A PROPOSAL FOR INNOVATIVE SEDIMENT DECONTAMINATION TECHNOLOGIES USING A CROSS PROGRAM – CROSS MEDIA BUSINESS MODEL

Eric A. Stern[1], Keith W. Jones[2], W. Scott Douglas[3], and Huan E. Feng[4]

ABSTRACT

Essential features of a regional sediment decontamination *treatment train* program for processing dredged material to produce environmentally acceptable beneficial-use materials is critical to regional integrated sediment management. This train consists of components that include use of environmentally sound dredging methods, a storage facility that acts as a buffer to match disparate dredging and processing rates, decontamination technologies for removal of contaminants, and beneficial use of the post-treated material. This treatment train is being demonstrated during 2005-2006 using Passaic River, NJ Superfund sediment and navigational dredged material from the Port of New York/New Jersey. The near commercial level operations employ both a non-thermal sediment washing and a thermo-chemical rotary kiln technology to manufacture soil and construction-grade cement. On a commercial-scale level, ex-situ technologies need to be cost-competitive with other disposal/placement components of a dredged material management plan such as stabilization/solidification, CDFs, CADs, and containment islands. Important factors in the economic performance include the development of regional markets for the beneficial use products, and a long-term flow of dredged material to optimize the processing economics by keeping a system operating 24/7, 330 days/year. These are essential factors for securing the capital needed to develop a self-sustaining enterprise in sediment decontamination processing or *environmental manufacturing*. However, navigational dredged material alone does not support an attractive business model for sediment processing with innovative technologies because of uncertainties in dredging cycles and volumes, construction schedules, fish and spawning migratory windows, dredging contract litigation etc. The economic model can be improved by adding co-processing of contaminated sediments from Superfund sites, aquatic brownfields and upland contaminated soils, fly-ash, and kiln dust from RCRA programs, electronic-waste, and tires from solid-waste programs. This is needed to obtain higher income streams and the needed long-term multi-feed material to operate a regional facility with common-front end material handling capabilities for several technologies. Other beneficial use applications utilizing dredged material/contaminated sediments co-mingled with waste products for beneficial use include steam, and electrical generation from thermal systems. This is one application of environmental sustainability using different feedstocks to sustain a long-term economical operation in *environmental manufacturing* that is economically viable, but that requires cross-program coordination within state and federal regulatory agencies

Keywords: Decontamination, contaminated sediments, cross-media, Passaic River, beneficial use

INTRODUCTION

Sediment quality in the New York/New Jersey (NY/NJ) Harbor varies widely, but many areas are moderately to highly contaminated with both organic and inorganic compounds generated from historical and ongoing sources. Over the last decade, considerable efforts have been undertaken to evaluate methods to manage these sediments for both operation and maintenance (O&M) navigational dredging and environmental (source control) objectives. Sediment decontamination technologies with beneficial use applications comprise one component of an integrated contaminated sediment management program that shows promise for sediments that are too highly contaminated for more traditional, less expensive placement approaches.

---

[1] Regional Contaminated Sediment Program Manager, U.S Environmental Protection Agency, New York, New York 10007, USA, T: 212-637-3806, Fax: 212-637-3889, Email: stern.eric@epa.gov .

[2] Senior Physicist, Brookhaven National Laboratory, Environmental Sciences Department, Upton, New York 11973, USA, T: 631-344-4588, Fax: 631-344-5271, Email: jones@bnl.gov .

[3] Dredging Program Manager, Office of Maritime Resources/NJDOT, 1035 Parkway Avenue, Trenton, New Jersey 08625, USA, T: 609-530-4773, Fax: 609-530-4860, Email: scott.douglas@dot.state.nj.us .

[4] Associate Professor, Montclair State University, Earth and Environmental Studies Department, Upper Montclair, New Jersey 07043, USA T: 973-655-7549, Fax: 973-655-4072, Email: fengh@mail.montclair.edu .

