DECONTAMINATION AND BENEFICIAL REUSE OF DREDGED ESTUARINE SEDIMENT: THE WESTINGHOUSE PLASMA VITRIFICATION PROCESS

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ABSTRACT

Operation of the New York/New Jersey Harbor requires regular dredging. The offshore dumping facility has been closed due to regulations on ocean dumping of contaminated sediments, forcing the Harbor to consider alternative treatment and disposal options. The current report describes development of the Westinghouse Plasma Vitrification Process for decontamination and beneficial reuse of contaminated sediments. Phase I bench testing characterized the sediment and provided verification that good quality glass could be prepared with addition of less than 15% fluxing agents. Kilogram quantities were prepared, and tested for decontamination efficiency; organics were destroyed to 99.9999% efficiency, and the product passed the TCLP leaching test for all heavy metals by several orders of magnitude.

Phase II pilot testing followed, including large-scale sediment pretreatment (screening, dewatering, and blending). Four metric tonnes (Mg) of pretreated Harbor sediment were melted at approximately 0.8 Mg/hour in a full-sized plasma melting reactor powered by a Westinghouse Marc-11 plasma torch. Processing characteristics were evaluated, and detailed heat and material balances were prepared, including offgas and wastewater characterization. All gaseous and liquid effluents met discharge requirements.

Pilot plant data were then used to prepare preliminary plant designs for a 76,000 cubic meter per year Demonstration Plant (100,000 yd^3/yr) and a 380,000 cubic meter per year full-scale facility. This study included material handling, pretreatment, vitrification, offgas treatment, and pollution control systems, and predicts an overall 99% reduction in waste volume compared to the original sediment. Preliminary costs were developed for the integrated sediment processing (including amortized capital), with a range between $90 and $120/Mg depending on the cost of electricity.

Finally, Phase III testing demonstrated conversion of an additional 1.4 Mg of vitrified sediment into commercial architectural tile, using technology developed by Futuristic Tile of Allenton WI. This tile represents a high-value product with a large potential demand, sale of which could more than offset all of the cost of sediment decontamination, even before credit is taken for a tipping fee.

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INTRODUCTION

Many of the major harbors in the United States have become contaminated with a wide variety of toxic chemical species as the result of 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 sediments, once a simple process of offshore hauling and dumping in deep coastal waters, is no longer simple due to toxic contamination and increasingly stringent regulation of ocean dumping.

In the specific case of the New York/New Jersey Harbor (see Figure 1), ocean dumping at a site southeast of the harbor (the "Mud Dump") 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. Toxic contaminants (both organic and inorganic species) are ubiquitous, however. The 1994 EPA 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 industrial waste water discharges and combined sewer overflows. Although much progress has been made in the reduction of point sources of new pollutants, large inventories of toxic materials still exist which feed into the Harbor. These especially include sewage residues in the Gowanus Canal, industrial and petroleum wastes in Newtown Creek, and a variety of industrial sites along the Passaic River (including the notorious Diamond Alkali site, formerly used for manufacture of Agent Orange, and the source of much of the dioxin and furan contamination in 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 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 that time, the Mud Dump has been closed to further dumping.

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 appropriate to the level and type of contamination. 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.

Figure 1 - New York/New Jersey Harbor

- Stabilization by addition of some additive such as cement to reduce contaminant leaching, followed by surface disposal. This approach provides some degree of beneficial reuse, since stabilized sediment may be used for land development applications such as filling spent mines or capping of industrial "brownfield" sites.
- Decontamination by some alternative technology, preferentially including reuse 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 contaminants which may be present. Sediment from New York/New Jersey Harbor contains low concentrations of a wide variety of heavy metals (including Ag, Cd, Cr, 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 (PAH's), polychlorinated biphenyls (PCB's), 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. Toxic microbiological agents such as *pseudomonas*, *streptococcus*, *clostridium*, and fecal *coliform* may also be present, further complicating handling and treatment.

THE WESTINGHOUSE PLASMA DECONTAMINATION PROCESS

Given the difficulty of designing a process for physically or chemically separating all of these toxic contaminants from the vastly larger body of non-toxic mineral sediment, an alternative process for sediment decontamination was investigated and developed by Westinghouse Electric Corporation. This process provides for near-quantitative destruction of toxic 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 reuse, specifically including production of architectural tile. This development effort was supported by the EPA Region 2, through an appropriation from the Water Resources Development Acts (WRDA) of 1992 and 1996. The program was administered through Brookhaven National Laboratory (BNL), and overseen by the Brookhaven Rensselaer Environmental Partnership/Multi-State Alliance (BREP/MSA).

The process is based on Westinghouse 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 quenched to maintain the vitreous characteristics, incorporating and trapping heavy metals in the glass matrix in 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.

DEVELOPMENT OF THE PLASMA VITRIFICATION PROCESS

Development of this process has occurred over a 2½-year period, beginning late in 1996 with a Phase I effort to characterize the Harbor sediment and determine the feasibility of converting it to a leach-resistant glass with complete destruction of toxic organics. Characterization studies were carried out at the Westinghouse Science and Technology Center (WSTC) in Pittsburgh PA. Whereas many decontamination processes would focus only on the concentrations and distribution of contaminant species, the vitrification process also required knowledge of the mineral oxide composition of the sediment in order to formulate a strategy for vitrification (conversion to glass).

Table 1 presents results of both X-ray diffraction analysis (for mineral phases) and chemical analysis (for metals). The bulk of the sediment consists of sand (quartz) and clay minerals, with

iron silicate. A large quantity of organics is also present, with 9 to 10% total carbon and substantial sulfur. The organic content provide the dried sediment solids with considerable

Table 1 - Mineral and Metals Analysis for New York/New Jersey Harbor Sediment

Element or Mineral Phase	Chemical Formula	Weight Percent (Dry Basis)
Quartz	SiO_2	66 to 75
Muscovite (Mica)	$K_2O•2MgO•Al_2O_3•8SiO_2•2H_2O$	11 to 15
Kyanite	$Al_2O_3•SiO_2$	3 to 13
Hydrated Aluminum Silicate	$19Al_2O_3•173SiO_2•9H_2O$	6 to 7
Cronstedtite	$4FeO•2Fe_2O_3•3SiO_2•2H_2O$	4 to 6
Organic Phase	Petroleum residues	3 to 13
Silicon	Si	20.7 to 25.0
Carbon	C (organic plus inorganic)	8.9 to 10.3
Aluminum	Al	5.5 to 5.7
Iron	Fe	4.5 to 5.0
Sodium	Na	1.2 to 1.3
Potassium	K	1.7 to 2.1
Sulfur	S	0.5 to 1.8
Calcium	Ca	1.2 to 1.4
Magnesium	Mg	1.0 to 1.3
Titanium	Ti	0.5
Copper	Cu	0.2
Zinc	Zn	0.2

heating value, measured at 3.7 to 4.5 MJ/kg (which improves the overall efficiency of the plasma vitrification process). Sodium chloride is also found, primarily from brine in the estuarine Harbor water. Analyses are presented on a dry basis; as-dredged sediment was found to be 30 to 35% solids by weight.

