THE EVOLUTION OF SUBAQUEOUS CAP DESIGN

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ABSTRACT

Subaqueous capping is an accepted approach for both the management of contaminated dredged material and the remediation of contaminated sediments. The design of subaqueous caps includes the selection of appropriate capping materials and the evaluation of the required thickness of various cap components. The U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency published technical guidance documents on dredged material capping and in-situ capping in 1998 that described the principle considerations of subaqueous cap design to include consideration of processes related to chemical isolation, physical isolation, bioturbation, erosion, consolidation, and operational factors. Cap design is based on a "layer cake" approach in which various components of the cap are designed to account for the processes pertinent to the site, with the total cap thickness determined as the sum of the cap components. Cap design in recent years has evolved to include consideration of dual functions for cap components, reactive cap materials to increase the effectiveness of the cap for isolation, and components related to habitat enhancement. This paper describes the evolution of subaqueous cap design to include consideration of conventional designs with granular materials, reactive cap materials, and specialized cap components for habitat or other purposes.

Keywords: Contaminated sediments, subaqueous capping, cap design and construction.

INTRODUCTION

Subaqueous capping of contaminated sediments is an accepted engineering option for managing contaminated dredged materials and for *in-situ* remediation of contaminated sediments. Engineered caps provide for physical isolation and stability of the contaminated sediments and control flux of contaminants through the cap. Although there are a number of aspects related to the successful design and implementation of a capping project, the "design" of the cap itself commonly refers to the selection of appropriate capping materials and the thickness of the cap components or layers. Cap design has evolved from conservative "rules of thumb" in the 1970s to a highly sophisticated engineering analysis approach used today. This paper describes the technical evolution of cap design and recent trends in cap design to include consideration of conventional designs with granular materials, reactive cap materials, and specialized cap components for habitat or other purposes.

A BRIEF HISTORY OF CAP DESIGN

Apparently, the first subaqueous capping project in the U.S. was a dredged material project in Providence, Rhode Island conducted in 1967. The U.S. Army Corps of Engineers (USACE) New England Division sequenced placement of more contaminated dredged material beneath a layer of cleaner dredged material with the intention of isolating contamination from the aquatic environment. NED subsequently pioneered the basic concept of dredged material capping in the 1970s with a number of dredged material capping projects in Long Island Sound, and has documented these projects in detail as a part of its Disposal Area Monitoring System (DAMOS) program (Fredette et al 1993). During that time span, capping was developed as a management approach for contaminated material from navigation projects, i.e., those materials determined to be unsuitable for conventional open water disposal. The materials used for capping during that time period were clean sediments from navigation dredging projects. The technical design of these early capping projects was primarily related to selection of placement operations to achieve good coverage of dredged material mounds in water depths on the order of 12 m (40 ft).

Capping received increased attention in other regions of the country beginning in the 1980s. A summary of capping projects through the mid-1980s was developed by Truitt (1987a). Most of these projects involved dredged material

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capping. However, Truitt's summary also documented perhaps the earliest in-situ capping projects for purposes of sediment remediation, which were bay-bottom capping projects in Japan, and perhaps the first Contained Aquatic Disposal (CAD) project, which was conducted in the Netherlands. Truitt also documented early design principles for capping (Truitt 1987b) that included basic concepts for cap design considering both the need for isolation and the need for evaluation of erosion potential. A "practical cap thickness" for dredged material capping on the order of 1 m (3 ft) was recommended by Truitt, based on early tests for cap isolation effectiveness (Brannon 1985 and 1986) and the construction and bathymetric surveying tolerances normally achievable in deeper water sites with the equipment then in common use. The relatively thick caps used for dredged material capping were easily accommodated in the early designs since the capping materials were also dredged materials that required disposal.