Table of Contents

Since 1994, the U.S. Environmental Protection Agency – Region 2, New York (EPA) and the New Jersey. Department of Transportation – Office of Maritime Resources (OMR) have designed and implemented a program to demonstrate and evaluate innovative sediment decontamination technologies to manage contaminated dredged materials on a commercial-scale level (250,000-500,000 yd^3/yr) utilizing an integrated *treatment train* approach. The program focuses on the environmental and economic feasibility of conducting bench through full-scale demonstrations utilizing contaminated dredged material non-suitable for ocean placement from the Port of New York & New Jersey (Port). Beneficial use products derived from these different processes include manufactured soil, construction-grade cement, lightweight aggregate, composite bricks, architectural tiles, and geo-technical structural fill. The program has progressed in 2005-2006 to demonstrating, at a full-commercial scale level, decontamination of dredged material at a New Jersey centralized processing facility(s) using a non-thermal sediment washing as well as thermo-chemical rotary kiln technology

PORT OF NEW YORK & NEW JERSEY

The NY/NJ Harbor, located in the lower Hudson River estuary, is dominated by the New York City urbanized metropolitan area. It is a coastal area affected by human activities and industrial development (Figure 1). The Harbor complex is naturally shallow, with an average depth of 5.6 meters at low tide.

Figure 1. New York/New Jersey Harbor Estuary, USA

The Port of NY/NJ is the largest on the East coast of the United States, and is the third largest in North America (behind Los Angeles and Oakland), providing the region with $30 billion in annual direct and indirect benefits. It is also the largest petroleum distribution point in the United States. Due to the Port's strategic position in regional and international trade, the U.S. Army Corps of Engineers (USACE) is responsible for maintaining and dredging some 400 kilometers of engineered waterways/channels at depths ranging from 6.1 to 13.7 meters. Over the next several years, deepening the main shipping channels to 15.2 - 16.8 meters in order to bring in larger size container vessels, will be critical to *safe* navigation, and will require dredging of 3 - 4.6 million cubic meters of sediment, or dredged material annually. Unfortunately, the proximity to heavily industrialized urban land use, coupled with historical and ongoing discharges, has resulted in a legacy of contaminated sediments. While the region does permit *clean* dredged material that has passed federal government ocean testing criteria to be placed as cover material at the Historic Area Remediation Site (HARS), located 9.7 kilometers off coastal New Jersey, more than half of the material being dredged is too contaminated for this placement. This *non*-HARS contaminated material must be managed in a way that reduces its risk to the aquatic environment. This *non*-HARS sediment is managed by placement in either confined upland or confined in-water disposal sites, with an emphasis on beneficial use as geo-technical capping material for landfills, and brownfield redevelopment; construction of golf courses, and sub-base for shopping mall parking lots. This *non*-HARS material, and particularly material that is too contaminated for upland placement undergoing stabilization/solidification with Portland cement, could be the material most suitable for decontamination treatment processing.

CONTAMINANT DISTRIBUTIONS IN NY/NJ HARBOR

Contaminants such as heavy metals, PCBs, and PAHs have historically found their way to the NY/NJ Harbor from land-based, and non-point sources and atmospheric deposition. Point sources include sewage wastewater inputs to the lower estuary. Particle reactive organic and inorganic contaminants that have entered the water column from land-based sources can be scavenged by suspended particles and eventually settle to the bottom. Olsen et al. (1984) discussed that scavenging of these contaminants onto suspended particles followed by deposition in NY/NJ Harbor removes virtually the entire input of these contaminants. Recent studies in the Hudson River estuary including NY/NJ Harbor showed that metal concentrations in sediment cores had declined by 50-90% from their maximum levels attained in the 1960s and 1970s (Brosan et al., 1994; Chillrud, 1996; Feng et al. 1998). A strong co-variance of metal and synthetic organic contaminants (Ag, Cd, Cu, Pb, Zn, and PCB), as indicated by trends of excess metals against excess Ag and PCB (Feng et al., 1998), imply that although the sources of these contaminants may differ, they are mixed in the suspended sediment reservoir of the lower estuary and deposited in NY/NJ Harbor sediments.