A detailed contaminants analysis was also performed on the sediment, providing a baseline for assessing the efficacy of the decontamination process. Results are shown in Table 2. Included in the organic phase (7.3% total organic carbon) are nearly 30 regulated PAH species, as well as a range of chlorinated pesticides. Total dioxins are measured at 6.5 ppb, and ten toxic heavy metals are present above detection limit.

Given the mineral composition shown in Table 1, the next step in developing the process was to establish the design glass formulation. The sediment as shown is high in alumina and silica, which when melted alone would form a viscous melt with high fusion point. Handling of the molten product was therefore expected to be difficult unless the viscosity were reduced. Modeling of the melt viscosity was therefore done using the method of Riboud *et al*. (1981), in which the melt viscosity η (Pa-sec) is represented by the following function of temperature T (°K):

Table 2 - Toxic Organic Compounds in New York/New Jersey Sediment

Contaminant	Weight Fraction (Dry Basis)
Sulfides	7.8E-3
Total Organic Carbon (TOC)	7.3E-2
Polychlorinated Biphenyls (PCB's)	5.2E-6
Chlorinated Pesticides	4.6E-7
Polyaromatic Hydrocarbons (PAH's)	1.2E-4
Total Dioxins	6.5E-9
Total Furans	1.7E-8
As	3.3E-5
Cd	3.7E-5
Cr	3.7E-4
Cu	1.2E-3
Hg	1.3E-6
Ni	3.0E-4
Pb	6.2E-4
Zn	1.7E-3

$$\eta = A\,T\,exp(B/T) \tag{1}$$

$$\begin{aligned} ln(A) = {} & -17.51 - 35.76\,\Sigma_i\, x_i\,(Al_2O_3, Cr_2O_3) + 5.82\,x(NaCl) \\ & + 7.02\,\Sigma_i\, x_i(Na_2O, Na_2S, K_2O) \\ & + 1.73\,\Sigma_i\, x_i(CaO, MgO, FeO, MnO, PbO, ZnO, CuO) \end{aligned} \tag{2}$$

$$\begin{aligned} B = {} & 31140 + 68833\,\Sigma_i\, x_i(Al_2O_3, Cr_2O_3) - 46351\,x(NaCl) \\ & - 39519\,\Sigma_i\, x_i(Na_2O, Na_2S, K_2O) \\ & - 23896\,\Sigma_i\, x_i(CaO, MgO, FeO, MnO, PbO, ZnO, CuO) \end{aligned} \tag{3}$$

where x_i is the mole fraction of each species i. The balance is assumed to be SiO_2.

For ease in handling, the target glass composition was designed to exhibit a pour viscosity of less than 100 Pa-sec at 1250°C, a temperature readily obtained within a plasma-fired shaft furnace. To accomplish this goal, a mixture of fluxing agents were added to the sediment. The viscosity was initially modeled using Equations (1) through (3) to identify predicted melt viscosities, and then coupon melt samples were prepared to confirm that the composition formed a fully vitreous product (entirely glassy, with no precipitated crystalline inclusions). Coupon tests of twelve candidate glass compositions were carried out with the assistance of Savannah River Technology Center (SRTC), at the Savannah River National Laboratory, Aiken SC. It was determined that test Composition #7 containing 83.2% (dry basis) Harbor sediment, 11.2% CaO flux (provided as slaked lime), and 5.6% Na_2O flux (provided as soda ash, Na_2CO_3) exhibited both the desired melting point (see Figure 2) and a fully vitrified final product. The resulting glass was lustrous and black (deep green-gold in thin cross-section), contained a high loading of sediment, and used a high ratio of lime to soda ash to achieve fluxing (soda ash being the considerably more expensive of the two fluxes).

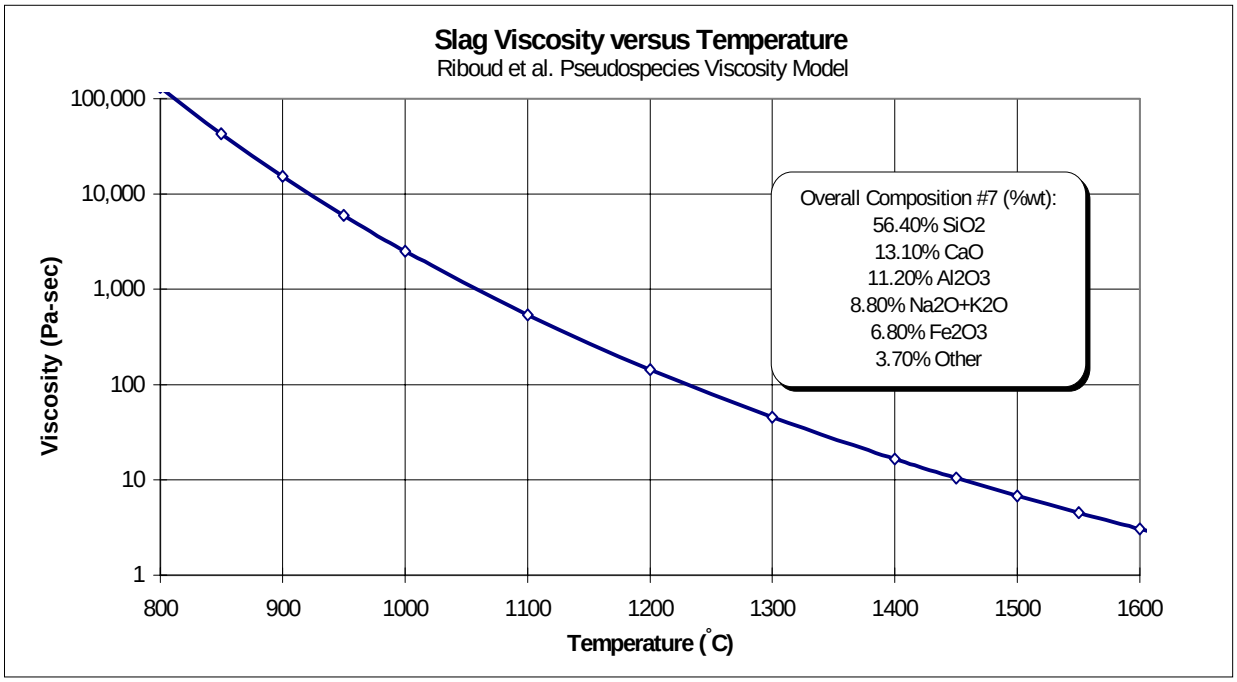

Figure 2 - Computed Viscosity-Temperature Profile for Target Sediment Glass Composition

CHARACTERIZATION OF THE PRODUCT GLASS ENVIRONMENTAL QUALITY

Larger samples of sediment-derived glass were then generated to permit leach testing and detailed analysis for various toxic contaminants. To produce 10 kg of glass for this purpose, samples of sediment were first rinsed with fresh water to remove the bulk of the salt, and then dried at low temperature (to minimize evolution of volatile organic compounds, or VOC's). Dried sediment solids were then blended with flux, and delivered to Ferro Corporation in Cleveland OH for melting in 1 kg crucible batches. Melt testing was carried out over a range of temperatures from 1250 to 1450°C. Approximately 12 kg of glass were produced in this way, with 7.5 kg shipped to Brookhaven National Laboratory for detailed analysis.