However, as capping was considered for a wider range of project conditions, it became apparent that a number of technical considerations were important for cap design and capping project implementation. This was especially true once capping became more commonly considered for sediment remediation projects. The studies associated with the U.S. Navy Homeport project at Everett, Washington (Palermo et al 1989) clearly defined the need for more rigorous approaches to dredged material cap design and capping project evaluations. This project proposed a CAD option sited in water depths exceeding 76 m (250 ft), and issues of potential contaminant release during placement and contaminant migration through the caps required comprehensive laboratory testing and modeling efforts. The feasibility studies for the Manistique, Michigan CERCLA project defined in a similar way the need for application of more sophisticated methods to assess cap isolation effectiveness, the physical stability of caps, and the consideration of episodic events for in-situ cap design.

A more technically-based approach to subaqueous capping and cap design was developed in the early 1990s by the USACE and documented in a series of technical notes that included a systematic approach to dredged material capping evaluations to include cap design, site selection, cap placement, and cap monitoring (Palermo 1991a, b, and c; and Palermo, Fredette, and Randall 1992). These technical notes were subsequently incorporated by the USACE into the more comprehensive ***Guidance for Subaqueous Dredged Material Capping*** (Palermo et al 1998a). Concurrently, the USEPA sponsored the development of ***Assessment and Remediation of Contaminated Sediments (ARCS) Program Guidance for In-Situ Subaqueous Capping of Contaminated Sediments***, a report documenting procedures for design and evaluation of in-situ capping projects for sediment remediation (Palermo et al 1998b). Both of these documents include an evaluation sequence for cap design and recommendations for testing approaches and diffusion/advection models for evaluation of chemical isolation effectiveness developed by Reible (1998a and b). Since the 1998 documents were published, much experience has been gained by application of the USACE and USEPA design procedures to a wide range of project conditions and additional technical information related to cap design and construction has been developed. USEPA has also adopted the design approaches and detailed design information in the 1998 documents by reference in the recent ***Contaminated Sediment Remediation Guidance for Hazardous Waste Sites*** (USEPA 2005).

CONVENTIONAL CAP DESIGN – THE LAYER APPROACH

Dredged material caps are usually composed of a single material, most commonly a sandy dredged material that is clean, i.e. is acceptable for open water placement. In-situ caps are usually composed of a sandy layer for purposes of isolation, but commonly include a separate layer of armor material for physical stability, composed of a coarse sand, gravel, or armor stone. These designs may be described as "conventional" caps in the sense that they are the most common approach and do not include cap components such as geotextiles or active/ reactive materials.

The total thickness of a cap and the composition of the cap components are based on an evaluation of all the pertinent processes for the site and the ability of the design to achieve the intended functions of the cap. Processes that should normally be considered for the cap design include bioturbation, cap consolidation, erosion, operational factors, and chemical isolation. For cap design with a granular material, a conservative "layer approach" should be used as recommended by USACE and USEPA (Palermo et al 1998a and b, and USEPA 2005). Each component is considered and appropriately evaluated, and the necessary cap thickness is assumed as the sum of the layers for each component. Figure 1 illustrates this layer approach and shows the various components or cap layers that are normally considered in design.

