

Evaluation, Design, and Construction of Amended Reactive Caps to Restore Onondaga Lake, Syracuse, New York, USA

DIMITRI VLASSOPOULOS^{1*}, KEVIN RUSSELL², PAUL LAROSA³, RANDY BROWN²,
RAM MOHAN⁴, EDWARD GLAZA⁵, TOM DRACHENBERG⁵, DANNY REIBLE⁶,
WILLIAM HAGUE⁷, JOHN MCAULIFFE⁸ AND STEVE MILLER⁸

¹Anchor QEA, LLC, 421 SW Sixth Avenue, Suite 750, Portland, OR 97204, USA

²Anchor QEA, LLC, 290 Elwood Davis Road, Suite 340, Liverpool, NY 13088, USA

³Anchor QEA, LLC, 9 Water Street, First Floor, Amesbury, MA 01913, USA

⁴Anchor QEA, LLC, 404 E. Savannah Road, Unit 3, Lewes, DE 19958, USA

⁵Parsons Corporation, 301 Plainfield Road, Suite 350, Syracuse, NY 13212, USA

⁶Texas Tech University, Box 41023, Lubbock TX, 79409, USA

⁷Honeywell International Inc., 115 Tabor Road, Morris Plains, NJ 07950, USA

⁸Honeywell International Inc., 301 Plainfield Road, Suite 330, Syracuse, NY 13212, USA

Onondaga Lake is a 12-square-kilometer urban lake located in Syracuse, New York, USA. The legacy of industrialization and municipal development since the late nineteenth century resulted in impaired water quality and contamination of lake sediments. A comprehensive lake restoration plan was developed following two decades of intensive multi-disciplinary technical studies. The restoration plan includes removal of approximately 1.5 million cubic meters of lake sediments (completed November 2014, one year ahead of schedule); transport of the dredge slurry through a 6.5-kilometer-long, double-walled pipeline; and dewatering in geotextile tubes strategically placed in a dedicated 20-hectare

upland confined facility. More than 160 hectares of the lake received an engineered cap to isolate the remaining contamination after dredging and provide a habitat restoration surface. The deepest portion of the lake will be monitored for ongoing natural recovery. The restoration and design process involved close coordination and discussions with multiple regulatory agencies and stakeholders and was supported by several technical studies, including: 1) development of sediment and fish tissue remedial goals; 2) detailed evaluations of capping, dredging and upland containment, natural recovery, and nitrate addition to the lower part of the lake water column (to limit production of methyl mercury); and

*Corresponding author e-mail: dvllassopoulos@anchorqea.com

3) integration of habitat restoration into the lake-wide cleanup effort. As one of the largest sediment capping projects constructed to date, the multi-function cap design incorporated several innovative components, including site-specific biodegradation and reactive media (activated carbon [AC] for contaminant sequestration and siderite amendment for pH control) to ensure remedial performance requirements for long-term chemical isolation and habitat restoration were met. The innovative capping concepts were developed through multiple years of field investigations, laboratory and bench-scale studies, and field pilot testing. In addition, state-of-the-science contaminant migration and cap effectiveness modeling studies were conducted to evaluate the required layering of the cap and to optimize the amendment media and required dosage for the various layers. Successful integration and regulatory acceptance of these unique design features provided opportunities for significant optimization of raw material needs (cap thickness and amendment dose). The innovative study methods also resulted in streamlined and efficient construction, while retaining environmental effectiveness. Construction began with a field pilot project in 2011, followed by full-scale field implementation in 2012; sediment removal was completed in 2014 and lake capping was completed in 2016. Details of the study methodology, analysis of amendment and cap effectiveness (laboratory testing and modeling), and construction verification methods and monitoring results are presented in this paper.

Keywords: Capping, sediments, remediation, amendment, lake, restoration, dredging

INTRODUCTION

Figure 1 illustrates Onondaga Lake, a 12-square-kilometer urban lake located in Syracuse, New York, USA, that has been impacted by past industrial and municipal activi-