While physical mixing of the sediments takes place, there are also local regions of *hot spots* of high contaminant concentrations where mixing has not resulted in their dispersal. This can be seen in the 3-dimensional spectral domain interpolation data plots of downcore sediment data plots of 2,3,7,8 -TCDD (dioxin) distribution in the lower 9.5 kilometers of the Passaic River, New Jersey (Ma et al. 1998) (Figure 2). Even though the Passaic River is a waterway with a dynamic tidal and current regime, local *hot spot* concentrations of dioxin can be seen, attributed to many historical point sources and depositional areas. Thus, a watershed assessment approach, coupled with remedial designs that will encompass sediment restoration of impacted areas with widespread contamination and, *hot spots,* will merit specific attention for treatment technology applications.

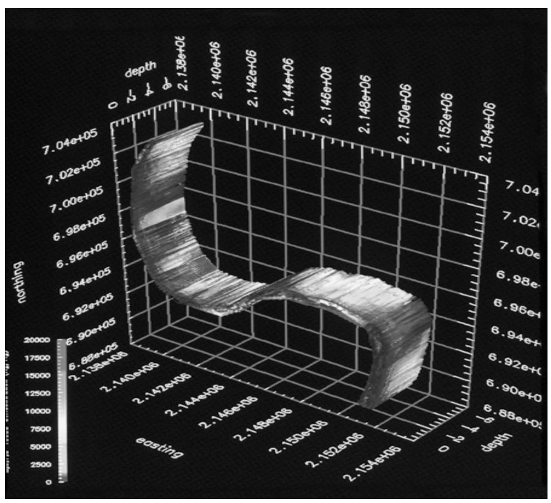
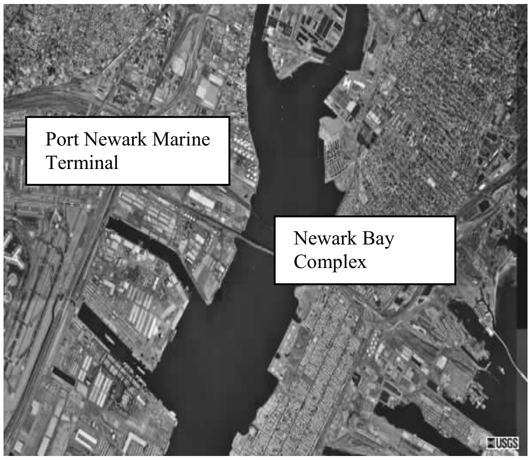


Figure 2. Three-dimensional plot of 2,3,7,8-TCDD (dioxin) concentrations downcore lower Passaic River - Newark, New Jersey .

Due to considerable efforts at sediment characterization, and over 20 years of environmental analysis assessments of dredged material, much is known about the geographic distribution and character of contaminated sediments in the Harbor. Of considerable concern to regional planners is the Newark Bay, Passaic and Hackensack River complex shown in Figure 3. Dredged material in these waterways is known to contain sediments that are too contaminated for HARS in-water placement. There are also *hot spots* where extremely high concentrations of metals and organics are found. Some of these *hot spots* have been shown to be a continuing source of contaminated sediment fluxes to the rest of the Harbor, ensuring that special management of navigational dredged material will be needed unless they are stabilized, capped and/or removed. The need for a multi-faceted integrated approach to sediment management is apparent. Unfortunately, this is complicated by the highly developed urban nature of the surrounding land area. Activities include Port commerce, transportation, chemical and petroleum manufacturing, as well as city centers and residential areas, all in close proximity. This mixed-use development pattern and highly congested land use, makes siting of dredged material decontamination facilities highly challenging.



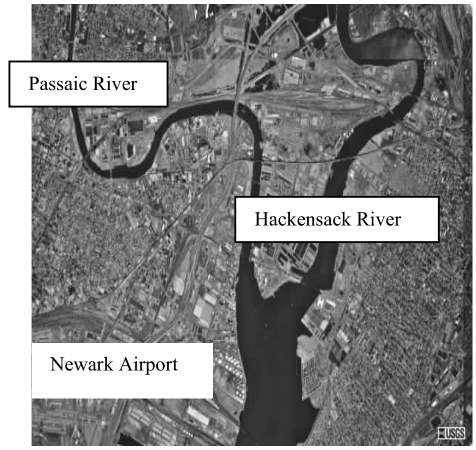


Figure 3. A region of particular interest for the decontamination program contains the Passaic, Hackensack - Newark Bay Complex, NJ. The left aerial view shows Newark Bay including Port Newark and Port Elizabeth Marine Terminal, a major container port for the region and the northeast US. The aerial view at the right, shows upper Newark Bay and the Passaic and Hackensack Rivers. Contaminant loading from both historically impacted rivers (dioxin, Hg, Cr, Pb, PAHs) will have an effect on navigational dredging and disposal of *non*-HARS dredged material in the Port. This is critical to the economic engine of the region.