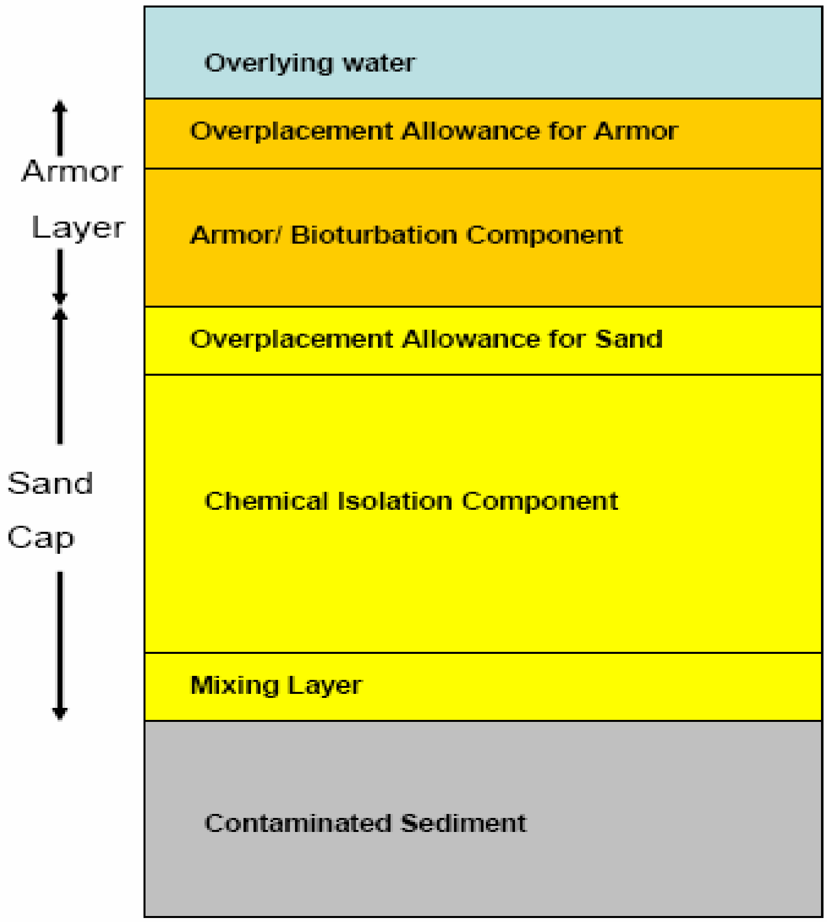

Figure 1. Illustration of cap components of a conventional armored sand cap.

Descriptions of each cap component and design considerations based on recent experience are as follows:

Erosion Component

This component of the cap is intended to stabilize the contaminated sediment being capped, and prevent the sediment from being resuspended and transported off site. The potential for erosion may be a function of current velocity forces due to tides or flood flow, wave-induced currents due to storms, and propeller-induced scour. This type of analysis should be based on the controlling shear stress due to the various erosion forces and required grain size for stability. The analysis would normally include an evaluation of a 100-year flow event, 100-year wind event, and use of an appropriate design vessel(s) for prop wash (USEPA 2005). Physical stability against ice erosion has also been considered in recent studies. For in-situ caps, the erosion component is usually an armor layer designed to provide physical stability. For some dredged material caps, the erosion layer can be designed as a sand layer with additional thickness that may be eroded as a result of an extreme episodic event and later restored with subsequent placements of clean material. This design would be appropriate at sites with continuing needs for clean dredged material disposal that may serve as cap material. For an armored cap with the surface layer composed of coarse sand, gravel, or stone, the erosion protection layer may also act effectively as the bioturbation component, so a dual function is possible for that layer.

Bioturbation Component

Aquatic organisms that live in or on bottom sediment can greatly increase the migration of sediment contaminants upward into the cap through bioturbation. Bioturbation activity varies with depth, and the design thickness (depth) of bioturbation selected for cap design should be equivalent to the biologically active zone (BAZ), where most of the biological activity takes place. The bioturbation cap component should lie above any chemical isolation cap component. The depth to which species will burrow is dependent on the species' behavior and the characteristics of the substrate (e.g., grain size, compaction, and organic content). In general, the depth of bioturbation by marine organisms is greater than that of freshwater organisms. The thickness of the cap surface layer must therefore exceed the bioturbation depth for organisms likely to recolonize the cap following cap construction. The types of organisms likely to colonize a capped site and the normal behavior of these organisms is generally well known. The USACE has developed information for evaluating bioturbation depths for purposes of cap design and approaches for considering bioturbation activities and depths in contaminant flux modeling for design of the chemical isolation component for cap design (Clarke and Palermo, 2001). The thickness of the bioturbation layer is usually considered as a completely mixed layer for purposes of flux modeling for design of a chemical isolation component of the cap.

