5.0 IN-SITU CAPPING

5.1 INTRODUCTION

For purposes of this guidance, in-situ capping refers to the placement of a subaqueous covering or cap of clean material over contaminated sediment that remains in place. Caps are generally constructed of granular material, such as clean sediment, sand, or gravel. A more complex cap design can include geotextiles, liners, and other permeable or impermeable elements in multiple layers that may include additions of material to attenuate the flux of contaminants (e.g., organic carbon). Depending on the contaminants and sediment environment, a cap is designed to reduce risk through the following primary functions:

- Physical isolation of the contaminated sediment sufficient to reduce exposure due to direct contact and to reduce the ability of burrowing organisms to move contaminants to the surface;
- Stabilization of contaminated sediment and erosion protection of sediment and cap, sufficient to reduce resuspension and transport to other sites; and/or
- Chemical isolation of contaminated sediment sufficient to reduce exposure from dissolved and colloidally bound contaminants transported into the water column.

Caps may be designed with different layers to serve these primary functions or in some cases a single layer may serve multiple functions.

As of 2004, In-situ capping has been selected as a component of the remedy for contaminated sediment at approximately fifteen Superfund sites. At some sites, in-situ capping has served as the primary approach for sediment, and at other sites it has been combined with sediment removal (i.e., dredging or excavation) and/or monitored natural recovery (MNR) of other sediment areas. In-situ capping has been successfully used at a number of sites in the Pacific Northwest, several of which were constructed over a decade ago (see site list at http://www.epa.gov/superfund/resources/sediment/sites.htm). When hazardous substances left in place are above levels allowing for unlimited use and unrestricted exposure, a five-year review pursuant to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) §121(c) may be required [U.S. Environmental Protection Agency (U.S. EPA 2001i)].

Variations of in-situ capping include installation of a cap after partial removal of contaminated sediment and innovative caps, which incorporate treatment components. Capping is sometimes considered following partial sediment removal where capping alone is not feasible due to a need to preserve a minimum water body depth for navigation or flood control, or where it is desirable to leave deeper contaminated sediment in place to preserve bank or shoreline stability following removal. There are pilot studies underway to investigate the effectiveness of in-situ caps that incorporate various forms of treatment (see Chapter 3, Section 3.1.3, In-Situ Treatment and Other Innovative Alternatives). Application of thin layers of clean material may be used to enhance natural recovery through burial and mixing with clean sediment when natural sedimentation rates are not sufficient (see Chapter 4, Section 4.5, Enhanced Natural Recovery). Placement of a thin layer of clean material is also sometimes used to backfill dredged areas, where it mixes with dredging residuals and further reduces risk from contamination that remains after dredging. In this application, the material is not often designed to act as an engineered cap to isolate buried contaminants and is, therefore, not considered in-situ capping in this guidance.

Much has been written about subaqueous capping of contaminated sediment. The majority of this work has been performed by, or in cooperation with, the U.S. Army Corps of Engineers (USACE). Comprehensive technical guidance on in-situ capping of contaminated sediment can be found in the EPA's *Assessment and Remediation of Contaminated Sediment (ARCS) Program Guidance for In-Situ Subaqueous Capping of Contaminated Sediments* (U.S. EPA 1998d) and the *Assessment and Remediation of Contaminated Sediments (ARCS) Program Remediation Guidance Document* (U.S. EPA 1994d), available through EPA's Web site at http://www.epa.gov/glnpo/sediment/iscmain. Additional technical guidance is available from the USACE's *Guidance for Subaqueous Dredged Material Capping* (Palermo et al. 1998a)

Although each of the three potential remedy approaches (MNR, in-situ capping, and removal) should be considered at every site at which they might be appropriate, capping should receive detailed consideration where the site conditions listed in Highlight 5-1 are present.