INTEGRATION OF SEDIMENT DECONTAMINATION TECHNOLOGIES

One possible model for innovative sediment decontamination technologies is the integration into a program that includes both O&M navigational and environmental restoration dredging in order to have enough flow-through capacity for these technologies to succeed economically on a large scale. Other agency programs and projects that may benefit from treatment technologies include applications to brownfield restoration and revitalization (EPA-USACE/Urban Rivers Restoration Initiative), aquatic large-scale or *mega* Superfund sites, integration with CDFs and CADs in order to make them renewable, and environmental dredging and/or *hot spot* removals. Applications of co-generation utilizing a turbine for electrical generation with thermal technologies coupled with beneficial use / environmental manufacturing materials perhaps makes this application of innovative technologies a true environmental sustainability program – moving from *remediation* to *restoration*. The decontaminated sediment may be used beneficially as manufactured soil, construction-grade cement, lightweight aggregate, bricks, tiles, and/or geotechnical structural fill. These products and the economic benefits derived from their manufacture may in turn serve as an economic driver for the redevelopment of impacted waterways, ports and harbors, and adjacent impacted communities.

NY/NJ HARBOR FEDERAL /STATE PROGRAMS DECONTAMINATION PROGRAMS

EPA Sediment Decontamination Program

EPA Region 2 – New York, and the USACE - New York District, under authorization and funding from the congressional Federal Water Resources Development Acts (WRDA) of 1992, 1996, and 1999 was tasked to examine and demonstrate the feasibility for decontaminating estuarine sediments from the Port of NY/NJ. The Department of Energy – Brookhaven National Laboratory (BNL) has also been involved in the technical project management component of this program since its inception. The EPA decontamination program was conceived in order to develop options for dredged material management that could not be disposed of in the coastal HARS placement site after more stringent ocean testing guidelines were initiated in 1992. With more stringent guidelines in place, more dredged material failed ocean placement, which translated to a significant economic hardship overnight for the Port of NY/NJ and created a regional navigational dredging crisis.

Technologies chosen would need to demonstrate sediment decontamination at an environmentally and economically acceptable level. The charge of the congressional authorization was to evaluate those technologies that would both have the greatest potential for commercial scale-up applications at the level of 380,000 cubic meters per year (m^3/yr) on an individual technology basis, and would have a marketable end-product for beneficial use applications. The program progressed from a *proof of concept* bench or laboratory scale test through pilot and presently full/commercial-scale demonstrations on the order of up to 23,000 m^3. The intent of the program is to stimulate growth of long-term self sustaining enterprises in this business sector.

New Jersey Sediment Decontamination Program.

With incremental testing progress being made under the EPA Program during 1993 to 1998, the State of New Jersey Department of Transportation - Office of Maritime Resources (OMR) issued a competitive procurement process in 1988 under the New Jersey Environmental Bond Act. The purpose of this procurement was to *demonstrate new and innovative technologies that can decontaminate dredged materials, and to produce a marketable product at commercial-scale (500,000 yd^3/yr) levels at a cost of no more than \$35 per yd^3*. The OMR Decontamination Program is working closely with EPA in coordinating critical paths and milestones and by combining program resources to reduce overlap, and to fast-track commercial-scale implementation.