Consolidation Component

Potential consolidation of the cap materials may influence the required cap thickness, and since most contaminated sediment is highly compressible, the underlying contaminated sediment layer will almost always undergo consolidation due to the added weight of capping material or armor stone. Gravel, sand, or stone materials are not compressible, so consolidation of the cap itself is not a common design consideration. However, an analysis of consolidation of the underlying contaminated sediments should be conducted as a part of the evaluation of the chemical isolation cap component (see discussion below). Consolidation should also be evaluated to determine the final post-capping elevation of the cap surface, since water depth above the cap can be in important consideration for shallow water sites.

Chemical Isolation Component

If a cap has a properly designed physical isolation component, contaminant migration associated with the movement of sediment particles should be controlled. However, the movement of contaminants by advection (flow of pore water) upward into the cap is possible, while movement by molecular diffusion (across a concentration gradient) over long periods is inevitable. The performance standards for chemical isolation are usually framed in terms of an action level for pore water contaminant concentrations or sediment concentrations in the upper layers of the cap (the biologically active zone). For both dredged material and in-situ caps, the isolation effectiveness of the sand layer may rely on providing a minimum total organic carbon (TOC) content for the layer, commonly 0.5% TOC by weight. The approach for design of the chemical isolation layer is a combination of testing to determine partitioning coefficients for the cap and contaminated sediments and flux modeling. In recent years, batch and column tests as well as analysis of sediment pore water have been used to determine partitioning parameters for flux modeling. A number of computer and analytical flux models have also become available to predict long-term movement of contaminants into or through caps due to advection and diffusion processes. These include updated versions of the USACE RECOVERY/CAP model and web-based models available through the USEPA Hazardous Substances Research Center, South/Southwest. The results generated by such models include flux rates and sediment pore water concentrations for either steady state or time varying conditions. Model results can be used to determine the needed chemical isolation cap component thickness for specific cap materials to meet applicable performance standards.

Mixing Layer

Cap design should also allow for "operational" components for cap and sediment mixing and variability in placed cap thicknesses for both the sand and armor layers. These component thicknesses are best determined based on past experience with other projects. The mixing layer is the operational cap component accounting for potential mixing of the cap material with underlying fine grained contaminated sediment. Mixed layers up several inches have been observed for constructed caps, even with placement methods designed to achieve gradual build up of the desired cap thickness and minimize mixing. In recent designs, a concentration of contaminants corresponding to the anticipated mixed condition has been considered for this layer when conducting contaminant flux modeling for design of the chemical isolation layer.

Overplacement Allowance

A wide variety of equipment types and placement methods have been used for capping projects, but all methods result in some variability of the placed thickness. Mechanically dredged materials, soils excavated from upland sites, or commercially available sands or armor materials can be handled mechanically in a dry state until released into the water and/or spread over the contaminated site. Hydraulic methods may also be used to place granular cap material. The wide variety of methods used for cap placement has been recently summarized by the USACE (Bailey and Palermo 2005). Important considerations in selection of placement methods include the need for controlled, accurate placement of capping materials. Slow, uniform application that allows the capping material to accumulate in layers is often necessary to avoid displacement of or excessive mixing with the underlying contaminated sediment. In considering placement methods in the cap design, an allowance for the potential variability in placed thickness may be considered in terms of an overplacement allowance, essentially an additional cap thickness corresponding to the variability. In some cases, water depth limitations may constrain where caps may be placed, and the overplacement allowance should be carefully considered as a part of the overall cap thickness in determining the potential capping footprint.