ties. Contaminants of concern (COCs) include mercury from a former chlor-alkali facility, multiple organic contaminants (volatile and semi-volatile organic compounds and polychlorinated biphenyls) from other chemical/manufacturing operations, and hyperalkaline (pH greater than 12) inorganic materials. The selected lake restoration measures included dredging approximately 1.5 million cubic meters of contaminated sediment and placing the material in an upland sediment consolidation area. The sediments were dewatered using geotextile tubes and the effluent treated to meet discharge requirements. More than 160 hectares of subaqueous cap was placed within the lake to isolate a portion of the impacted sediments in place. Habitat restoration also played a critical role in the project, and dredge cuts and cap surfaces were designed to provide suitable habitat throughout the capping area. Several technical studies were completed during the design of this complex environmental remediation and restoration program. Studies included: developing sediment and fish tissue remedial goals; detailed evaluations of capping, dredging, upland disposal, natural recovery, and nitrate addition to the lake's lower waters (to limit production of methyl mercury); and integration of habitat restoration into the lake-wide cleanup. More than 6 years of pre-design field investigations were conducted to collect critical information necessary to complete the design. The sampling program included sediment core sampling, porewater sampling, seepage measurements, surface water sampling, sampling of biota (sport fish, prey fish, and benthic macroinvertebrates), geotechnical testing (e.g., standard penetration testing and vane shear testing), and a comprehensive multi-year baseline monitoring program consisting of key water quality and biological parameters.



FIGURE 1
Onondaga Lake and environs.

One of the more challenging aspects of the project was the design of the cap system. Cap design involved several unique assessments, including site-specific biodegradation and innovative reactive media, which were evaluated through laboratory and modeling studies (Kiehl-Simpson et al. 2011). Cap effectiveness was simulated via numerical computer modeling of the transport of mercury and several organic chemicals through the proposed cap. This involved the use of a chemical fate and transport model to predict contaminant concentrations within the various layers of the proposed cap over time to assist in specification of the thickness and sorptive capacity (e.g., AC dose) needed to meet risk-based design goals. The design life of the cap predicted

based on the numerical modeling is at least 1,000 years, as required by the regulatory agencies; this is believed to be the most robust sediment remediation cap ever designed. The final surface of the cap is also conducive to the establishment of desired habitat features over time, which are expected to provide habitats for a wide variety of native species (i.e., fish, reptiles, amphibians, invertebrates, mammals, and plants). The completed in-lake habitat will be tied to the shoreline habitat through the lake-wide restoration program.

In the sections that follow, the challenging technical aspects associated with the cap design, including laboratory studies, amendment and cap effectiveness assessments (testing and modeling), and construction verification

methods and monitoring results, are discussed in more detail.

TECHNOLOGY DEVELOPMENT – MEANS AND METHODS

Approximately half of the 160-hectare sediment cap incorporates reactive amendments to sequester contaminants and neutralize elevated porewater pH associated with hyperalkaline sediments. Amendments are critical to ensure long-term isolation and biodegradation of organic contaminants including BTEX compounds, chlorinated benzenes, and naphthalene. Extensive pre-design investigations included collection of sediment, porewater, and groundwater upwelling data, in combination with laboratory experiments and chemical fate and transport modeling to identify the most effective amendments.

Building upon basic research and experimental design used historically for smaller scale contaminated sediment sites, an experimental approach was taken to evaluate the performance of various cap amendments for sequestering COCs. Sorption isotherm studies (e.g., similar to those reported in McDonough *et al.* 2008) were performed with the following candidate amendment materials that have been used as cap amendments in past projects (e.g., ITRC 2014): peat, AC, and organoclay. AC was ultimately identified as the amendment of choice in terms of effectiveness.

An extensive series of laboratory bench-scale studies was conducted to evaluate biological degradation of site organic contaminants, which is a key process integrated into cap effectiveness. Initial stages of batch and column laboratory testing indicated that anaerobic degradation can occur naturally in

most areas of the lake, but that it would likely not occur at significant rates in areas with elevated pH porewater without prior neutralization. More extensive batch slurry testing with site sediments and porewater, which consisted of over 70 experimental treatments conducted in triplicate to provide additional detail on biological degradation rates, mechanisms, and geochemical processes, document organic COC biodegradation under both aerobic and anaerobic conditions. Those studies also showed that degradation was inhibited for porewater in which pH was elevated due to hyperalkaline sediment deposits. However, this testing also confirmed that biodegradation could reliably occur after pH adjustment to values below 8. Despite the inherent complexities involved in replicating long-term environmental processes with relatively short-term laboratory studies, the observed rates of anaerobic degradation from the batch slurry studies were well within the range of rates documented in the literature (e.g., Howard *et al.* 1991).