Analysis was done at BNL for 121 organic compounds. Of these, only five were identified in the final product above detection limit. As shown in Table 3, destruction efficiencies were at least 99.8% for all organic categories, 99.9999% overall, and exceeded 99.99% for dioxins, believed to be the most refractory (heat resistant) of all of the compounds present. Leach of the glass product was also carried out, testing using the U. S. EPA Toxic Characteristic Leaching Procedure, or TCLP. Of all the metals analyzed for, only lead was detected in the TCLP leachate; the concentration was only between 2 and 5% of the EPA regulatory limit.

Table 3 - Decontamination Efficiencies for Sulfides and Toxic Organic Species

Chemical	Units	Product Glass	Untreated Sediment	Destruction Efficiency
Total Organics	g/kg	0.048	119.0	99.9999%
Sulfides	mg/kg	0.50	7,800	99.994%
PCB's	µg/kg	1.28	5,260	99.976%
Pesticides	µg/kg	<Detection Limit	462	>99.35%
PAH's	µg/kg	259	137,000	99.81%
Dioxins	ng/kg	<Detection Limit	6,440	>99.99%
Furans	ng/kg	0.41	16,480	99.78%

SEDIMENT PRETREATMENT

Given the success of the bench testing program, a plant design material and energy balance was then developed, as shown in Figure 3. In addition to defining the optimum plasma processing conditions and the glass-flux formulation, consideration was given to pretreatment of the sediment. Ideally, all of the salt would be removed from the sediment prior to vitrification, since NaCl is volatilized during the melting process and provides both a corrosion problem and the potential for solid salt deposits in the offgas system. The first step in the pretreatment process is therefore washing the sediment. Fresh water is added during a prescreening process, which removes large debris and ensures that no particles pass through which could clog the sediment injection nozzle into the plasma melter. Note that for New York/New Jersey Harbor sediment exhibits a very fine particle size distribution, with 98.4% less than 1 mm, 96% less than 400 µm, and 50% less than 10 µm. Less than 1.6% of the total dredged material would therefore be rejected due to excessive particle size (greater than one millimeter), most of which consists of sticks, leaves, and various artificial debris.

Once rinsed substantially free of salt, the sediment is then be partially dewatered. Since electrical power is the largest single cost in the plasma vitrification process, it is beneficial to remove as much water as possible prior to injection into the melter. If too much water is extracted, however, the sediment becomes dry and clay-like, and is very difficult to pump into the melter. Viscosity measurements and pumping tests determined that approximately 50 to 55% solids represents the upper practical limit to slurry pumping. This solids concentration can readily to achieved by large, industrial plate and frame filtration equipment. Agglomeration of the sediment fines is enhanced by addition of $Ca(OH)_2$ (which later calcines to CaO, providing part of the flux). The dewatered sediment is then blended with the balance of the fluxing agents CaO and Na_2CO_3, and fed to the melter.

The material balance for major streams in Figure 2 is presented in Table 4. The sediment processing rate is 63 Mg/hr, equivalent to the program target of 500,000 cubic yards (382,000 m^3) dredged sediment per year. Chemical feeds to the plant (besides air and water) include:

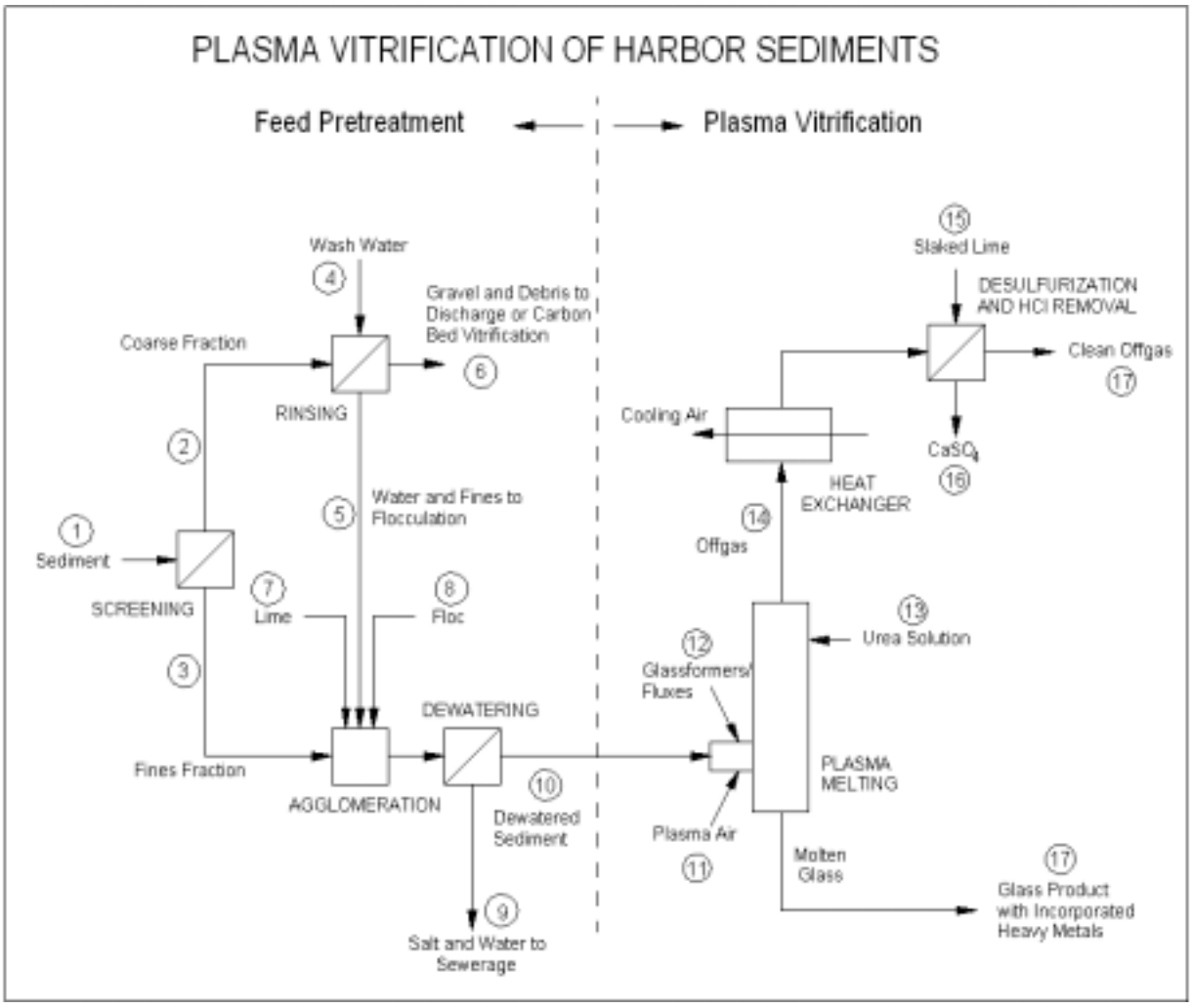

Figure 3 - Process Flow Diagram for Sediment Pretreatment and Vitrification Plant

- 1.0 Mg/hr $Ca(OH)_2$ (hydrated lime) for agglomeration of fines prior to filtration,
- 0.01 Mg/hr of organic flocculating agent,
- 4.3 Mg/hr of Na_2CO_3 (soda ash) for flux,
- 1.3 Mg/hr of CaO (slaked lime) for flux,
- 2.0 Mg/hr additional slaked lime for sulfur emissions control, and
- 0.07 Mg/hr of urea for NO_x control.