Highlight 5-1: Some Site Conditions Especially Conducive to In-Situ Capping

- Suitable types and quantities of cap material are readily available
- Anticipated infrastructure needs (e.g., piers, pilings, buried cables) are compatible with cap
- Water depth is adequate to accommodate cap with anticipated uses (e.g., navigation, flood control)
- Incidence of cap-disrupting human behavior, such as large boat anchoring, is low or controllable
- Long-term risk reduction outweighs habitat disruption, and/or habitat improvements are provided by the cap
- Hydrodynamic conditions (e.g., floods, ice scour) are not likely to compromise cap or can be accommodated in design
- Rates of ground water flow in cap area are low and not likely to create unacceptable contaminant releases
- Sediment has sufficient strength to support cap (e.g., higher density/lower water content, depending on placement method)
- Contaminants have low rates of flux through cap
- Contamination covers contiguous areas (e.g., to simplify capping)

5.2 POTENTIAL ADVANTAGES AND LIMITATIONS

Two advantages of in-situ capping are that it can quickly reduce exposure to contaminants and that, unlike dredging or excavation, it requires less infrastructure in terms of material handling, dewatering, treatment, and disposal. A well-designed and well-placed cap should more quickly reduce the exposure of fish and other biota to contaminated sediment as compared to dredging, as there should be no or very little contaminant residual on the surface of the cap. Also, the cap often provides a clean substrate for recolonization by bottom-dwelling organisms. Changes in bottom elevation caused by a cap may create more desirable habitat, or specific cap design elements may enhance or improve habitat substrate. Another possible advantage is that the potential for contaminant resuspension and the risks associated with dispersion and volatilization of contaminated materials during construction are typically lower for in-situ capping than for dredging operations and risks associated with transport and disposal of contaminated sediment are avoided. Most capping projects use conventional equipment and locally available materials, and may be implemented more quickly and may be less expensive than remedies involving removal and disposal or treatment of sediment.

In-situ capping may be less disruptive of local communities than dredging or excavation. Although some local land-based facilities are often needed for materials handling, usually no dewatering, treatment, or disposal facilities need to be located and no contaminated materials are transported through communities. Where clean dredged material is used for capping, a much smaller area of land-based facilities is needed.

The major limitation of in-situ capping is the contaminated sediment remains in the aquatic environment where contaminants could become exposed or be dispersed if the cap is significantly disturbed or if contaminants move through the cap in significant amounts. In addition, in some environments, it can be difficult to place a cap without significant contaminant losses from compaction and disruption of the underlying sediment. If the water body is shallow, it may be necessary to develop institutional controls (ICs), which can be limited in terms of effectiveness and reliability, to protect the cap from disturbances such as boat anchoring and keel drag.

Another potential limitation of in-situ capping may be in some situations, a preferred habitat may not be provided by the surficial cap materials. To provide erosion protection, it may be necessary to use coarse cap materials that are different from native soft bottom materials, which may alter the biological community. In some cases, it may be desirable to select capping materials that discourage colonization by native deep-burrowing organisms to limit bioturbation and release of underlying contaminants.

5.3 EVALUATING SITE CONDITIONS

A good understanding of site-specific conditions typically is critical to predicting the expected feasibility and effectiveness of in-situ capping. Site conditions can affect all aspects of a capping project, including design, equipment and cap material selection, and monitoring and management programs. Some limitations in site conditions can be accommodated in the cap design. General aspects of site characterization are discussed in Chapter 2, Remedial Investigation Considerations. Some specific aspects of site characterization important for in-situ capping are introduced briefly in the following sections.

5.3.1 Physical Environment

Aspects of the physical environment that should be considered include water body dimensions, depth and slope (bathymetry) of sediment bed, and flow patterns, including tides, currents, and other potential disturbances in cold climates, such as an ice scour. Existing infrastructure such as bridges, utility crossings, and other marine structures are discussed in Section 5.3.3.

The bathymetry of the site influences how far cap material will spread during placement and the cap's stability. Flat bottoms and shallow slopes should allow material to be placed more accurately, especially if capping material is to be placed hydraulically. Water depth also can influence the amount of spread during cap placement. Generally, the longer the descent of the cap material through the water column, the more water is entrained in the plume, resulting in a thinner layer of cap material over a larger area.