Overall Thickness of Engineered Caps

The above cap component thicknesses must be considered in an additive fashion to determine the overall design cap thickness. These components meet the basic requirements for physical stability and chemical isolation common to most cap designs. A recent trend at some in-situ capping sites is the consideration for cap placement in shallow waters. Shallow water placement is often constrained by the need to preserve water depth for habitat, the need to avoid potential for ice scour, the need to minimize exposure of the cap to prop wash, etc. Since the cost of capping is usually less than dredging and disposal, there is a strong economic incentive for cap design with the minimal thickness required to meet performance standards. This need can sometimes be accommodated by consideration of dual functions for a given cap component or the selection of cap materials that meet performance standards with less thickness. The potential for dual functions may be evaluated as part of the cap design. As mentioned above, the upper cap layer is commonly designed to meet both the erosion and bioturbation functions for a cap. This same surface layer can also meet functions related to habitat enhancement (discussed below). The concept of selecting certain cap materials to meet standards with less thickness is one premise for consideration of active/ reactive caps (also discussed below).

CAP COMPONENTS FOR HABITAT ENHANCEMENT

It has long been recognized that caps provide an opportunity to restore and even enhance the benthic habitat at a contaminated sediment site. Habitat enhancement as a part of cap design can be as simple as selecting a sand or armor material size distribution for the cap that corresponds to desirable substrate for aquatic organisms. This concept was implemented at number of sites in the Puget Sound area where “fish mix” was used as the surface layer of remediation caps.

A recent development is the design of a habitat layer as a distinct and dedicated cap layer component. The habitat layer would logically be placed as the surface layer of the cap, and would be designed to provide optimum value as habitat for selected target species of fish or benthic organisms. The proposed cap designs for the Onondaga Lake CERCLA site near Syracuse, NY (Exponent 2004; and Palermo, Reible, Hayes and Verduin 2004) are good examples of this approach. The caps proposed for the Onondaga project included a dedicated habitat layer of 15 cm (6 in) which would lie above the cap armor layer in certain areas of the lake. The grain size distributions of the habitat layers varied by water depth and were selected as optimum for differing target fish species. In other areas of the lake, the surface cap component would serve the dual purpose of habitat and armor, and the armor grain size was selected to provide optimum habitat for fish as well as the needed resistance to erosion. Ludwig et al (2006) expanded on the concept of a habitat layer and proposed a modular approach to design of this layer as an “EpiCap” or outer layer. In this way, various habitat layers could be designed as modules to serve various habitat functions. Types of habitat modules might include those for emergent wetlands, submerged aquatic vegetation, hard bottom, or soft bottom.

One important design consideration for a habitat layer is the influence of episodic events such as flood flows or storm-generated waves on the stability of the habitat layer. In most cases, the habitat layer would lie above any armor layer designed to provide stability of the cap against extreme events. And, the habitat layer would most commonly be composed of materials with smaller grain size than the armor layer. This means that the habitat layer is a “softer” layer prone to erosion and redistribution during such extreme events. The remediation plan under such conditions must be designed to either allow for habitat layer redistribution (as would occur in the natural environment) or provide for some degree of maintenance of the habitat layer if needed.

ACTIVE AND REACTIVE CAPS

Although a conventional sand cap can be very effective at managing exposure and risk from strongly sediment-sorbed contaminants, there are a variety of sediment conditions where such a cap may not be sufficiently protective. If a contaminant is only weakly associated with the solid phase, groundwater upwelling may result in unacceptable contaminant migration through porewater. Similarly, if the contaminants are associated with a separate nonaqueous phase liquid, the migration of that phase may control the flux to the sediment-water interface and the overlying water. Even for strongly sediment-associated contaminants, the long term flux associated with porewater migration processes may be unacceptable without further attenuation beyond what a conventional sand cap can provide.