The need for a reactive amendment to provide long-term pH control and facilitate biodegradation, as well as the need to provide suitable habitat conditions at the cap surface, presented a unique challenge. Several materials, including compounds of hydrolysable metals (e.g. containing iron and/or aluminum) and peat were screened in batch kinetic tests with site porewater (pH 12, sodium-calcium-chloride brine) over a range of liquid-to-solid ratios. Siderite (FeCO_3), a naturally occurring mineral-based amendment (O'Day and Vlassopoulos 2010), was found to be the best option due to favorable kinetics (reaction completed within days to weeks; Figure 2), circumneutral final pH, and long-term buffering capacity due to its limited solubility (Vlassopoulos *et al.* 2011, 2013a,b).

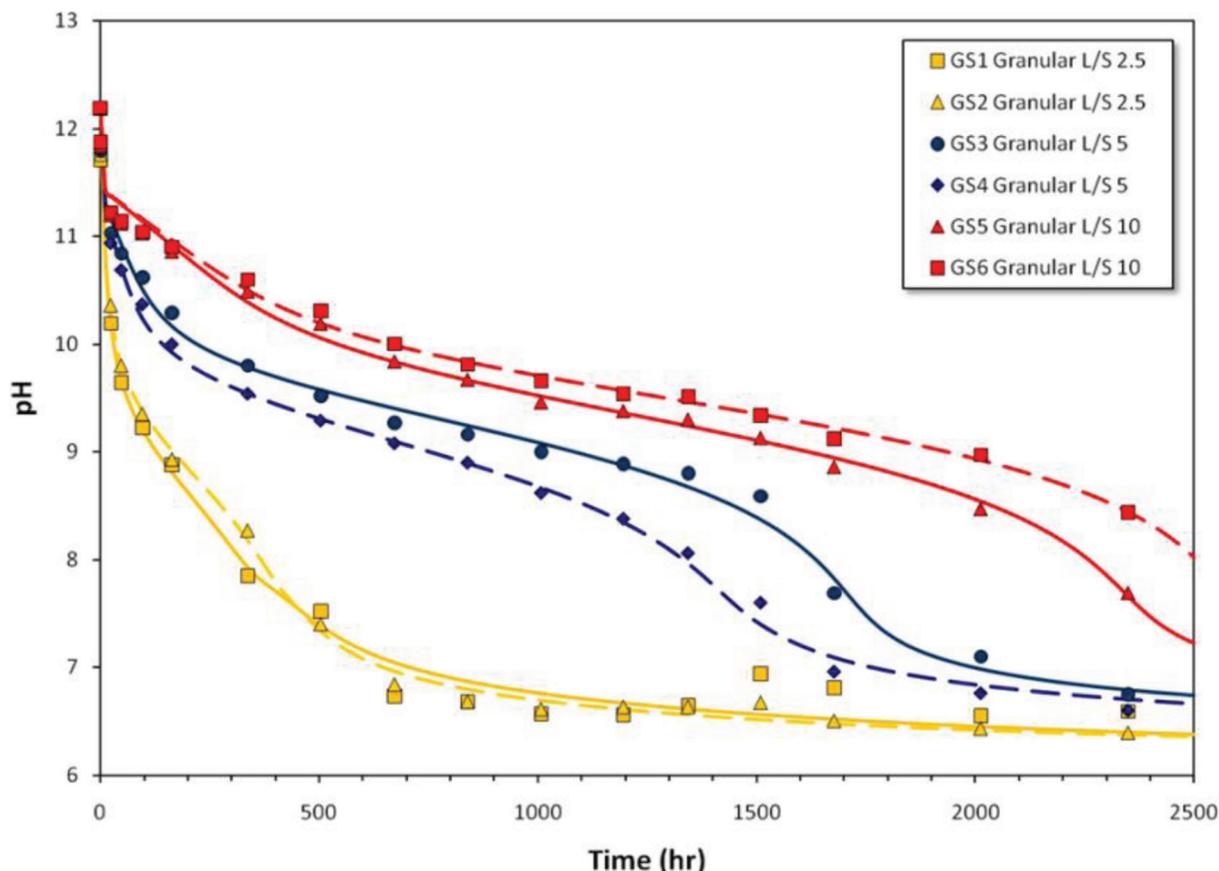


FIGURE 2
Porewater pH neutralization by siderite.

Geochemical and microscopic investigations revealed that the dissolution of siderite consumed hydroxyl (OH^-) and resulted in the precipitation of iron oxyhydroxide (FeOOH) and calcium carbonate (CaCO_3), a solid phase mineral assemblage which buffers pH to a final value near 7 (Figure 3). The process can be described according to the following overall reaction:



Laboratory column tests using site porewater, under dynamic flow conditions represent-

ative of groundwater upwelling through the contaminated sediments, confirmed that pH neutralization could be achieved with relatively modest doses of siderite (e.g. as low as 2% by weight in a 15-centimeter-thick sand layer; Figure 4).