EPA has funded \$22 million towards development of innovative technologies since the inception of the program in 1993 while OMR under the NJ Bond Act has contracted up to \$20 million in their program; thus nearly \$42,000,000 has been funded in the NY/NJ Harbor region towards decontamination with beneficial use applications. The technologies tested under both programs (bench through full-scale demonstration) include (1) sediment washing (2) thermo-chemical rotary kiln (3) plasma-arc vitrification (4) base-catalyzed decomposition (5) thermal desorption (6) solvent extraction (7) fluidized bed reactor, and (8) solidification / stabilization with oxidation. Analytical testing, dredging, dewatering, permitting, siting infrastructure, community outreach, etc. all continuing components of this program. The EPA/OMR Sediment Decontamination Program has/is presently demonstrating four technologies at full/commercial scale; (1) Harbor Resources Environmental Management Group solidification /stabilization with oxidation (2005), (2) BioGenesis Sediment Washing (2006), (3) Gas Technology Institute / Endesco (Cement-Lock) thermo-chemical rotary kiln (2004-2006) and (4) Baycycle lightweight aggregate rotary kiln process (TBD). The EPA/OMR programs continue to collaborate with other technologies outside the programs such as the Minergy Glass Furnace Vitrification process which was bench-scaled on Passaic River, NJ sediments in 2004.

Full-scale demonstration of a commercial-scale start-up of a sediment washing system (manufactured soil) and a thermo-chemical rotary kiln process (construction-grade cement) will be underway in 2005-2006 at a regional staging site in Keasbey, NJ. Programmatic integration of sediment decontamination demonstrations with brownfields and Superfund tasks related to highly-impacted contaminated in-water sites such as the Passaic River, NJ, and Gowanus Canal and Newtown Creek, NY, is planned. These are regional waterways where the *clean-up* of contaminated sediments are vital to the restoration and economic revitalization of impacted communities coupled with a watershed management approach. Challenges to implementation such as long-term contracts, shared risk between public and private partnerships, and beneficial use testing and marketability need to be overcome to make use of the decontamination option/integration.

REGIONAL INNOVATIVE DEMONSTRATION TECHNOLOGIES

The EPA/OMR test program is now focused during 2005-2006 on full and commercial-scale demonstrations of two technologies. One is a low temperature sediment washing process developed by BioGenesis Enterprises, Oak Creek, Wisconsin). The other is a high-temperature process developed by the Gas Technology Institute/Endesco – (Cement-Lock) of Des Plaines, Illinois. These technologies complement each other in terms of the applicability to different types of sediment contamination levels. The siting of the low-temperature process is easier from the public acceptance standpoint and the capital cost of the equipment is also lower. The endpoint for beneficial use as a manufactured soil is a state soil criteria. On the other hand, the high temperature process is very effective in handling very high concentrations of organic compounds and in removing or *locking*/immobilizing metals in the crystal structure of the melted sediments.

Siting of decontamination technology demonstrations as well as for future commercial-scale operations has always been and continues to be a challenge. Siting for any upland industrial application for dredged material management/processing is also a long-term process and commitment. From the onset, the EPA/OMR sediment decontamination programs always envisioned a multi-technology / environmental manufacturing / beneficial use facility that would have an integrated up-front materials handling component that could "feed" several technologies. A *true* public-private partnership between the private sector, federal, state governments, and local municipalities are critical to the success of this model. The EPA/OMR programs have been working with one such facility, Bayshore Recycling Corporation, located on the Raritan River, NJ where the 2005-2006 BioGenesis demonstration took place. The Endesco Cement-Lock process will conduct their 2006 demonstration on Passaic River, NJ sediment at the IMTT facility located in Bayonne, NJ. Their material has already been dewatered (April, 2006) by BioGenesis and transported to its demonstration kiln.

BioGenesis Sediment-Washing Technology

The sediment washing technology is designed to decontaminate fine-grained (silt- and clay-size) particles by isolating individual particles and removing their sorbed materials, biota, and biofilm coatings. The process has been designed to use a five-step approach to achieve particle isolation and contaminant removal. A diagram of the BioGenesis process is shown in Figure 4.

A 540 m^3 pilot-scale demonstration was completed at the Koppers Coke Seaboard Brownfield Site, Kearny, NJ in March 1999. Surfactant chemistry, chelator (for metals) and oxidant (for organics) adjustments will increase system capability for achieving greater overall reductions when required. Beneficial use is a manufactured topsoil for landscaping, highway and Department of Transportation projects, polymer-sediment composite building material, daily land fill cover, and brownfield applications. Treatment results are compared against NJ Department of Environmental Protection residential /non residential soil criteria. The BioGenesis process is configured as a modular unit that can be assembled as a 192,000 m^3/yr system. In the event greater capacity is needed it could conceivably handle a throughput volume of 765,000 m^3/yr.