The energy of flowing water is also an important consideration. Capping projects are easier to design in low energy environments (e.g., protected harbors, slow-flowing rivers, or micro-tidal estuarine systems). In open water, deeper sites are generally less influenced by wind or wave generated currents and less prone to erosion than shallow, near-shore environments. However, armoring techniques or selection of erosion-resistant capping materials can make capping technically feasible in some high energy environments. Currents within the water column can affect dispersion during cap placement and can influence the selection of the equipment to be used for cap placement. Bottom currents can generate shear stresses that can act on the cap surface and may potentially erode the cap. In addition to ambient currents due to normal riverine or tidal flows, the project manager should consider the effects of storm-induced waves and other episodic events (e.g., floods, ice scour).

The placement of an in-situ cap can alter existing hydrodynamic conditions. In harbor areas or estuaries, the decrease in depth or change in bottom geometry can affect the near-bed current patterns, and thus the flow-induced bed shear stresses. In a riverine environment, the placement of a cap generally reduces depth and restricts flow and may alter the sediment and flood-carrying capacity of the channel. Modeling studies may be useful to assess these changes in site conditions where they are likely to be significant. Project managers are encouraged to draft decision documents that include some flexibility in requirements for how a cap affects carrying capacity of a water body, while still meeting applicable or relevant and appropriate requirements (ARARs). For example, in some water bodies, a cap may be appropriate even though it decreases, but not significantly, the flood-carrying capacity. In depositional areas, the effect of new sediment likely to be deposited on the cap should be considered in predicting future flood-carrying capacity. Clean sediment accumulating on the cap can increase the isolation effectiveness of the cap over the long term and may also increase consolidation of the underlying sediment bed.

5.3.2 Sediment Characteristics

The project manager should determine the physical, chemical, and biological characteristics of the contaminated sediment pursuant to using the data quality objective (DQO) process during the remedial investigation. The results of the characterization, in combination with the remediation goals and remedial action objectives (RAOs), should determine the areal extent or boundaries of the area to be capped.

Shear strength, especially undrained shear strength, of contaminated sediment deposits is of particular importance in determining the feasibility of in-situ capping. Most contaminated sediment is fine-grained, and is usually high in water content and relatively low in shear strength. Although a cap can be constructed on sediment with low shear strengths, the ability of the sediment to support a cap and the need to construct the cap using appropriate methods to avoid displacement of the contaminated sediment should be carefully considered. The presence of other materials within the sediment bed, such as debris, wood chips, high sludge fractions, or other non-mineral-based sediment fractions, can also present special problems when interpreting grain size and other geotechnical properties of the sediment, but their presence can also improve sediment stability under a cap. It could be necessary to remove large debris prior to placing a cap, for example, if it will extend beyond the cap surface and cause scouring. Side-scan sonar can be an effective tool to identify debris.

The chemical characteristics of the contaminated sediment are an important factor that may affect design or selection of a cap, especially if capping highly mobile or highly toxic sediment. Capping may change the uppermost layer of contaminated sediment from an oxidizing to an anoxic condition, which may change the solubility of metal contaminants and the susceptibility of organic contaminants to microbial decomposition in this upper zone. For example, many of the divalent metal cations (e.g., lead, nickel, zinc) become less soluble in anaerobic conditions, while other metal ions (e.g., arsenic) become more soluble. Mercury, in the presence of pore water sulfate concentrations and organic matter, can become methylated through the action of anaerobic bacteria, and highly chlorinated, polychlorinated biphenyls (PCBs) may degrade to less chlorinated forms in an anaerobic environment. These issues are also discussed in Chapter 4, Section 4.3.2, Biological and Chemical Processes.