CAP MODELING AND ENGINEERING DESIGN

As described in the previous section, isotherm testing and bench-scale studies were performed to evaluate the effectiveness of various adsorptive amendment materials to

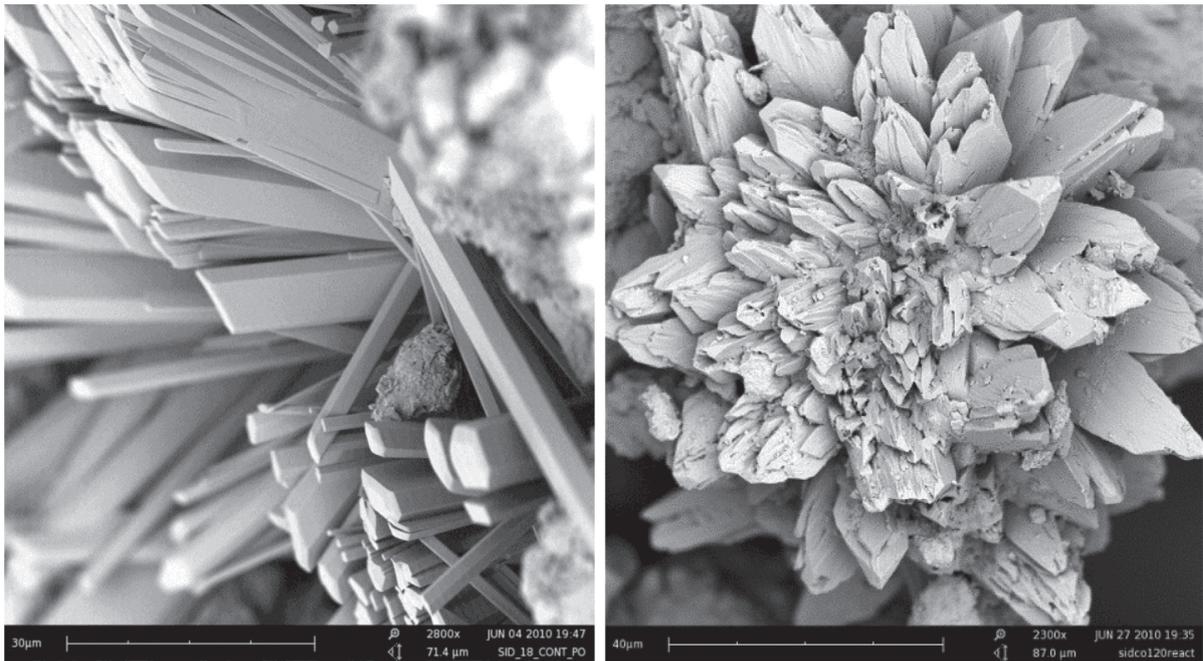


FIGURE 3 Scanning electron microscope images of products of siderite reaction with high pH porewater – iron oxyhydroxide (left) and calcium carbonate (right).

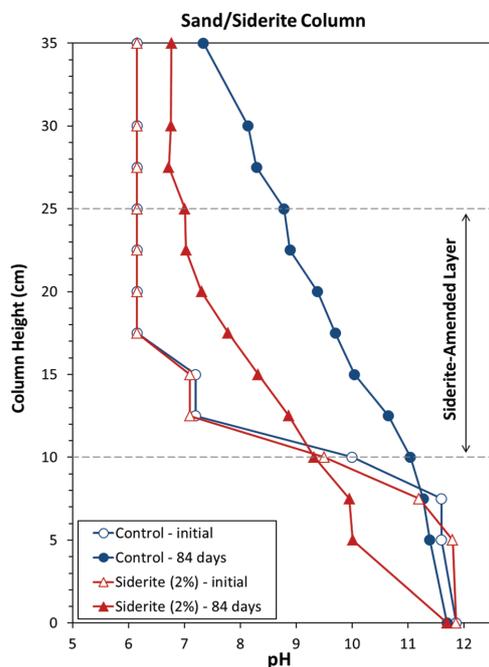


FIGURE 4 Sand-siderite column testing results. Flow was upward at a rate of 0.27 cm/day.

enhance the chemical isolating functions of the cap; based on these studies, AC was selected. Following the isotherm and bench-scale studies, numerical modeling was performed to develop the chemical isolation component of the cap design. Chemical isolation is achieved through placement of a clean cap material containing adsorptive amendment material (as needed) to inhibit contaminant migration for a long timeframe (1,000 years or more was used in this study based on regulatory agency requirements). This long-term isolation is the result of contaminant adsorption onto the cap materials, as well as contaminant biodegradation within the cap.