In January 2004, BioGenesis completed its 540 m^3 pilot-scale demonstration for the Port of Venice, Italy. EPA has been collaborating with the Port of Venice since 2000 in sediment decontamination technology technical transfer. The EPA Superfund Innovative Technology Evaluation Program (SITE) was involved in this Venice demonstration as well as the 2006 efforts by conducting a 2nd party analytical verification of residual products.

In Figure 4, the sediment pre-processor uses physical action to disaggregate sediment particles from each other, and to separate the loosely-associated material from a thin layer of organic matter (biofilm) absorbed on the surface of particles. The result is that clumped particles are disaggregated into the sediment slurry. These resulting finer particles are suspended in the water phase. In addition, organic compounds are fractionated and transferred to the water phase. Proprietary bio-degradable surfactants are added prior to the pre-processor to prepare the solids for decontamination by decreasing the affinity among contaminants, solids, and organic matter. Collision impact forces (physical action) are applied to the isolated particles in the collision chamber to strip the biofilm layer from the solid particles and also transfer it into the water phase. Contamination that was sorbed to the individual solid particles as well as the biofilm has been transferred to the water phase.

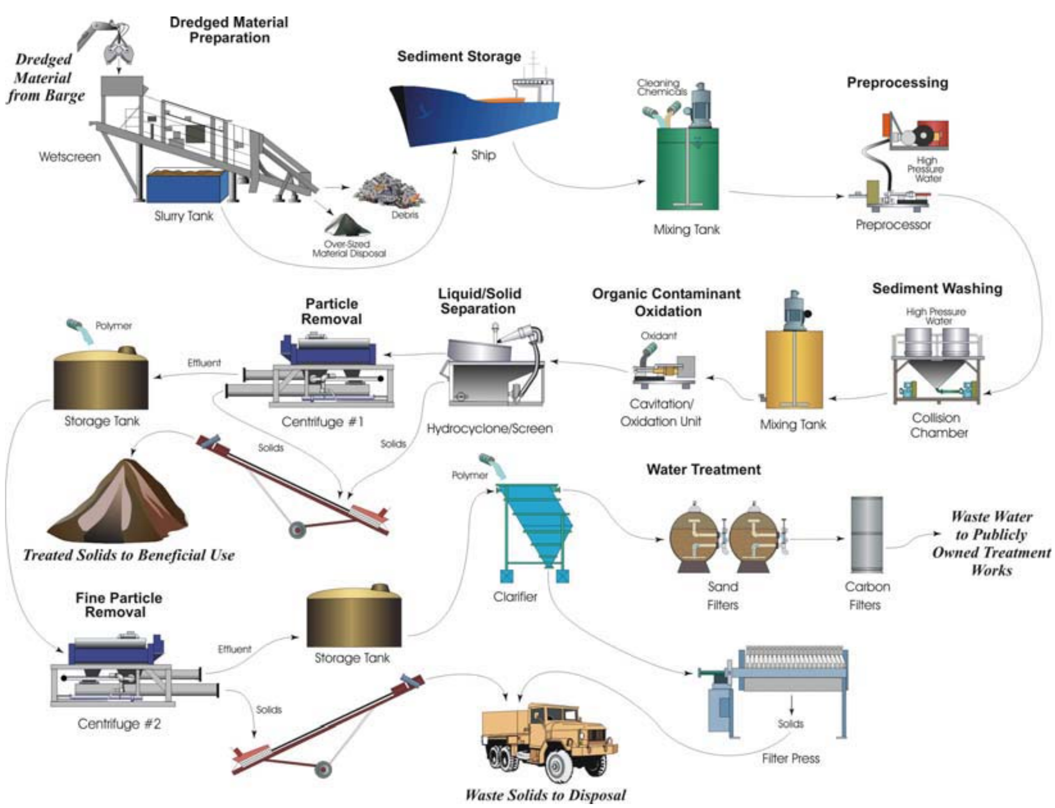


Figure 4. Diagram of the BioGenesis sediment washing process.