When contaminated sediment is capped, chemical conditions in the contaminated zone change. Mercury methylation is generally reduced as organic matter deposition and biological processes are reduced. Organic matter remaining beneath a cap may be decomposed by anaerobic microorganisms and release methane and hydrogen sulfide gases. As these dissolved gases accumulate, they could percolate through the cap by convective or diffusive transport. This process has the potential to solubilize some contaminants and carry them upward, dissolved in the gaseous bubbles. The grain size of the capping material controls in part how these avenues are developed. Finer grained caps may develop fissures whereas coarser grained caps such as sands allow gas to pass through. However, a compensating factor in some cases is caused by the caps' insulation ability, which can cause underlying sediment to stay cooler and thus reduce expected decomposition rates. Where gas generation is expected to be significant, these factors should be considered during cap design.

5.3.3 Waterway Uses and Infrastructure

If the site under consideration is adjacent to or within a water body used for navigation, recreation or flood control, the effect of cap placement on those uses should be evaluated. As described in Section 5.3.1, the flood-carrying capacity of a water body could be reduced by a cap. If water depths are reduced in a harbor or river channel, some commercial and recreational vessels may have to be restricted or banned. The acceptable draft of vessels allowed to navigate over a capped area depends on water level fluctuations (e.g., seasonal, tidal, and wave) and the potential effects of vessel groundings on the cap. Potential cap erosion caused by propeller wash should be evaluated. Where circumstances dictate, an analysis should be conducted for activities that may affect cap integrity such as the potential for routine anchoring of large vessels. Anchoring by recreational vessels may or may not compromise the integrity of a cap, depending on its design. Such activities may indicate the need for restrictions (see Chapter 3, Section 3.6, Institutional Controls) or a modification of the cap design to accommodate certain activities. It may be necessary to restrict fishing and swimming to prevent recreational boaters from dragging anchors across a cap. In some situations, partial dredging prior to cap placement may minimize these limitations of capping.

Other activities in and around the water body may also impact cap integrity and maintenance needs and should be evaluated. These include the following:

- Water supply intakes;
- Storm water or effluent discharge outfalls;
- Utilities crossings;
- Construction of bulkheads, piers, docks, and other waterfront structures;
- Navigational dredging adjacent to the cap area; and
- Future development of commercial navigation channels in the vicinity of the cap.

Utilities (e.g., storm drains) and utility crossings (e.g., water, sewer, gas, oil, telephone, cable, and electric lines) are commonly located in urban waterways. It may be necessary to relocate existing utility crossings under portions of water bodies if their deterioration or failure might impact cap integrity. More commonly however, pipes or utilities are left in place under caps, and long-term operation and maintenance (O&M) plans include repair of cap damage caused by the need to remove, replace, or repair the pipes or utilities. Future construction or maintenance of utility crossings would have to consider the cap, and it may be necessary to consider limiting those activities through institutional controls (ICs) if cap repair cannot be assured. The presence of the cap can also place constraints on future waterfront development if dredging would be needed as part of the development activity.

In designing caps to be placed within federal navigation channels, horizontal and vertical separation distances may be developed by USACE based on considerations of normal dredging accuracy and depth allowances. This can provide a factor of safety to protect the cap surface from damage during potential future maintenance dredging.

To date, environmental agencies have little experience with the ability to enforce use restrictions necessary to protect the integrity of an in-situ cap (e.g., vessel size limits, bans on anchoring, etc.), although experience is growing. Generally, a state or local enforcement mechanism is necessary to implement specific use restrictions. Project managers should consider mechanisms for compliance assurance, enforcement, and the consequences of non-compliance, on use restrictions when evaluating in-situ capping.

