Flexural Strength (psi)
1	4.000	0.458	186	1995
2	3.973	0.428	156	1929
3	3.976	0.443	183	2111
4	3.980	0.440	0	0
5	3.948	0.453	253	2811
Average	3.975 ± 0.019	0.444 ± 0.012	195 ± 41*	2212 ± 407*

*Not including Sample #4.

five samples tested. One of the samples (#4) failed during the test, exhibiting zero flexural strength, apparently indicative of an internal flaw. The other four exhibited an average flexural strength of 2212 ± 407 psi (15.25 ± 2.81 MPa). Note that no ANSI standard exists for flexural strength, but the testing was carried out to better characterize the properties of the tile.

5.3 MODULUS OF RUPTURE

Testing of the modulus of rupture was also carried out, again as a characterization test (but without an established ANSI standard). Testing used ASTM C99 protocol, and involved five samples. Results are presented in Table 5.3. The average modulus for the five samples (no failures were observed in this test) was 2621 ± 325 psi (18.07 ± 2.24 MPa).

Table 5.3 - Modulus of Rupture Testing

Sample	Width (in)	Thickness (in)	Ultimate Load (lb)	Rupture Modulus (psi)
1	3.950	0.462	178	2217
2	3.910	0.419	162	2478
3	3.950	0.448	202	2675
4	3.950	0.457	244	3106
5	3.950	0.462	211	2628
Average	3.942 ± 0.018	0.450 ± 0.018	199 ± 32	2621 ± 325

5.4 COMPRESSIVE STRENGTH

Compressive strength represents another property of the tile which is valuable for material characterization, but for which no ANSI standard exists. Tile samples were tested using procedure ASTM C170, with perpendicular loading. Results are presented in Table 5.4. The material is seen to have a very high

Table 5.4 - Compressive Strength Testing

Sample	Width (in)	Length (in)	Ultimate Load (lb)	Compressive Strength (psi)
1	2.000	1.900	59,187	15,576
2	2.010	1.990	89,511	22,376
3	1.990	2.010	59,790	14,948
4	2.010	2.010	110,634	27,384
5	2.010	2.010	78,841	19,515
Average	2.004 ± 0.009	1.984 ± 0.048	79,593 ± 21,628	19,960 ± 5,135

compressive strength of 19,960 ± 5,135 psi (137.6 ± 35.4 MPa). Note that the variability in compressive strength is rather large (± 26%), which is probably the result in poorly controlled melt cooling (as discussed in Section 4.3), with accompanying variability in grain crystallinity and sintering behavior. It is expected that carefully controlled cooling to ensure completely vitreous feed material will greatly reduce the variability in all of the physical properties of the final tile.

5.5 BONDING STRENGTH

The final mechanical strength test performed on the sediment glass tile was a measurement of bonding strength. In this test the tile is cemented to a backing with a standard Portland cement composition, and adhesion to the surface is measured. The ANSI standard provides that when tested according to ASTM C482, the tile shall exhibit a bond strength exceeding 50 psi. Results are summarized in Table 5.5. Again, five samples were tested, exhibiting an average shear pressure of 172.7 ± 45.5 psi (1.19 ± 0.31 MPa) required to break the tile loose from its backing. This performance value exceeds the ANSI standard by more than a factor of three. Again, considerable variability was observed (± 26%), which may be attributed to

Table 5.5 - Compressive Strength Testing

Sample	Load (lb_f)	Shear Pressure (psi)
1	3510	219.4
2	3327	207.9
3	2037	127.3
4	1950	121.9
5	2995	187.2
Average	2764 ± 728	172.7 ± 45.5
ANSI Standard		≥ 50

variations in material properties derived from uncontrolled cooling of the molten glass.