In such situations, cap amendments might be considered which may provide additional sorption capacity and retardation of contaminant migration or may encourage contaminant degradation. These cap amendments actively control the sediment contaminants relative to the passive action of a conventional sand cap and thus are referred to as active caps, or when transformation is encouraged, reactive caps. Active cap materials that have been proposed include phosphate minerals for metals control, organoclays and sorbents such as activated carbon or coke for organic contaminant control, and clays for control of permeability. Laboratory testing has shown the potential for such materials to more effectively control contaminants that might migrate through a cap, primarily by retarding contaminant motion by sorption. In some cases, degradation can also be enhanced, but the opportunities for incorporating degradative layers into cap materials are less well developed. Active cap layers that sorb or sequester contaminants more effectively than conventional sand caps will increase the capacity of a cap to control finite contaminant sources and increase the period of effectiveness for continuous sources. This results in more effective containment for a given cap thickness or allows a given degree of containment to be achieved with a thinner cap, thereby reducing the impact of a cap on water depth or strength and consolidation concerns in the underlying sediment.

The design of an active cap proceeds via one of two paths. Degradative active caps seek to provide sufficient residence time in the cap for the desired degradation processes to render the contaminant harmless before reaching the sediment-water interface. If τ_{rxn} represents the characteristic time for the reaction (e.g. a half-life or 1/e time) in a particular reactive media, the required cap thickness to ensure degradation of the contaminant in the face of a upwelling (Darcian) velocity U would be

$$h_{cap} > \frac{U}{\varepsilon}\tau_{rxn} \tag{1}$$

Where ε is the void fraction in the cap layer. As with any cap design, this required cap thickness defines the confining layer and additional cap material must be placed to account for intermixing with the underlying sediment, bioturbation and/or habitat layers, any required armoring thickness, and any allowance for variation and placement uncertainty.

An active cap with the objective of providing additional sorptive capacity is designed to provide sufficient retardation of the contaminant to ensure that no contaminant "breakthrough" occurs for a time τ_b. This time may be sufficient for the source to be eliminated, until fate processes are expected to render any breakthrough negligible, or until deposition of clean sediment can effectively bury the sediments. For a cap subject to groundwater upwelling at velocity U carrying the contaminant of concern, the desired confinement layer can be defined by

$$h_{cap} > \frac{U}{R_f}\tau_b \tag{2}$$

Where the retardation factor associated with sorption in the active cap layer, R_f, is defined by $\varepsilon + \rho_b K_{cw}$ in which ρ_b is the dry bulk density of the cap materials and K_{cw} is the partition coefficient between the cap material and the interstitial water. The greater the cap-water partition coefficient, the greater the retardation of the contaminant migration and the smaller the cap thickness required to provide containment for the specified breakthrough time, τ_b.

Although these relationships have been written for contaminant migration controlled by groundwater upwelling, similar relationships can be derived for other active processes. In all cases, however, the purpose of the active cap design is to provide sufficient residence time for the contaminants to allow time for either degradation or to render any potential migration negligible.

Although potentially effective, the introduction of active capping materials into the environment has been limited as a result of the lack of precedent experience as well as cost. In order to encourage the consideration of active capping materials for sediment caps, a field demonstration of selected active capping technologies was conducted in the Anacostia River in Washington DC. The river suffers from overall poor water quality caused by numerous pollutants, including suspended solids, excess nutrients, toxics, trash, and debris. The sediments contain a large inventory of contaminants of concern including metals and polynuclear aromatic hydrocarbons (PAHs) and additional contaminants are introduced, particularly after rainfall events from combined sewer overflows (CSOs). The combination of continuing sources and past sources are reflected by the poor sediment quality, which makes management of the river quality difficult.

The demonstration project was implemented by a team led by Danny Reible, then at Louisiana State University but currently at the University of Texas, in cooperation with the prime on-site contractor, Horne Engineering Services, and with the active support and contributions from the Anacostia Watershed Toxics Alliance, a group of Anacostia River stakeholders and interested parties including the DC Department of Health. The Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program also provided extensive field support as part of a supplemental and complementary analysis of the AquaBlok™ cap. The lead project team was from the EPA supported Hazardous Substance Research Center/South and Southwest, a multi-university research consortium of Louisiana State University, Rice University, Georgia Tech University, Texas A&M University and the University of Texas. A variety of other groups also contributed to the overall project.