5.3.4 Habitat Alterations

In-situ capping alters the aquatic environment and, therefore, can affect aquatic organisms in a variety of ways. As is discussed further in Chapter 6, Dredging and Excavation, while a project may be designed to minimize habitat loss or degradation, or even to enhance habitat, both sediment capping and sediment removal do alter the environment. Where baseline risks are relatively low, it is important to determine whether the potential loss of a contaminated habitat is a greater impact than the benefit of providing a new, modified but less contaminated habitat. Habitat considerations are especially important when evaluating materials for the uppermost layers of a cap. Sandy sediment and stone armor layers are often used to cap areas with existing fine-grained sediment. Through time, sedimentation and other natural processes will change the uppermost layer of the cap. At least initially, changes in organic carbon content of the capping material may change the feeding behavior of bottom-dwelling organisms in the capped area. Generally, the uppermost cap layers become a substrate for recolonization. Where possible, caps should be designed to provide habitat for desirable organisms. In some cases it is possible to provide a habitat layer over an erosion protection layer by filling the interstices of armor stones with materials such as crushed gravel. In some cases, natural sedimentation processes after cap placement can create desirable habitat characteristics. For example, placement of a rock cap in some riverine systems can result in a final cap surface that is similar to the previously existing surface because the rock may become embedded with sands/silts through natural sedimentation.

Desirable habitat characteristics for cap surfaces vary by location. Providing a layer of appropriately sized rubble that can serve as hard substrate for attached molluscs (e.g., oysters, mussels) can greatly enhance the ecological value at some sites. Material suitable for colonization by foraging organisms, such as bottom-dwelling fish, can also be appropriate. A mix of cobbles and boulders may be desirable for aquatic environments in areas with substantial flow. In addition, the potential for attracting burrowing organisms incompatible with the cap design or ability to withstand additional physical disturbances should be considered. Habitat enhancements should not impair the function of the cap or its ability to withstand the shear stresses of storms, floods, propeller wash, or other disturbances. Project managers should consult with local resource managers and natural resource trustee agencies to determine what types of modifications to the cap surface would provide suitable substrate for local organisms.

Habitat considerations are also important when evaluating post-capping bottom elevations. Capping often increases bottom elevations, which in itself can alter the pre-existing habitat. For example, a remediated subtidal habitat can become intertidal, or lake habitat can become a wetland (Cowardin et al. 1979). Changes in bottom elevation may either enhance or degrade desirable habitat, depending on the site.

Project managers should consult EPA staff familiar with implementing the Clean Water Act, as well as natural resource trustees and USACE, where Section 404 of the Clean Water Act is either applicable or relevant and appropriate [see Chapter 3, Section 3.3, Applicable or Relevant and Appropriate Requirements (ARARs) for Sediment Alternatives]. Where remedies under consideration degrade aquatic habitat, substantive requirements may include minimizing the permanent loss of habitat and mitigating it by creation or restoration of a similar habitat elsewhere. However, it should not be assumed that in-situ caps result in a permanent loss of habitat; this is a site-specific decision. In addition, project managers should be aware that any mitigation related to meeting the substantive requirements of ARARs for the site, such as the Clean Water Act, may be independent of the Natural Resource Trustees' natural resource damage assessment process.

5.4 FUNCTIONAL COMPONENTS OF A CAP

As introduced in Section 5.1 of this chapter, caps are generally designed to fulfill three primary functions: physical isolation, stabilization/erosion protection, and chemical isolation. In some cases, multiple layers of different materials are used to fulfill these function and in some cases, a single layer may serve multiple functions. Project managers are encouraged to consider the use of performance-based measures for caps in remedy decisions to preserve flexibility in how the cap may be designed to fulfill these functions.

5.4.1 Physical Isolation Component

The cap should be designed to isolate contaminated sediment from the aquatic environment order to reduce exposure to protective levels. The physical isolation component of the cap should also include a component to account for consolidation of cap materials.