The process produces 21.5 Mg/hr of molten glass, which is quenched quickly and granulated.

As shown above in Figure 3 above, the overall process produces very little solid waste. The total waste which must be disposed of consists of only 1% of the original sediment volume. A small fraction of the sediment is rejected as oversize; this material would probably be landfilled, consisting primarily of debris and gravel rinsed of surface contamination. Offgas treatment consists of dry absorption for removal of sulfur oxides and acid gases (HCl), generating a small calcium sulfate/sulfite stream to landfill. Note that coal-fired power plants generate much larger quantities of the same $CaSO_4/CaSO_3$ scrubber waste, which is routinely landfilled.

Table 4 - Material Balance for 500,000 yd^3/yr Sediment Pretreatment and Vitrification

	Stream	Flowrate (kg/hr)	Notes
1	Dredged Sediment	62,730	33%wt solids
2	Oversize Fraction	1,820	Particle size ≥1 mm; also 33% solids
3	Fines Fraction	60,910	Particle size <1 mm
4	Rinse Water	4,540	
5	Rinse Water and Fines	5,330	
6	Washed Debris	1,030	Assumed 1.6%wt of feed
7	Hydrated Lime [$Ca(OH)_2$]	1,150	Agglomerating agent at 0.12 kg/L
8	Flocculating Agent	10	Added at 1 gm/L of slurry
9	Rinse Water to POTW Sewerage	141,900	0.2%wt solids (mostly NaCl)
10	Dewatered Sediment	35,120	60%wt solids
11	Plasma System Air	41,800	Includes 5,620 kg/hr for pneumatic transport of fluxing agents
12	Fluxing Agents [Soda Ash + Lime]	5,610	77%wt Na_2CO_3 + 23%wt CaO
13	Urea Solution [$CO(NH_2)_2$]	1,360	5.0%wt solution for NO_x control
14	Melter Offgases	59,750	0.4%wt solids carryover
15	Slaked Lime [CaO]	1,990	22%wt slurry for sulfur control
16	Calcium Sulfate [$CaSO_4$]	820	To landfill
17	Clean Stack Gas	46,940	Meets discharge limits for SO_x and
18	Glass Product	21,540	86% sediment metal oxide loading

Rinse water is essentially clean except for possible trace concentrations of organics, and can simply be discharged back to the harbor (being no more contaminated than water than drains from the excavation bucket during dredging). Most of the RCRA metals in the sediment are trapped in the glass matrix, as shown in Table 5 (data taken from Test #3, described in the next section). Most of the metals which partially escape the melter would report to the $CaSO_4$/$CaSO_3$ stream. The concentration of these metals in the calcium sulfate would remain very low, and would this material to be landfilled without special precautions.

PILOT SCALE DEMONSTRATION OF THE DECONTAMINATION PROCESS

Phase II of the EPA program consisted of pilot scale demonstration of the integrated process (pretreatment plus vitrification), treating 16.7 Mg of contaminated sediment from Newtown Creek. Large-scale pretreatment and process development assistance was provided during Phase II by Sevenson Environmental of Niagara Falls NY, experts in handling and dewatering of soils and sediments. The pretreatment steps outlined above were carried out for the full 16.7 Mg of sediment, using portable washing, screening, filtration, and blending equipment brought to and installed by Sevenson at the Westinghouse Plasma Test Center (WPTC) in Madison PA.

Table 5 - Retention of RCRA Heavy Metals in Glass Product During Vitrification

Metal Species	Concentration in Glass (ppm)	Fraction Retained in Glass
As	5.3	66.8%
Ba	26.9	99.8%
Cd	1.0	61.3%
Cu	1061.2	97.2%
Hg	<Detection Limit	(Not Measurable)
Ni	255.5	98.9%
Pb	106.7	79.8%
Se	1.6	79.4%
Zn	1232.9	72.6%

Pretreatment operations are summarized in Table 6. A total of 13.4 cubic meters of raw sediment were processed during July and August of 1997, starting from an initial 37% solids content. The initial sediment was black and tarry, with a strong creosote odor. Screening and washing eliminated 85% of the salt and 5% of the sediment mass, consisting mostly of debris and trash. Note that this fraction was higher than the oversize fraction in the Table 4 material balance; much of the debris was material discarded into the rolloff during sample collection (wood, plastic film, tools, protective clothing, etc.). Filtration with the aid of calcium hydroxide agglomerating agent produced a dewatered sediment product containing 52% solids. A total of 1,555 kg of fluxing agents was added (including the $Ca(OH)_2$), representing about 20% of the final melter feed on a dry basis (83% loading of sediment metal oxides into the final glass). The final 52% solids melter feed was a gray clay-like material which could be pumped by high pressure injection pumps.

Table 6 - Pilot Test Pretreatment System Performance Summary

Pretreatment Parameter	Value
Sediment Processed (m^3)	13.4
Sediment Solids Processed (kg wet basis)	16,700
Sediment Solids Content (%wt)	36.7
Oversize Cuttings Removed (kg dry basis)	328
Rejection of NaCl During Washing (%)	85.6
Rinse Water Consumption (liters)	28,700
$Ca(OH)_2$ Filtration Aide Consumption (kg)	460
Mass of Dewatered Sediment Produced (kg)	11,000
Solids Content of Dewatered Sediment (%wt)	52.0
Volume of Filtrate Water Generated (liters)	32,700
CaO Flux Added (kg)	285
Na_2CO_3 Flux Added (kg)	810

Plasma Melter Feed Generated (kg)	13,600

Vitrification testing was carried out between October and December, 1997, with a total of three tests. Most of the material processed was melted during Test #3 on December 5, during which a total of 3,980 kg of feed was converted to glass over 7.7 hours at an average rate of 533 kg/hr, with peak production as high as 800 kg/hr.

A schematic of the full-scale plasma melter design is shown in Figure 4 (as designed for the full scale plant, but functionally similar to the unit tested at Westinghouse PTC). The melter consists of a cylindrical furnace with refractory lining. Near the bottom is the injection port (one in the WPTC design, three in the full-scale plant design), referred to as the "tuyere" for its similarity to the air injection ports of a blast furnace or metal-melting cupola. At the outer end of the tuyere is mounted a Westinghouse plasma torch, rated at 2.3 MWe full power for the WPTC tests, or 5 MWe for the full-scale design. Full production in the larger design is accomplished by construction of five independent plasma melter trains of three torches each, arranged radially around the melter.