As a result of site characterization efforts, active capping materials appropriate for the site contaminants and conditions were included in the demonstration. The materials included AquaBlok™, coke, and apatite. Aquablok™ is a manufactured material (Hull and Associates, Toledo, OH) that is a bentonite clay around a granular core. The granular core encourages settling of the clay through the water column. After settling to the bottom, the clay absorbs water and swells, thereby reducing the permeability of the surface layer. In this manner, the AquaBlok™ is expected to reduce tidal pumping of porewaters in the contaminated sediment and divert groundwater upwelling away from the contaminated sediments to other, presumably less contaminated portions of the site. Post-placement monitoring efforts showed that the AquaBlok™ was indeed effective at effectively eliminating groundwater upwelling through the capped area of contaminated sediments. Monitoring also showed, however, that occasional gas release was noted causing occasional rapid uplift of a portion of the cap. No negative impacts were noted with this gas release although in other locations gas release has led to surface sheens when oil is brought up with the gas. Gas release effectively ended within a year of capping as a result of the elimination of labile organic matter deposition onto the contaminated sediments due to the separation provided by the cap layer.

Coke was included in the demonstration as an organic sequestration agent. Coke is a petroleum pyrolysis product that is widely available at low cost. The coke employed in this project was provided by U.S. Steel (Clairton Works, Clairton Pa) and exhibited particle sizes of 0.425 to 2 mm (10 - 40 mesh). Sorption measurements showed that the coke is similar in sorptive capacity to moderate organic carbon sediments while other sequestration agents (e.g. activated carbon) may exhibit 10-100 times greater capacity (Murphy et al., 2006). Coke contains residual PAH levels but pre-demonstration leaching tests showed low levels of mobile PAHs due to the organic sequestration properties of the coke. Because cost was of paramount concern, the original plan was to place the coke in bulk, and ignore more sorptive (but more expensive) cap materials such as activated carbon. Initial investigations, however, showed that the coke contained a significant fraction (10-20%) of nonsettleable material, raising concerns about bulk placement. An alternative placement approach was discussed with CETCO (Arlington Ill) and ultimately selected. This alternative involved placement of the coke within a mat (also referred to as a reactive core mat or RCM) in a high void fraction polyester core with two filtering polyester laminate layers on each side. The mats were constructed in a roll approximately 3 m (10 ft) wide and approximately 30 m (100 ft) long. Although used here for coke placement, the inclusion of this technology in the demonstration also served to illustrate its use for the controlled, thin layer placement of any high cost or nonsettleable granular material. The potential effectiveness of various sorptive materials placed in a thin (1.25 cm) reactive core mat is shown in Figure 2 for a particular PCB congener subject to diffusion (a) and groundwater upwelling (b) as the primary means of contaminant migration (Lowry et al., 2006).