To provide long-term protection, a cap should be sufficiently thick to effectively separate contaminated sediment from most aquatic organisms that dwell or feed on, above, or within the cap. This serves two purposes: 1) to decrease exposure of aquatic organisms to contaminants, and 2) to decrease the ability of burrowing organisms to move buried contaminants to the surface (i.e., bioturbation). To design a cap component for this second purpose, the depth of the effective mixing zone (i.e., the depth of effective sediment mixing due to bioturbation and/or frequent sediment disturbance) and the population density of organisms within the sediment profile should be estimated and considered in selecting cap thickness. Especially in marine environments, the potential for colonization by deep burrowing organisms (e.g., certain species of mud shrimp) could lead to a decision to design a thicker cap. Measures to prevent colonization or disturbance of the cap by deep burrowing bottom-dwelling organisms can be considered in cap design, and in developing biological monitoring requirements for the project. Project managers should refer to Chapter 2, Section 2.8.3 and consult with aquatic biologists with knowledge of local conditions for evaluation of the bioturbation potential. In some cases, a site-specific biological survey of bioturbators would be appropriate. In addition, the USACE Technical Note *Subaqueous Cap Design: Selection of Bioturbation Profiles, Depths and Process Rates* [Clarke et al. 2001, (Dredging Operations and Environmental Research (DOER)-C21 at http://el.erdc.usace.army.mil/dots/doer/technote.html], provides information on designing in-situ caps and also provides many useful references on bioturbation. Although not usually a major pathway for contaminant release, project managers should also be aware of the potential for wetland/aquatic plants to penetrate a cap and create pathways for some contaminant migration.

The project manager should consider consolidation when designing the cap. Fine-grained granular capping materials can undergo consolidation due to their own weight. The thickness of granular cap material should have an allowance for consolidation so that the minimum required cap thickness is maintained following consolidation. An evaluation of consolidation is important in interpreting monitoring data to differentiate between changes in cap surface elevation or cap thickness due to consolidation, as opposed to erosion.

Even if the cap material is not compressible, most contaminated sediment is compressible and some may be highly compressible. Underlying contaminated sediment will almost always undergo some consolidation due to the added weight of the capping material or armor stone. The degree of consolidation should provide an indication of the volume of pore water expelled through the contaminated layer and capping layer to the water column due to consolidation. The consolidation-driven advection of pore water should be considered in the evaluation of short-term contaminant flux. Also, consolidation may decrease the vertical permeability of the capped sediment and thus reduce long-term flux. Methods used to define and quantify consolidation characteristics of sediment and capping materials, such as standard laboratory tests and computerized models, are available (U.S. EPA 1998d, Palermo et al. 1998a, Liu and Znidarcic 1991).

5.4.2 Stabilization/Erosion Protection Component

This functional component of the cap is intended to stabilize both the contaminated sediment and the cap itself to prevent either from being resuspended and transported from the capping location. The potential for erosion generally depends on the magnitude of the applied bed shear stresses due to river, tidal, and wave-induced currents, turbulence generated by ships/vessels (due to propeller action and vessel draft), and sediment properties such as particle size, mineralogy and bed bulk density. At some sites, there is also the potential for seismic disturbance, especially where contaminated sediment and/or cap material are of low shear strength. These and other aspects of investigating sediment stability are discussed in Chapter 2, Section 2.8, Sediment Stability and Contaminant Fate and Transport. Conventional methods for analysis of sediment transport are available to evaluate erosion potential of caps, ranging from simple analytical methods to complex numerical models (U.S. EPA 1998d, Palermo et al. 1998a). Uncertainty in the estimate of erosion potential should be evaluated as well.

The design of the erosion protection features of an in-situ cap (i.e., armor layers) should be based on the magnitude and probability of occurrence of relatively extreme erosive forces estimated at the capping site. Generally, in-situ caps should be designed to withstand forces with a probability of 0.01 per year, for example, the 100-year storm. As is discussed further in Chapter 2 (Section 2.8, Sediment Stability and Contaminant Fate and Transport), in some circumstances, higher or lower probability events should also be considered.

Another consideration for capping, especially capping of contaminated sediment with high organic content is whether significant gas generation due to anaerobic degradation will occur. Gas generation in sediment beneath caps, especially those constructed of low permeable materials, could either generate significant uplift forces and threaten the physical stability of the overlying capping material, or carry some contaminants through the cap. Little has been documented in this area to date, but the possible influence of this process on cap effectiveness presents an uncertainty the project manager should consider in the analysis of remedial alternatives.