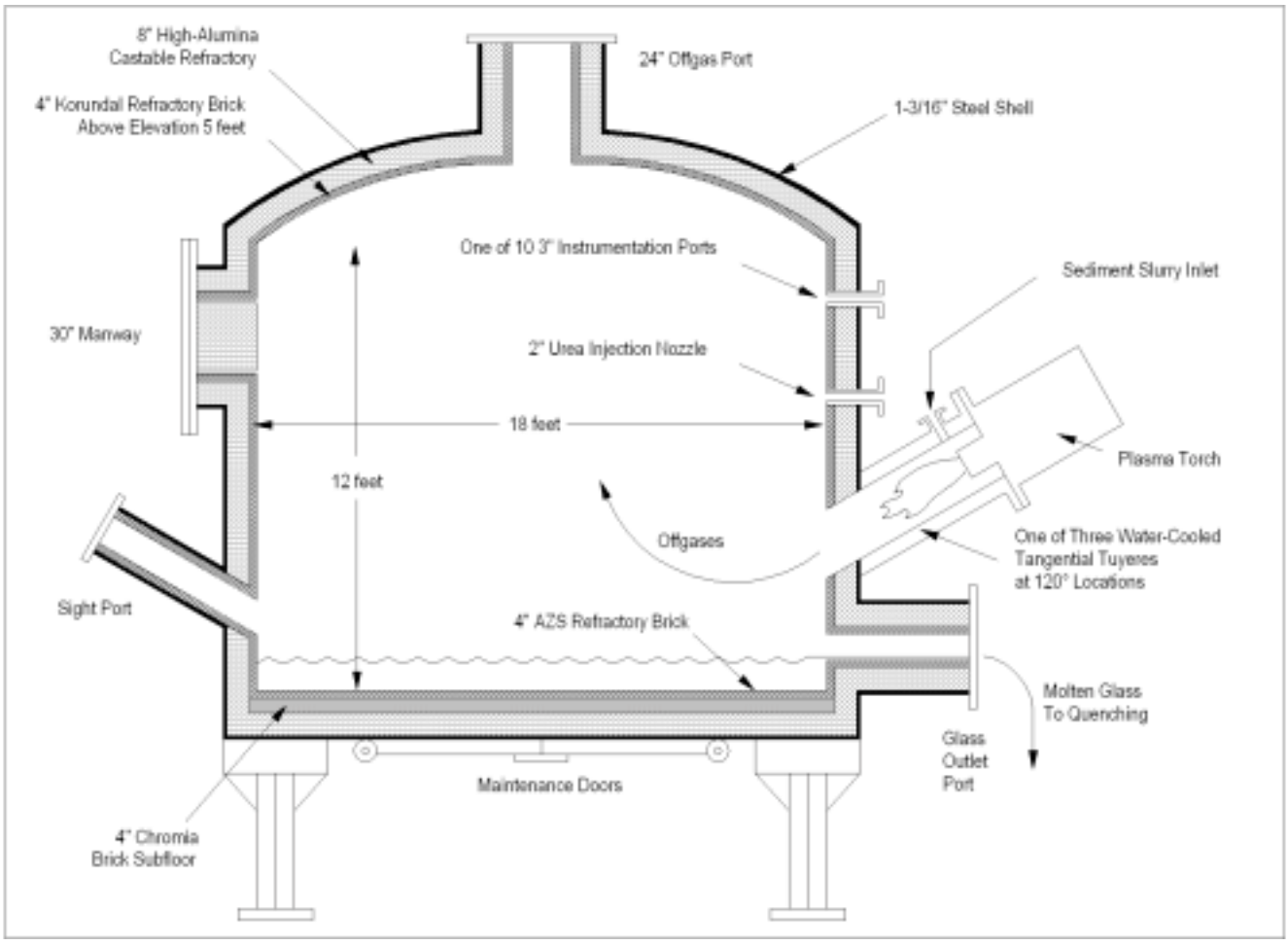

Figure 4 - Plasma Melter Schematic

Sediment and flux mixture is pumped as a slurry through an injection nozzle directly into the plume of the plasma torch. The water content of the dewatered and blended feed is adjusted by the requirements of the pumping system. Higher solids content produces more economical operation since less water must be heated and evaporated, but more difficulty is introduced in transporting the viscous slurry to the tuyere. It was noted that the viscosity behavior of the sediment is highly non-Newtonian, behaving as a Bingham plastic material. Pumping proved to be the largest single difficulty encountered during the demonstration testing, when the slurry solids content was higher than optimal.

Air flow through the tuyere totals approximately 12.7 m^3/min, divided between torch air (passing through the plasma torch electrodes) and shroud air (serving the mix the plasma plume with the incoming sediment slurry, and to cool and protect the tuyere walls from the superheated plume). During Test #3, the plasma power averaged 1600 kWe. The specific energy consumption for processing of the sediment was therefore 10.8 MJ/kg of sediment feed slurry. Similar or better energy efficiencies would be expected in the full-scale plant.

As sediment enters the tuyere and mixes with the superheated plasma plume, it is rapidly dried and the organic surface deposits are combusted. Large agglomerated clumps disintegrate into fine, dry particles which are carried down the duct and thrown against the walls of the tuyere. Because of extremely rapid heat transfer, calcination of flux materials and melting of metal oxides occur within the tuyere, forming a homogeneous glass melt before the material enters the melter crucible (bottom). The liquid is continuously tapped from the crucible, with an exit temperature of approximately 1250 to 1350°C. Molten product may be cast into large masses, roll quenched into thin sheets for later crushing, or water quenched to form a fine aggregate.

BENEFICIAL REUSE OPTIONS

Vitrified sediment provides a safe and stable wasteform for landfilling (or, theoretically, ocean dumping), but the properties of vitrified harbor sediment are such that a wide range of possible beneficial reuse options also exist. Among the simplest involve use as roadbed aggregate, an end use currently being practiced for vitrified ash ("glasphalt"). The requirements for roadbed aggregate are not well defined, but both the processing cost and product value are low. If the particle size is controlled to some degree, the glass may also be used for sandblasting applications. In this market, sediment glass would compete directly with products such as Black Beauty®, a registered trademark of Reed Minerals (a division of Harsco Corporation). Black Beauty® is made from fused coal ash, and is chemically very similar to vitrified harbor sediment.

Somewhat higher value products which have been considered include:

- Roofing granules (requiring control of both particle size and Fe(II)/Fe(III) ratio for ultraviolet absorption characteristics; the iron ratio in New York/New Jersey Harbor sediment glass is favorable for this application, however).
- Replacement glass cullet (although considerable market demand for cullet exists, the market for Harbor sediment cullet would be limited by the black color of the high-iron glass).

- Additive to brown bottle glass (where the color would be advantageous; application for beverage bottles would be difficult to market given the origin of the material, however).
- Filler material for artificial onyx bathtubs and similar fixtures (where the color is irrelevant since the surface gel coat is the only visible material; the market is limited, however).
- Rock wool insulating fiber (requiring control of product viscosity to allow spinning into fibers, and relatively expensive processing equipment; the market value is nearly $200/Mg, however).