5.6 FREEZE-THAW RESISTANCE

Another critical measure of the ability of exterior paving tile to withstand environmental insults is its ability to tolerate multiple freeze-thaw cycles without cracking. Samples were tested in both air and water, in accordance with test method ASTM C 1026-87 (re-approved 1996). Specimens were subjected to 15 cycles of rapid freezing and thawing. Intermittent checks were performed on the samples after each cycle for facial defects. The presence or absence of surface cracks was also examined using a fluorescent dye solution. Note that no specific ANSI standard for freeze-thaw resistance exists.

Results from these tests showed that after 15 cycles, none of the four specimens tested showed any detectable evidence of cracks or surface defects (crazing, chipping, or spalling) as the result of the cycling. Note that a typical Futuristic Tile recycle glass tile product showed evidence of minor spalling after 12 to 15 rapid freeze-thaw cycles, so that (similar to the breaking strength test), sediment glass tile actually exhibits superior performance to the recycled glass tile currently in commercial production. The sediment glass tiles should therefore be suitable for unlimited application for both indoor and outdoor applications where severe thermal cycling could take place.

5.7 THERMAL SHOCK RESISTANCE

Testing of thermal shock resistance was done according to ASTM C484, "Thermal Shock Resistance of Glazed Ceramic Tile." The testing is designed to simulate the resistance to tile used (for example) as countertop material surrounding stoves or in contact with hot kitchen cooking equipment. Three samples were tested, as shown in Table 5.6. One of the samples apparently had an internal flaw, and failed during the initial heatup cycle. The other two showed no signs of failure during the testing, surviving six cycles of very rapid heatup and cooling with no indication of cracking, crazing, or other disintegration.

Table 5.6 - Thermal Shock Resistance

Sample	Performance
1	Sample fractured during initial heating cycle
2	Sample was noted to be in good condition after 6 heating cycles (no cracks, crazing, or failures)
3	Sample was noted to be in good condition after 6 heating cycles (no cracks, crazing, or failures)

5.8 MOISTURE ABSORPTION

The freeze-thaw resistance of a tile is related directly to its moisture absorption, as well as the structural strength of the sintered matrix. Table 5.7 presents the results of moisture absorption testing (ASTM C-373-94) of five Westinghouse sediment glass tile samples, as compared to the ANSI A137.1-1998 performance standard of less than 5.0% weight. Note that although ANSI A137.1-1988 provides an upper limit of 5.0% moisture absorption, in practice the

Table 5.7 - Moisture Absorption Test Results

Specimen	Dry Wt (gm)	Wet Wt. (gm)	Volume (cm^3)	Specific Gravity	Absorption (pct.wt.)
Test #4 Sample #1	23.10	23.43	9.93	2.406	1.43
Test #4 Sample #2	23.54	24.04	10.18	2.432	2.12
Test #4 Sample #3	23.40	23.61	10.01	2.388	0.90
Test #4 Sample #4	23.41	23.60	10.02	2.381	0.81
Test #4 Sample #5	23.30	23.68	9.96	2.432	1.63
Average			10.02	2.403±0.020	1.38±0.54
Typical FT Tile Specimen					0.73±0.06
ANSI A137.1-1998 Standard • Impervious • Semi-Vitreous • Vitreous • Non-Vitreous					*< 5.0%* ≤0.5% 0.5 to 3.0% 3.0 to 7.0% > 7.0%

absorption value in Table 5.7 determines the classification of the tile (vitreous, semi-vitreous, etc.), rather than providing a "pass-fail" determination. Each tile classification has specific applicability in various environmental settings.

The average sediment tile picked up 1.38 ± 0.54% weight moisture, less than one-third of the standard, and providing it with the classification "semi-vitreous." This value is higher that typical Futuristic Tile vitreous tile product (averaging 0.73±0.06% moisture), and also shows a greater variability than is typically observed for tile derived from recycle glass.