Detailed computer modeling was conducted to predict the movement of mercury and several organic chemicals through the proposed cap. This effort involved the use of a chemical fate and transport model (Lampert

and Reible 2009; Go et al. 2009) to predict COC concentrations within the various layers of the proposed cap to assist in specification of the thickness and amendment dose needed to meet risk-based design goals. Transient numerical modeling was used to predict time-varying COC concentrations within the cap system as part of this study and confirm predicted concentrations at the end of a 1,000 year simulation period would be at or below the design goals. This simulation period was based on regulatory agency requirements and was selected in conjunction with other model inputs to achieve a realistic, yet appropriately conservative design. The 1,000 year life cycle exceeds that used for most other capping projects. However, this variable was a key means of adding conservatism. Values for other model inputs were specified in light of this approach—for example, the groundwater upwelling velocity used to simulate a given capping area was specified based on the spatial average rather than a maximum value. Unique and innovative aspects of this modeling included: simulation of non-linear adsorption processes for AC within the cap (based on the Freundlich (1926) equation); simulation of time-variable upward porewater advection to represent short-term increases due to consolidation settlement of underlying sediments following cap placement; time-variable biodegradation rates to account for a lag time associated with the establishment of a biological community following the initial pH buffering period; and a long-term simulation of fate and transport within the amended cap areas. Monte Carlo simulations were also performed as part of the modeling study to account for the variability in the site data, including porewater concentrations, Freundlich AC isotherm parameters, and groundwater upwelling, which were used to parameterize the model.

A reactive transport model was also developed and applied to simulate evolution of porewater pH within the amended cap using the PHREEQC geochemical modeling software (Bessinger et al. 2012; Vlassopoulos et al. 2013a). The model simulates porewater advection and solute dispersion and diffusion within the cap, as well as the kinetics of siderite dissolution (pH-dependent kinetic rate law) and precipitation of secondary solid phase products, with site-specific reaction rate constants derived from the batch experiment data. The cap pH model was used to evaluate the extent of pH neutralization under different sediment cap designs, conduct sensitivity analyses to assess potential effects of vertical segregation of amendments during subaqueous cap materials placement, and develop optimal siderite dose estimates for different cap areas.

Engineering design evaluations for the chemical isolation layer also included consideration of constructability, cost effectiveness, and other engineering factors. Given the vast area to be capped (including some areas where dredging was planned and others not), it was critical that the cap design be optimized to meet performance criteria without excessive conservatism beyond the design requirements specified in the Record of Decision (ROD) issued by the regulatory agencies. Therefore, the total capping area was divided into approximately 20 different zones based on the variability in observed sediment and porewater contaminant concentrations, porewater pH, groundwater upwelling velocities, and other site characteristics. Area-specific cap designs were developed with siderite and AC amendment doses optimized to achieve the design goals in each zone.

Based on the bench-scale testing and results from the cap modeling summarized above, the chemical isolation layer of the cap was

designed to consist primarily of sand or gravelly sand with AC and siderite amendments incorporated into the cap in certain areas to promote long-term effectiveness of the cap.

In addition to the chemical isolation design modeling described above, computer modeling was also performed to evaluate and design the erosion protection layer of the cap to resist forces such as currents, waves, ice, and vessel propeller wash. Given the size of the lake and the available fetch distances, wind-induced waves were typically a driving force for the erosion protection design for the caps.

Finally, species-specific habitat requirements and remediation objectives were evaluated to determine the composition and thickness of an additional habitat layer to comprise the top surface of the cap. In some locations, the habitat requirements were consistent with the grain size requirements for erosion protection such that a single layer could effectively provide both functions.