Destruction of the organic contaminants and organic matter which have been removed from the sediment particles is accomplished through cavitation and oxidation. After cavitation/oxidation, the slurry consists of 1) washed solid particles, 2) residual organic material in the aqueous phase that may still contain some organic and inorganic contaminants, 3) inorganic contaminants in the water phase, and 4) water that contains the majority of contaminants (primarily inorganic constituents) desorbed from sediment solids and organic material. At this stage, the slurry is ready for (5) liquid/solid separation, which results in a decontaminated solids fraction and a liquid fraction that contains inorganic and organic contaminants and residual sediment particles.

BioGenesis demonstrated in 2005-2006 a commercial-scale operation utilizing sediment from a navigational dredging project (7,600 m^3), and from a more highly dioxin contaminated site in the Passaic River, NJ (3,800 m^3). Results of the demonstration will demonstrate a *treatment train* approach to materials handling, the treatment and cost effectiveness of the technology, and beneficial use applications on a commercial scale level.

Endesco Cement-Lock Thermo-chemical Process

High-temperature processes were demonstrated by several different commercial developers during the early stages of the EPA program. Thermal energy was supplied in a fluidized bed reactor, plasma torch, and rotary kiln heaters. The operating temperatures varied, but in all cases were sufficient to destroy the organic contaminants and lock the less volatile metals in the matrix of the sediment minerals. The destruction efficiencies for the organic component was >99.99%. The product material met state criteria for leachate testing. High-value beneficial use products included architectural glass tiles, construction-grade cement, and lightweight aggregate. The high-destruction efficiency makes these processes useful for decontamination of sediments with high organic concentrations.

The Endesco Cement-Lock thermo-chemical process using a rotary kiln at temperatures of up to 1400^{o}C Cement-Lock (1) mixes sediments with modifiers, (2) melts the feed mixture at specific conditions for decontamination while promoting specific chemical/physical reactions, and (3) rapidly quenches the molten slag with water to immobilize the inorganic pollutants. State of the art pollution equipment includes secondary combustion for organic destruction, lime injection, baghouse, and carbon adsorption units for volatile metals such as mercury. The beneficial use product *Ecomelt*, is a glassy pozzolonic material that is pulverized and added to manufacture a construction-grade cement similar to Portland cement. Other interest is the utilization of this technology for processing of flyash, municipal solid waste (MSW), and electronic (E) waste coupled with a turbine for electric co-generation.

The Endesco demonstration is being carried out at the International Matex Tank Terminal (IMTT) site located in Bayonne, NJ. This testing program involved the design, permitting, construction, public outreach, and operation of a demonstration rotary kiln that is capable of processing 7500 m^3 of dredged material per year. From November 2004 – March 2005, Endesco processed 80 m^3 of navigational dredged material from a private applicant located in upper Newark Bay, NJ. This material was used for the start-up phase under slagging and non-slagging modes. The operational results were used to (1) troubleshoot equipment/processing challenges, (2) evaluate front end-material handling, (3) assess the acceptability of the emissions from the plant (4) determine the destruction efficiency of the organic constituents (5) evaluate the leachability of inorganics (6) determine the quality of the ashed sediment and *Ecomelt* produced for beneficial use, and (7) derive the process economics. In 2006, Endesco will be re-vamping their front-end material handling system as well as making modifications to the kiln melter itself. This will be in preparation for further confirmation testing on navigational dredged material and on Passaic River Superfund sediment. A diagram of the system process is given in Figure 5. Photographs of the Endesco demonstration plant in Bayonne, NJ are shown in Figure 6.