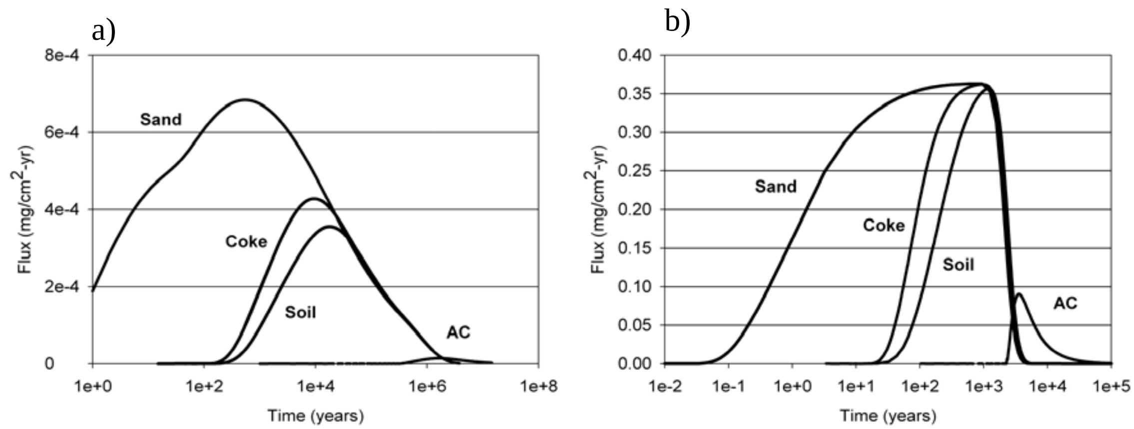

Figure 2. Simulated flux of 2,4,5-PCB through a 1.25-cm layer filled with various sorbents. A) diffusion only. B) with groundwater seepage (Darcy velocity =1cm/d).

The final capping material to be demonstrated was apatite (PCS Phosphate Company, Inc., Aurora, NC), a phosphate with the ability to preferentially adsorb certain metals. The material had the consistency of a coarse sand and was delivered and placed in bulk. To provide a comparison of the effectiveness of the active capping materials, a fourth 743 m^2 (8000 ft^2) capping plot was used to place sand. A fifth area slightly outside of the four capping areas was used as an uncapped control area. All cap materials were placed between March 8, 2004 and April 23, 2004. Sampling for the evaluation placement performance was conducted in May 2004 while additional sampling for post-cap monitoring was conducted annually in Fall 2004-2006. Additional sampling is planned for Fall 2007.

Monitoring has demonstrated that all of the active cap materials were placed with minimal intermixing with the underlying sediment and no measurable migration has been noted (Reible et al., 2006). No measurable migration has also been noted with the sand cap used as a control, however, and thus, to-date, it has not been possible to demonstrate the improved containment possible with the active caps. This illustrates that even a conventional sand cap can provide extremely effective containment of strongly solid associated contaminants.

More recently, organoclays have been used as an active cap material to control creosote seeps into the Willamette, River, Portland, OR, at the McCormick and Baxter site. Organoclays are treated with tertiary and quarternary amines to produce organophylic clay that can effectively sorb hydrophobic organic compounds. The placement of the organoclay at the McCormick and Baxter site has ended, at least in the short term, any release of creosote into the river. Some of the organoclay was placed in a bulk 30 cm (12 in) layer to control direct creosote migration. Additional organoclay was placed via the reactive core mat approach described above to control creosote brought to the surface in specific locations due to the release of gas generated at depth in the sediments. Evaluation of cores and segments from selected mats have shown that essentially none of the potential capacity of the organoclay has been compromised by contact with the underlying creosote (Moretti et al., 2007). Thus the organoclay has arrested the migration of the creosote by either mechanism and retains essentially the full capacity to continue to provide such control.

These examples illustrate that active caps can be effectively placed in the environment and have the potential to provide significantly greater containment and control over sediment contamination than conventional sand caps. Although essentially all active caps demonstrated thus far are designed to provide greater containment, it is expected that caps that can encourage greater degradation will receive greater interest and application in the future.

CONCLUSIONS

Conclusions from this paper are as follow:

- Cap design has evolved from conservative "rules of thumb" in the 1970s to a highly sophisticated engineering analysis approach used today.
- Development of cap designs is influenced by project experience and ever-increasing need to answer questions in a more rigorous and technically defendable manner.
- The layer approach for design of conventional sand and armor caps as described in current USACE and USEPA technical documents remains valid and has been applied at numerous sites.
- Evaluation of dual functions for specific cap components is now an accepted design principle and has led to more efficient cap designs.
- Consideration of potential habitat enhancement should be considered as an integral part of cap design, and dedicated habitat cap components are appropriate for many sites.
- Active caps, those with amendments that actively control the sediment contaminants relative to the passive action of a conventional sand cap, and reactive caps, where contaminant transformation is encouraged, are emerging as viable capping design options in cases where conventional sand caps are not sufficiently protective.

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