Figure 5 presents a general schematic of the multi-layer amended cap. From the base upward, the layers include: 1) pH control layer (sand/siderite blend); 2) chemical isolation

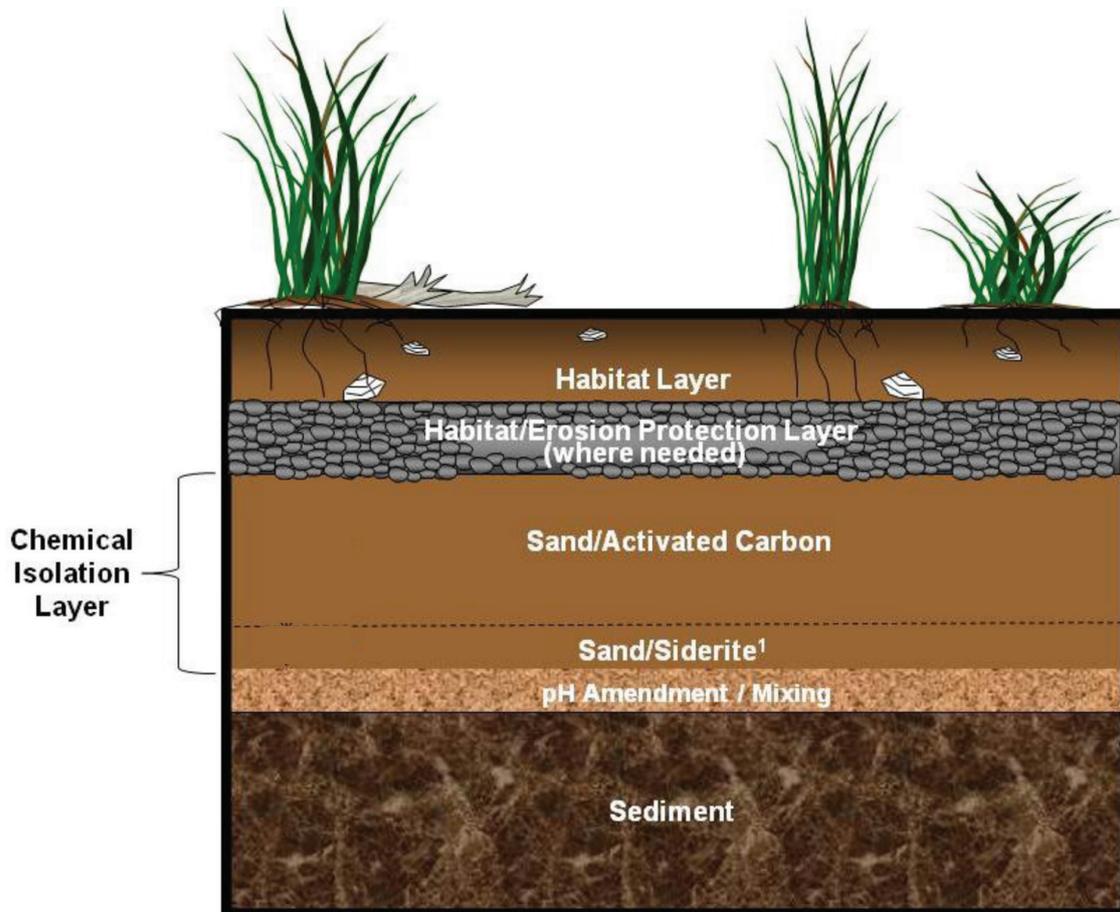


FIGURE 5
Example schematic of an amended cap.

layer (sand/AC blend); 3) erosion protection layer; and 4) habitat layer. The thickness of these layers varied based on location-specific designs, but were also required to meet minimum thicknesses outlined in the ROD. In areas where chemical isolation amendments were not required to achieve long-term chemical isolation, the cap design profile was similar except that the chemical isolation layer consisted of a minimum of 30 centimeters of sand only, consistent with the ROD.

FIELD CONSTRUCTION – PILOT- AND FULL-SCALE DATA AND RESULTS

Placement of the multi-layer cap presented an unprecedented challenge to the project

team. The cap consists of more than 2 million cubic meters of cap material and includes siderite and granular AC amendments. Cap installation required consideration of several factors, including desired high production rates, cap placement over very soft sediments and slopes, and ability to mix amendments into the cap in a uniform manner. To meet this challenge, the project team developed a multi-faceted approach to placing the cap and measuring the suitability of the completed cap relative to the design standards.

A specialty contractor (Sevenson Environmental Services) was selected to place the materials using a combination of mechanical and hydraulic placement techniques. Mechanical placement techniques (Figure 6) were generally used for the placement of gravel and cobble layers. Sand layers containing siderite



FIGURE 6
Mechanical cap placement.



FIGURE 7
Hydraulic cap placement using Sevenson's spreader barge. Photo courtesy of Sevenson Environmental.

or AC amendments were generally placed hydraulically via a specially fabricated hydraulic spreader barge (Figure 7).