At the high-value end of the spectrum, the New York/New Jersey Harbor sediment produces a glass which has physical and chemical properties similar to "E-Glass" which is one of the major commercial fiberglass compositions. Samples of Phase I Harbor sediment glass were forwarded to a major U.S. fiberglass manufacturer for evaluation. Samples were spun into greenish gold fibers, and exhibited both good forming properties (1000 Pa-sec fiber-forming temperature of approximately 1200°C) and excellent strength characteristics (490,000 psi single-fiber strength, only slightly below that of "E-glass"). Environmental TCLP testing of the fibers was also found to be no issue.

The major issues associated with fiberglass concerned product uniformity. The plasma melting process was designed to rapidly decontaminate and fuse the sediment, with short residence time to minimize energy costs and equipment size. Feed glass to a fiberglass spinning operation is required to be exceptionally homogeneous, with near-zero concentrations of incompletely melted or crystalline material. One fiber break per day in a spinning machine is considered a serious problem. To provide this degree of homogeneity, the molten glass would have to be held for a considerable length of time at elevated temperature to ensure complete dissolution of crystalline phases ("fining"). Both the capital and energy cost of equipment for this process as well as for fiber spinning is substantial. Also, it is difficult to guarantee the uniformity of the glass chemical composition, since the source will vary from day to day within the Harbor environment.

A far more robust application and one requiring much lower capital investment is fabrication of commercial 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 $170/Mg. Higher grade tiles use feldspar ($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 $250/Mg.

The tile market is also favorable, with approximately 75% of all ceramic tile being consumed by new construction. Demand should be good in the New York City urban area, providing a local market requiring minimal transportation costs. At current production figures, a 380,000 m^3/yr sediment decontamination facility could generate 166,000 Mg/yr of glass product, equivalent to as much as 5% of the current ceramic tile market. However, due to the relatively low anticipated cost of the glass, vitreous tile must be viewed as a high-quality, low-cost substitute for current

tile products, where market impact would be minimized as vitreous tile replaced other lower quality or higher cost products.

Based on this market analysis, Westinghouse collaborated with one company currently producing vitreous tile from waste materials, namely Futuristic Tile LLC (soon to be known as Environmental Stone Products) of Allenton WI. Futuristic Tile accepts from municipalities scrap recycle clear ("white") bottle glass and "three-mix." (Note: current technology for glass recycling allows up to 90% of mixed green/brown/white glass to be automatically sorted into three pure-color streams. The remaining 10%, primarily broken material too small to be sorted, is known as "three-mix"). The mixed glass stream is first crushed, cleaned, and sized. It is then blended with additives designed to adjust the melt viscosity, sintering temperature, and thermal expansion coefficient. The glass powder is then fed into ceramic molds using a feed distributor known as a "dozer." This forms the bottom layer of the tile.

Clear glass is also crushed and cleaned, and sized to a smaller particle diameter (<1 mm). Using patented technology, the white fines are blended with coloring pigments (other metal oxide powders), and formed into granules which are then distributed into the mold to form the top layer. Between 30 and 40 colors are available, and by controlling the "dozer" distribution pattern, colors may be distributed in such a way as to visually mimic a wide range of natural stones in the final product (granite, marble, gneiss, etc.). The mold is then passed through a kiln under carefully controlled residence time and temperature profile, producing the finished tile product in roughly one square meter sheets. These are then cut to size, depending on the application. The complete flowsheet for tile production is shown in Figure 5.

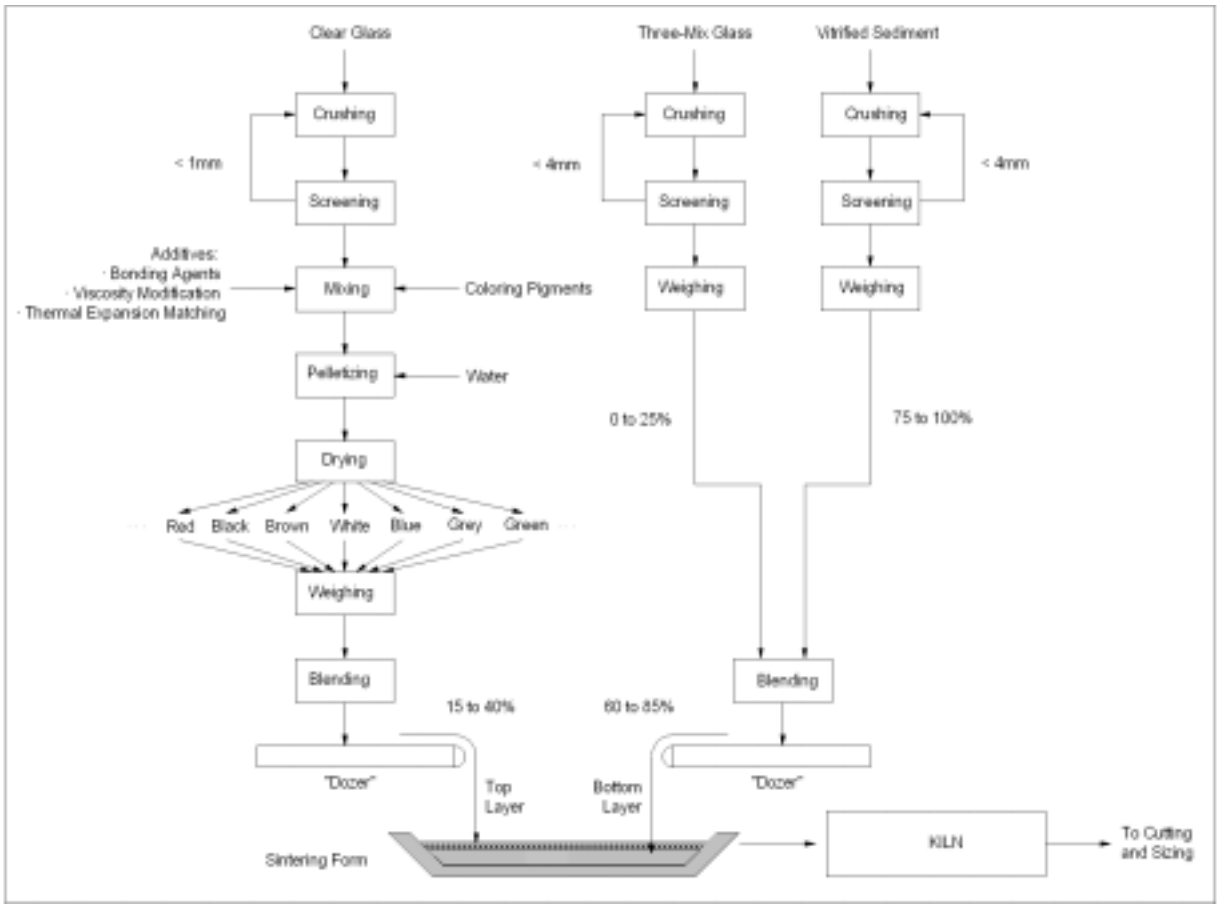

Figure 5 - Process Flow Diagram for Futuristic Tile Manufacturing Process

Futuristic Tile, working with Westinghouse, determined that vitrified sediment may be substituted for "three-mix" glass in the bottom structural layer of the tile. Initial testing with Phase I sediment glass produced good quality tiles using 100% sediment glass for the bottom layer. Based on the results of these exploratory tests, a Phase III program was initiated in which an additional 1,400 kg of sediment glass was prepared at PTC, crushed to <¼", and shipped to Futuristic Tile for conversion to tile.