Both of these features are related to the higher sintering temperature for the sediment tile, which can be modified by fluxing of the original sediment, by changing the sediment-"three-mix" ratio, or by controlled cooling of the initial melt to avoid crystallinity. Note also that the sediment glass produced during Test #4 also has unusually high Al_2O_3 content resulting from startup loss of new refractory installed just before the beginning of the test. Alumina uptake contributes both to higher sintering temperature and to variability in its value. Commercial production of glass from sediment produced during long-term steady-state operation would not experience this startup problem suffered by the samples produced during Test #4.

Note also that although the moisture absorption of the sediment glass tile was higher than typical for recycle glass product, freeze-thaw resistance was not adversely affected. The greatest concern associated with elevated moisture uptake would be increased vulnerability to damage during freezing and thawing cycles. It was already shown in Section 0 that the sediment tile exhibits superior resistance to freeze damage, so that the somewhat higher moisture absorption of the Test #4 tile does not adversely impact the tile's performance.

A last comment about the results in Table 5.7 concerns the sample specific gravity. Note that the specific gravity is consistent from one sample to the next to within 0.8%. These data imply that despite the visually porous nature of the base layer material, the void fraction associated with tile porosity is very consistent. The quality control on the sintering process is therefore very good, despite variability in the properties of the sediment glass material.

5.9 SURFACE HARDNESS

The surface hardness of the tile is a measure of its durability, especially for flooring purposes. It is important to note that because of the nature of vitreous tile, the inherent hardness of glass is between 4.5 and 5.0 on the Moh's hardness scale, and *no vitreous tile* will exceed that value. (Note that some natural mineral tiles such as granite or marble may exceed 6.0). It is also important to realize that the surface hardness for the Futuristic Tile product is a function of the *top layer*, and is essentially independent of the material used in the base layer (either "three-mix" or sediment glass). Hence no difference would be expected between sediment glass tile and the current Futuristic Tile product line.

Indeed, no difference is seen, as shown in Table 5.8. Three samples of sediment glass tile each exhibited a surface hardness greater than Moh's 4.0, but

Table 5.8 - Results of Surface Hardness Testing

Specimen	Hardness (No Scratch)	Hardness (Scratch)
Test #4 Sample #1	1, 2, 3, 4	5
Test #4 Sample #2	1, 2, 3, 4	5
Test #4 Sample #3	1, 2, 3, 4	5
Average	4	5
Typical FT/ES Tile	4	5
Plate Glass	4	5

less than 5.0; the same results were obtained from both a typical Futuristic Tile/Environmental Stone product, and from plate glass.

5.10 COEFFICIENT OF FRICTION

The coefficient of friction (C/F) is another important feature of floor tile, both wet and dry. Like the surface hardness, the friction coefficient is a function of the nature of the top layer of the tile, and would not be expected to vary whether the bottom layer were fabricated from sediment glass or from recycle material. In general terms, a coefficient of friction of 0.50 or greater is desirable for a slip-resistant flooring material, although no requirement for the static coefficient of friction is given by ANSI (since the "area of use and maintenance by the owner of installed tile directly affect(s) coefficient of friction"). It is generally recognized that wet surfaces have a lower coefficient of friction than the same surface when dry. The ASTM C-1028 procedure is used to test the C/F for tile products, using a standardized Neolite shoe heel composition as the friction test plate.

Results are shown in Table 5.9 for "renovated" tile samples (where "renovation" refers to a standardized simulated janitorial cleaning treatment with a bristle brush and "Hillyard's Renovator"® cleaning solution). The average coefficient of static friction for dry sediment glass tile is 0.76 ± 0.04; this value would provide excellent overall walking traction. When wet, the C/F value falls to 0.35 ± 0.07, somewhat less than ideal. Typical Futuristic Tile/Environmental Stone product