To test the ability of the spreader barge to place a uniform layer of amended cap materials, the design and operations team completed numerous column studies in 2010 and 2011 to evaluate the effectiveness of placing a combined sand and AC chemical isolation layer. This included construction and use of an approximate 1-meter-square, 7-meter-tall settling column, with observation ports along the height of the column (Figure 8). The design height of the settling column allowed the team to conduct the demonstration in water depths representative of those in which capping was to be performed. The demonstration was done using multiple sand and AC mixes, application methods, and water depths. The

sand/AC mixture was hydraulically pumped into the top of the column and allowed to settle. Visual observations of the sand and AC that settled to the bottom of the column showed a well-dispersed dose of AC throughout the deposited layer. Samples for analytical confirmation testing of the deposited AC dose were removed by test pans similar to those used for sampling in the lake during construction. The test included input from the technical team as well as observations by the regulatory agency and experts in the field. Testing results were positive and achieved good mixing of AC and sand following settlement within the column. A range of granular AC particle sizes was evaluated in the column studies. No significant improvement in placement or mixing of the AC throughout the placed sand/AC layer was noted for the



FIGURE 8
Laboratory physical model evaluation of cap and amendment settling velocities and layer consistency post placement.

larger sized AC based on visual observations. Therefore, an AC with smaller sized particles was selected as the preferred amendment because it would result in a higher number of particles for the same application rate and, thus, more dispersed distribution of the AC throughout the sand/AC layer.

Based on the success of the AC large column settling tests in demonstrating the potential effectiveness of placing a chemical isolation layer consisting of a mixture of sand and AC, a capping field demonstration was completed in 2011 using full-scale capping equipment. The field demonstration was designed to provide additional design- and construction-related information necessary to place the AC-amended chemical isolation layer with precision. The hydraulic spreader barge placing the AC-amended sand layer was

specifically fabricated for this project, and the field demonstration was used to optimize the processes needed to place the layer uniformly both horizontally and vertically. A sand/AC slurry was generated from a land-based feed system (Figure 9). The feed system mixed sand and AC into two independent slurries with water. Then the AC/water slurry was mixed into the sand/water slurry at a constant feed volume to create sand/AC slurry with a known AC concentration. The sand/AC slurry was pumped to the hydraulic spreader barge where the slurry was passed over a spreader plate, which diffused the energy of the slurry across the entire width of the spreader barge and allowed it to settle by gravity through the water column to the sediment surface.

During the demonstration test, several modifications were made to the energy diffuser



FIGURE 9
Sand/AC slurry mixing tanks.

plate to maintain well-mixed slurry and minimize particle separation during settling. The optimal orientation tested during the demonstration included the addition of a horizontal metal grate at the end of the energy diffuser plate with an attached rubber belt extending across its entire height and width (Figure 10). These modifications forced the slurry to exit the spreader plate evenly across the metal grate, aiding the uniformity of in situ sand gradation without affecting the AC distribution.

Using the lessons learned during the demonstration test, full-scale construction was initiated in 2012 and completed in 2016. The following sampling techniques were employed during cap construction to verify that the individual cap layers were placed to the appropriate thickness: gravity core sampling,

vibracore sampling (Figure 11), collection of samples using catch pans (Figure 12), and bathymetric survey techniques.

In addition to verifying that the emplaced cap layers were of the appropriate thickness, innovative techniques were used to verify that the in situ cap contained the appropriate dose of cap amendment materials (e.g., siderite and AC). Samples were retrieved from the amended cap layers using catch pans or gravity cores, and thermal methods were employed to verify the presence of both siderite and granular AC in the retrieved samples.

For the sand/siderite layer, research indicated that heating to high temperatures has two primary effects on siderite: 1) discoloration to a dark brown or black color; and 2) enhanced magnetization, likely due to transformation to magnetite. These properties were exploited



FIGURE 10
Metal grate modification on spreader barge.



FIGURE 11
Core sample showing verification of cap layer thickness.

to qualitatively identify siderite in samples retrieved from the in situ cap. Retrieved samples were heated to approximately 500 degrees Celsius ($^{\circ}\text{C}$) and subsequently cooled. A magnet was used to separate the magnetized siderite from the sand in the sample. This technique effectively demonstrated the presence of siderite in the in situ cap materials (Figure 13).

For the sand/AC layer, the AC content of retrieved samples was determined by thermogravimetric analysis. The thermal method developed for the AC relied on heating the sample to a temperature that would drive off the AC by combustion without affecting the sand. Samples were pre-concentrated by sieving to remove sand particle sizes larger and smaller than the expected size range of the AC particles. This sieve step reduced the sample size to be dried and heated. Following



FIGURE 12
Cap thickness verification using catch pans.