The Phase III sediment glass was blended with slightly less flux than the Phase I samples, and therefore required a higher sintering temperature than for typical Futuristic Tile recycle glass operation. Because some of the pigments are temperature sensitive, and because higher sintering temperatures increase energy costs and require longer residence times, Futuristic Tile decided to blend the vitrified sediment with "three-mix" to obtain an optimized tile product. It was found that excellent quality tile could be prepared using bottom layer mixtures between 75 and 80% sediment glass, with the balance being "three-mix" (no other additives). Overall, the bottom layer represented 60 to 65% by weight of the total tile, so that a given Phase III tile was approximately 45% weight Harbor sediment glass.

Note that this sediment loading is low relative to what could be produced in commercial operation. Futuristic Tile has routinely produced tile with as low as 15 to 20% top glass. As was

noted above, the Phase I glass with slightly higher flux levels produced good bottom glass with no dilution by "three-mix." With only small increases in flux, the final tile could contain 80 to 85% sediment glass.

During Phase III testing, 1,000 kg of sediment glass were converted into approximately 2,200 kg of tile. Experience with production-scale quantities of sediment glass as tile feed, Futuristic Tile engineers have concluded that not only does this glass produce good quality tile, but that there is a significant processing advantage for using it in place of "three-mix." The quality of recycled glass is highly variable, depending on the degree to which a municipality sorts and segregates glass from non-glass materials. The presence on metallic debris (jar lids, bottle tops, etc.) require additional sorting and screening effort on the part of the tile maker. Organic material such as plastic and paper not successfully removed during sorting and crushing are generally destroyed during kiln operation, but may also introduce flaws and bubbles in the product, leading to breakage and scrap. Futuristic Tile has therefore concluded that sediment glass would be a "preferred feed material" to recycled glass, improved productivity from which would help to offset the higher cost.

A photograph of the four stages of conversion from raw sediment to final tile is presented in Figure 6. The figure illustrates the original harbor sediment, its appearance after dewatering and mixing with flux, samples of the aggregated sediment glass after plasma processing, and two examples of Futuristic Tile product made from the glass aggregate during February, 1999, Phase III testing. The tile has been subjected to product quality tests, and has been shown to be equal to or superior to the product which Futuristic Tile generally produces.

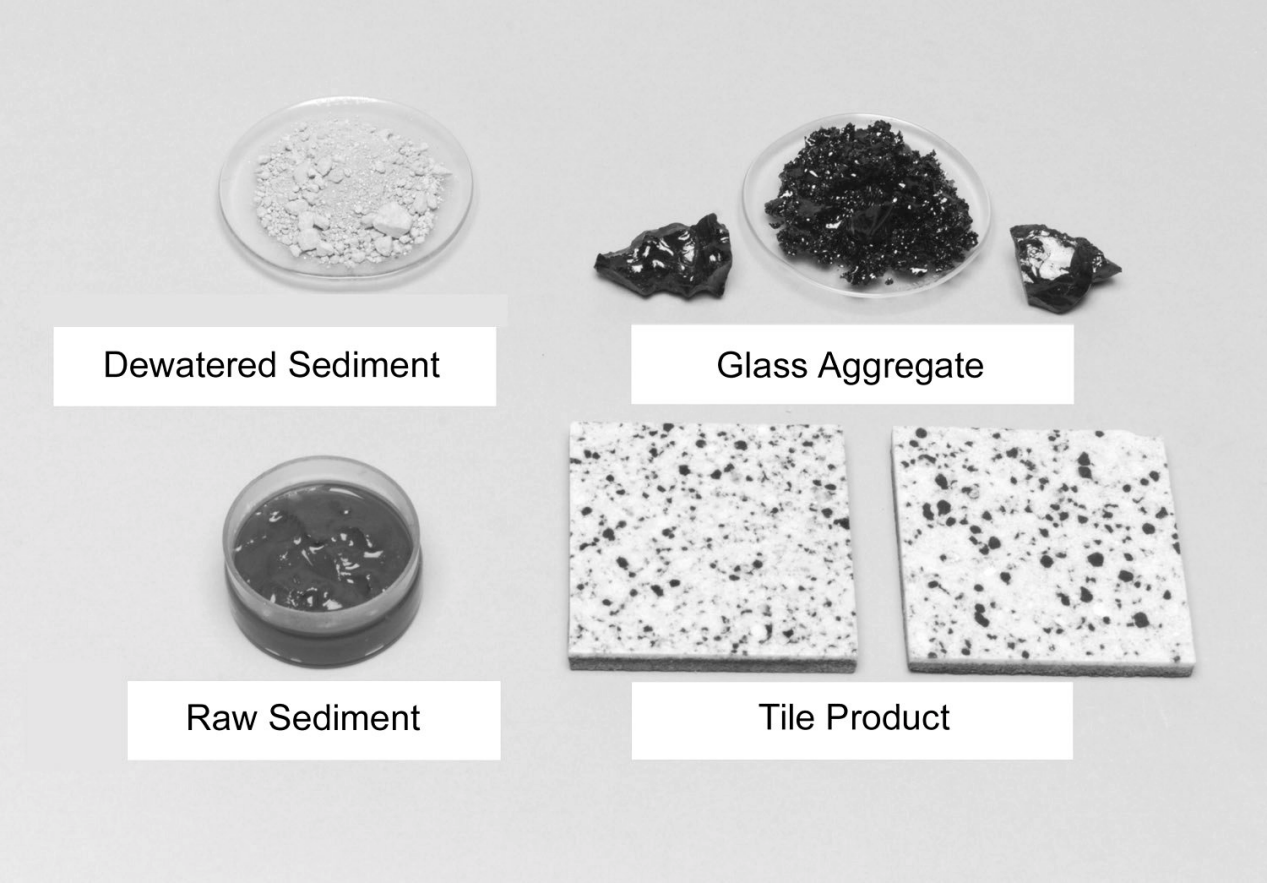

Figure 6 - Conversion of Raw Sediment into Finished Vitreous Tile

FULL-SCALE PLANT DESIGN AND TREATMENT COSTS

Following the success of the pilot plant demonstrations, a full-scale preliminary plant design was developed, based on the material balances shown in Figure 3 and Table 4. A summary of important parameters from this study is shown in

Table **7**. Two designs evolved from the Phase II studies, one for a 76,400 cubic meter (100,000 yd^3) per year demonstration facility, and a second for 382,000 cubic meter (500,000 yd^3) per year full-scale production; the latter plant is presented in the table.