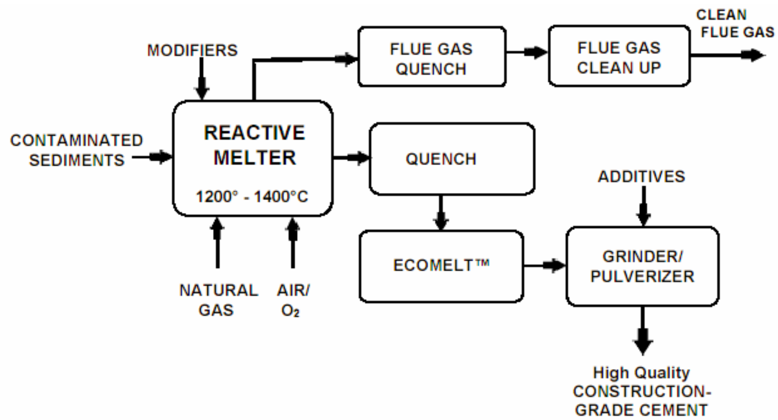


Figure 5. Endesco process flow for cement production from contaminated dredged material. The modifiers, such as $CaCO_3$ are added to optimize composition for best process conditions and product quality.

Figure 6. A general view of the Endesco thermo-chemical rotary kiln facility – Bayonne, NJ

CONCLUSIONS

Full-scale demonstration of a thermo-chemical rotary kiln process (cement) and commercial-scale start-up of a sediment washing system (manufactured soil and building materials) will be under way in 2005-2006 at a centralized processing site in NJ with barge access. On a commercial-scale level, ex-situ technologies need to be cost-competitive with other disposal and placement components of a dredged material management plan such as stabilization/solidification, CDFs, Confined Aquatic Disposal (CADs, and containment islands. Important factors in deciding economic performance include the development of regional markets for beneficial use products, and a long-term flow of dredged material in order to optimize the processing economics by keeping a system operating 24/7, 330 days/year. These are essential factors for securing the capital needed to develop a long-term self-sustaining enterprise in sediment decontamination processing or *environmental manufacturing*. Technology developers have long expressed frustration in not being able to secure long-term contracts that would make it attractive to investors in the private sector. Coupled with uncertainty in dredging cycles and volumes, construction schedules, fish and spawning migratory windows, dredging contract litigation, etc., navigational dredged material does not support an attractive business model for innovative technologies. Besides navigational dredged material programs, co-processing of contaminated sediments from highly contaminated mega-aquatic Superfund sites, aquatic brownfields (including upland contaminated soils), fly-ash, kiln dust, electronic-waste, and tires from solid-waste programs could contribute long-term multi-feed material situated at a regional facility with common-front end material handling capabilities. Other beneficial use applications utilizing dredged material-contaminated sediments co-mingled with waste products for beneficial use include steam and electrical generation from thermal systems. This is one application of environmental sustainability using different feed stocks to sustain a long-term economical operation in *environmental manufacturing*.

ACKNOWLEDGMENTS

Research supported in part by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 and through Interagency Agreement DW89941761-01 between the U.S. Environmental Protection Agency and the U.S. Department of Energy (KWJ, HF).

REFERENCES

Brosnan, T. M., A. I. Stubin, V. Sapienza, and Y. G. Ren. (1994). "Recent Changes in Metals Loadings to New York Harbor from New York City Water Pollution Control Plants. In C. P. Huang (Ed.) *Hazardous and Industrial Wastes*, pp. 657-666.

Chillrud, S. N. (1996). "Transport and Fate of Particle Associated Contaminants in the Hudson River Basin." Ph.D. Dissertation, Columbia University, Palisades, New York, NY.

Ebert, D. and H. Rushmeier (eds.). *Proceedings of Vis98 (IEEE Visualization 1998)*. Research Triangle Park, North Carolina. The Institute of Electrical and Electronics Engineers. ACM Press, New York, New York. Pp.467-470.

Feng, H., J. K. Cochran, H. Lwiza, and Brownawell, B., (1998). "Distribution of Heavy Metal and PCB Contaminants in the Sediments of an Urban Estuary: The Hudson River." *Marine Environmental Research. 45*: 69-88.

Ma, H., Jones, K.W., and Stern, E.A., (1998). "Scientific Visualization and Data Modeling of Scattered Sediment Contaminant Data in the New York/New Jersey Harbor Estuary".

Olsen, C. R., I. L. Larsen, R. H. Brewster, N. H. Cutshall, R. F. Bopp, and Simpson, H.J., (1984). "A Geochemical Assessment of Sediment of Sedimentation and Contaminant Distributions in the Hudson-Raritan Estuary." NOAA Technical Report NOS OMS 2.