FIGURE 13
Laboratory verification of siderite.

sieving, the samples were dried in an oven at 110°C to remove moisture. Once dried, samples were weighed and returned to the oven and heated to 500°C to combust the AC. The sample was re-weighed after heating, and the original AC content was determined from the weight loss, minus a correction for the background organic carbon present in the sand.

The methods employed to install and verify placement of the multi-layer cap enabled cap construction to proceed at a rate of approximately 5,000 cubic meters per day using two hydraulic and two mechanical capping operations working simultaneously, with daily production reaching a rate as high as 7,800 cubic meters per day. Cap placement was completed in 2016.

SUMMARY

As the largest AC-amended capping project to date, several aspects of the Onondaga Lake project are unique and include technological innovations that have resulted in significant efficiencies during construction of a sediment cap of this scale. First and foremost, the successful integration into the cap design of biodegradation, as a mechanism of COC mass reduction, is a key feature affecting overall effectiveness of the remedy by optimizing the AC dose needed in the chemical isolation layer for COC sequestration. Furthermore, incorporation of a siderite amendment layer for pore-water pH control ensures long-term reliability of in situ biodegradation in areas of initially elevated pH and promotes post-capping littoral habitat establishment in these areas. Proof of the effectiveness of bulk placement methods and development of rapid turnaround construction verification methods allowed cap construction to proceed at a rapid pace

that was once thought to be unachievable in the industry. Implementation of these innovations has led to an optimized, environmentally protective solution, yielding long-term habitat restoration benefits to the lake.

CITATIONS

- Bessinger, B.A., D. Vlassopoulos, S. Serrano, and P.A. O'Day, 2012. Reactive transport modeling of subaqueous sediment caps and implications for the long-term fate of arsenic, mercury, and methylmercury. *Aquatic Geochemistry* dx.doi.org/10.1007/s10498-012-9165-4.
- Freundlich, H., 1926. Colloid and Capillary Chemistry. Methuen & Company, London.
- Go, J., D.J. Lampert, J.A. Stegemann, and D.D. Reible, 2009. Predicting contaminant fate and transport in sediment caps: mathematical modeling approaches. *Applied Geochemistry* 24(7):1347-1353.
- Howard, P.H., R.S. Boethling., W.F. Jarvis., W.M. Meylan, and E.M. Michalenko. 1991. Handbook of Environmental Degradation Rates. Lewis Publishers, Inc., Chelsea, Michigan.
- ITRC (Interstate Technology & Regulatory Council). 2014. Contaminated Sediments Remediation: Remedy Selection for Contaminated Sediments (CS-2). Washington, D.C.: Interstate Technology & Regulatory Council, Contaminated Sediments Team. http://www.itrcweb.org/contseds_remedy-selection.
- Kiehl-Simpson, C., E. Glaza, D. Reible, G.V. Lowry, and D. Vlassopoulos, 2011. Amended cap design for control of VOCs, SVOCs, mercury, and pH for Onondaga Lake. *Sixth International Conference on Remediation of Contaminated Sediments, New Orleans, Louisiana*.
- Lampert, D.J., and D. Reible, 2009. An analytical modeling approach for evaluation of capping of contaminated sediments. *Soil and Sediment Contamination: An International Journal* 18(4):470-488.
- McDonough, K., J. Fairey, and G. Lowry. 2008. Adsorption of polychlorinated biphenyls to activated carbon: equilibrium isotherms and a preliminary assessment of the effect of dissolved organic matter and biofilm loadings. *Water Research* 42(3):575-584.
- O'Day, P.A., and D. Vlassopoulos, 2010. Mineral-based amendments for remediation. *Elements* 6:375-381.
- Vlassopoulos, D., J. Goin, B. Bessinger, C. Kiehl-Simpson, and E. Glaza, 2011. Evaluation of pH-buffering amendments for in situ capping of hyperalkaline contaminated sediments. *Sixth International Conference on Remediation of Contaminated Sediments, New Orleans, Louisiana*.
- Vlassopoulos, D., M. Swanson-Theisen, J. Goin, G.R. Johnson, C. Kiehl-Simpson, and E. Glaza, 2013a. A siderite-amended reactive cap for high pH sediments of Onondaga Lake, New York. *Seventh International Conference on Remediation of Contaminated Sediments, Dallas, Texas*.
- Vlassopoulos, D., J. Goin, and M. Carey, 2013b. Siderite amendment for in situ pH control in hyperalkaline environments. *Mineralogical Magazine* 77(5):2421.