Capital and operating costs were also developed, based around the previously presented flowsheet and material balance. These are also summarized in Table 7. The cost of electricity is the largest single factor in determining gross operating cost, representing 65 to 75% of the total figure. A range of electrical costs from $0.03 to 0.05 per kilowatt-hour were examined in sensitivity tests, although discussion with utility representatives in the New York City area indicated that at high volume the cost per kilowatt-hour could even be lower. Taking a nominal electrical cost of $0.04/kWh, the processing cost for the sediment is estimated to be $81/Mg. Including amortization of capital costs, the total gross processing cost for sediment treatment

from receipt of barged sludge to delivery of granulated sediment glass (suitable for tile manufacture) becomes

Table 7 - Summary of Full-Scale Sediment Treatment Plant Operating Parameters

Parameter	**Value (per metric tonne of dredged sediment)**	
Plant Capacity	500,000 yd^3/yr (461,000 Mg/yr)	
Turndown Capacity	12,800 kg/hr (20% of full load)	
Excess Capacity Built into Equipment Design	5%	
Sediment Delivery	Barge transport	
Plant On-Line Operating Factor	0.92	
Total Electrical Power Requirement	84 MWe (98% for plasma torch operation)	
Capital Cost Estimate	$81.4M	
Area 100: Pretreatment	$18.7M (23%)	
Area 200: Plasma Melters	$44.0M (54%)	
Area 300: Glass Quenching and Handling	$2.3M (3%)	
Area 400: Offgas Cleaning	$12.9M (16%)	
Non-Process Areas	$3.5M (4%)	
Land Requirement	8.2 acres (12 acres with glass product plant)	
Operating Cost	$30.5 to 44.1M/yr	$66.2 to 95.7/Mg
Chemical Raw Materials	$5.5M/yr	$11.9/Mg
Electricity (assuming $0.03 to 0.05/kWhr)	$20.5 to 34.1M/yr	$44.4 to 74.0/Mg
Other Utilities	$0.2M/yr	$0.4/Mg
Solids Disposal (oversize and $CaSO_4$)	$0.5M/yr	$1.1/Mg
Labor	$2.2M/yr	$4.8/Mg
Maintenance	$1.6M/yr	$3.5/Mg
Amortized Capital Cost	$12.2M/yr	$26.5/Mg
Total Sediment Processing Cost	$42.7 to 56.3M/yr	$92.6 to 122.1/Mg
Credit for Tipping Fee	($23.1M/yr)	($50/Mg)
Net Cost of Processing (Without Product	$19.6M/yr to 33.2M/yr	$42.5/Mg to $72.0/Mg

* Assumption that higher product manufacturing cost is associated with higher sale value.

$107.4/Mg. It is assumed in this analysis that "brownfield" industrial property for construction of the plant would be made available near the Harbor at no cost.

The net cost of processing with beneficial reuse must consider both the tipping fee received for treatment and disposal of the sediment, and the production costs and revenue associated with the final product. For the nominal case, it is assumed that essentially zero production costs are invested, and that the final product is roadbed aggregate, using the granulated sediment glass directly. (Note that for this application, a fully vitrified product may not be required, and that less expensive flux with less soda ash would probably be acceptable; no credit is taken for this detail). Roadbed aggregate typically sells for $7.50/ton, which converts to $2.33/Mg of dredged sediment (see material balance in Table 4).

A tipping fee for disposal of sediment must be assumed in order to project a net cost for treatment of the dredged material. For this purpose, a reference cost of $45/ton ($50/Mg) is assumed. This figure is based on current reported cost of disposal of sediment by stabilization and transfer to spent coal mines in Pennsylvania. Using the nominal $107/Mg vitrification cost, the nominal net cost of treatment is $55/Mg of dredged sediment.

In considering the economic viability of higher value products, one must consider the capital and operating costs for fabrication of that product, the "cost" of the sediment glass as compared to alternative feed materials (such as "three-mix" in the case of architectural tile), and impacts on the production process as a result of changing to sediment glass as the feedstock. As indicated above, demonstration tests with Futuristic Tile have shown that use of vitrified sediment will result in improved tile quality and productivity, due to the purity and consistency of the sediment glass. If an integrated sediment-to-tile process is considered, economic analysis by Westinghouse and Futuristic Tile indicates that the process will be profitable based on the reference design and tipping fee.

Note that with deregulation of the electric utility industry, the assumed $0.04/kWr electricity cost may reduce to $0.03 or even $0.02/kWh. The treatment cost to produce the vitrified aggregate would then reduce substantially to between $42 and $25/Mg of dredged sediment, resulting in greater economic margin for the overall sediment-to-tile production process.

As indicated above, any aggressive treatment option which truly destroys organic contaminants and immobilizes heavy metals will be more expensive than a procedure which seeks only to encapsulate contaminants, followed by landfilling (be it in an abandoned mine or engineered landfill). Although the economics of sediment vitrification followed by tile production appear to be favorable given a tipping fee based on competition with cement stabilization and landfilling, the overall economics of such a process improve with the degree of contamination of the material being treated. As contamination becomes more severe, the options for stabilization and disposal become fewer, and the treatment costs rise. The effective tipping fee against which the plasma vitrification process is to be compared therefore grows, making the overall process economics increasingly favorable. Even if low cost subaqueous burial within the Harbor (for example) were permitted for sediment with low contaminant levels, vitrification could remain the logical and economic approach to treatment of "hot spots."

This process is obviously not limited to harbor sediments, although this was the specific problem that WRDA and EPA resources were invested to solve. Many cases of Superfund sites exist where vitrification could be applied to treatment of highly contaminated sediments or sludges. The combination of near-quantitative destruction of organic contaminants, immobilization of heavy metals, and favorable economics for beneficial reuse of vitrified material make this process attractive for a wide range of applications.

CONCLUSIONS

Treatment and disposal of contaminated estuarine sediments will pose an increasingly costly problem to harbor managers and to communities which have a major investment in shipping as a livelihood. While many alternative treatment options such as cement stabilization plus landfill disposal are less expensive than the plasma vitrification process, these options depend on the continued availability of large areas of "free" land for disposal This represents an increasingly risky assumption for long term solution of the problem, the costs of which can only increase as public pressure against waste landfilling grows and land availability near such sites as New York City dwindles. In addition, such disposal options do not destroy any of the contaminants, but only move them to another, less sensitive, location. The ultimate liability still persists, which for many processes and sites has historically resulted in much larger legacy costs associated with later remediation.

The plasma vitrification process permanently and completely destroys all of the organic contaminants in the sediment, generating no organically-contaminated waste liquid streams in the process. The only wastes are treated oversize debris (which are partially decontaminated by washing) and a small stream of solid $CaSO_4$ which can be readily landfilled. The glass produced from this process has been demonstrated to be environmentally safe, meeting all EPA leaching requirements for the small quantities of heavy metals immobilized in the glass matrix. Coupled with options for beneficial reuse such as architectural tile for the environmentally safe glass product, this process provides an attractive option for permanent disposition of contaminated harbor sediments. A broad range of other applications are also apparent, including highly contaminated Superfund soil, sediment, sludge, and industrial waste remediations.

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