Table 5.9 - Results of Static Coefficient of Friction Testing

	Dry Surface			**Wet Surface**		
Specimen	**Test 1**	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
Normal Load (gm)	52.46			52.46		
Maximum Force						
Test #4 / Direction 1	44	42	45	22	19	22
Test #4 / Direction 2	46	41	43	23	18	27
Test #4 / Direction 3	42	43	46	24	20	28
Test #4 / Direction 4	40	42	46	19	16	20
Average	43.3 ± 2.1			21.5 ± 3.6		
Coefficient of Friction	0.83 ± 0.04			0.41 ± 0.07		
Correction	-0.07			-0.06		
Corrected C/F for Test #4	0.76 ± 0.04			0.35 ± 0.07		
Typical FT Tile Specimen	0.74 ± 0.05			0.31 ± 0.05		
Recommended Value	≥0.50			≥0.50		

exhibits a wet C/F value of 0.74 ± 0.05, which has been deemed generally acceptable for commercial and residential application. The specific formulation of the top layer can be modified to enhance friction by (for example) increasing the melting temperature of the color granules, leaving more surface texture after sintering.

As in the case of surface hardness, the coefficient of friction is a function of the top layer surface only, and is independent of the nature of the bottom layer (sediment glass or "three-mix"). Therefore, no difference would be anticipated between the Phase III samples and the tile which makes up Futuristic Tile's commercial product line, nor is any seen in Table 5.9.

6. DISCUSSION

The test results described above clearly indicate that high-quality paving and wall tile can be manufactured from vitrified harbor sediments, using the processes developed by Futuristic Tile. Indeed, by many of the ANSI quality measures, the sediment glass tile meets or exceeds the performance of recycled glass tile currently manufactured and marketed successfully by Futuristic Tile over a multi-state area.

With the exception of the two strength test samples which failed immediately, the three characteristics in which Phase III sediment glass tile is less than optimal as compared to recycle glass tile include the higher sintering temperature, greater porosity, and higher moisture absorption. The latter two parameters are related, but are not considered to present any product quality problem since neither apparently affects the tile breaking strength nor its freeze-thaw resistance in an adverse manner.

The higher sintering temperature is an economic issue, since longer processing times and increased temperatures increase equipment size and energy consumption. Sintering temperature is directly related to tile composition, and the higher sintering temperatures required for Phase III test material are related to the relatively low flux addition and high calcium-to-sodium ratio. The Phase III glass exhibited high alumina and calcia content, and low soda; these factors translate directly into elevated sintering temperature, and the decision to dilute the sediment glass with "three-mix" to produce optimum quality tile. In actual plant operation, the best overall process economics would dictate the tradeoffs between energy consumption, flux addition, and the composition of the flux (more expensive soda versus less expensive calcia). Determination of the optimum overall integrated plant strategy will be made during Demonstration Plant testing.

In terms of overall commercial-scale process economics, the estimated cost to treat contaminated sediment by this process and convert it to clean glass is between \$35 and \$62/yd^3, depending on the cost of electricity, and after taking credit for a \$50/yd^3 tipping fee. Using projected commercial performance (see Figure 4.7), a cubic yard of raw sediment is expected to yield 117 ft^2 of finished tile, with an expected wholesale market value of \$146. There is, therefore, substantial margin for making the overall integrated process profitable, even after taking into account the (proprietary) costs associated with converting sediment glass aggregate into finished tile. Given the favorable process economics and the high anticipated market demand for this product in the New York/New Jersey metropolitan area, the integrated plasma decontamination plus tile fabrication process is expected to be a profitable venture.

The next phase of development will be commercialization of the process at the Demonstration Plant scale. Since completion of Phase III testing, the plasma technology business has been divested, forming the Westinghouse Plasma Corporation (WPC) in April, 1999. WPC plans to continue the effort to commercialize plasma vitrification as a sediment decontamination technology, in collaboration with Futuristic Tile/Environmental Stone. Current scoping efforts by WPC and FT/ES in the New York/New Jersey area are considering the design throughput capacity for a demonstration plant for optimum process economics. The schedule for implementation has not yet been defined, but is under consideration as well.