5.4.3 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 vertical movement of dissolved contaminants by advection (flow of ground water or pore water) through the cap is possible, while some movement of contaminants by molecular diffusion (movement across a concentration gradient) over long periods usually is inevitable. However, in assessing these processes, it is important to also assess the sorptive capacity of the cap material, which will act to retard contaminant flux through the cap, and the long-term fate of capped contaminants that may transform through time. Slow releases of dissolved contaminants through a cap at low levels will generally not create unacceptable exposures. If reduction of contaminant flux is necessary to meet remedial action objectives, however, a more involved analysis to include capping effectiveness testing and modeling should be conducted as a part of cap design. Because of the uncertainties involved in predicting future flux rates over very long time periods, this guidance does not advocate a particular minimum rule of thumb for the appropriate time frame for design with respect to chemical isolation. In general, it is reasonable for the physical isolation component (i.e., physical stability) of a cap design to be based on a shorter time frame (e.g., a disruptive event with a more frequent recurrence interval) than the much longer time frames considered in design for chemical isolation (e.g., the time required for accumulation of contaminants in the cap material or that required to attain the maximum chemical flux through the cap), in part because erosion of small areas of a cap is easier to repair.

Nevertheless, both advective and diffusive processes should be considered in cap design. If a ground water/surface water interaction study indicates that advection is not significant over the area to be capped (e.g., migration of ground water upward through the cap would not prevent attaining the RAOs), the cap design may need to address only diffusion and the physical isolation and stabilization of the contaminated sediment. In this case, it may not be necessary to design for control of dissolved and/or colloidally facilitated transport due to advection (Ryan et al. 1995).

In contrast, where ground water flow upward through the cap is expected to be significant, the hydraulic properties of the cap should also be determined and factored into the cap design. These properties should include the hydraulic conductivity of the cap materials, the contaminated sediment, and underlying clean sediment or bedrock. According to a USACE laboratory study, ground water flow velocities exceeding 10^{-5} cm/sec potentially result in conditions in which equilibrium partitioning processes important to cap effectiveness could not be maintained (Myers et al. 1991). Such conditions should be carefully considered in the cap design. High rates of ground water flow through contaminated sediment may cause unacceptable exposures. In these areas, in-situ capping may not be an effective remedial approach without additional protective measures. Use of amended caps (caps containing reactive or sorptive material to sequester organic or inorganic contaminants) is one potential measure undergoing pilot studies. Project managers should refer to the Remediation Technologies Development Forum (RTDF) Web site at http://www.rtdf.org for the latest in-situ cleanup developments. More information on the interactions of ground water and in-situ caps can be found in the USACE Technical Note, *Subaqueous Capping and Natural Recovery: Understanding the Hydrogeologic Setting at Contaminated Sediment Sites* (Winter 2002).

Where non-aqueous phase liquids (NAPL) are present in part of an area to be capped, the process for potential contamination migration should be carefully considered. NAPL may be mobilized by consolidation-induced or ground water-induced advective forces. Field sampling and bench-scale tests such as the Seepage Induced Consolidation Test can be designed to test these issues (e.g., Hedblom et al. 2003). In situations where conventional cap designs are not likely to be effective, it may be possible to consider impervious materials (e.g., geomembranes, clay, concrete, steel, or plastic) or reactive materials for the cap design. Where this is done, however, care must be taken such that head increases along the edges of the impervious area do not lead to additional NAPL migration. Project managers are encouraged to draw on the experience of others who have conducted pilot or full scale caps in the presence of NAPL.

Laboratory tests can be used to calculate sediment- and capping material-specific diffusion and chemical partitioning coefficients. Several numerical models are available to predict long-term movement of contaminants due to advection and diffusion processes into or through caps, including caps with engineered components. The models can evaluate the effectiveness of varying thicknesses of granular cap materials with differing properties [grain size and total organic carbon (TOC)]. The results generated by such models include flux rates to overlying water and sediment and pore water concentrations in the entire sediment and cap profile as a function of time. These results can be compared to sediment remediation goals or applicable water quality criteria in overlying surface water, or interpreted in terms of a mass loss of contaminants as a function of time. Results could also be compared to similar calculations for other remediation technologies.

5.5 OTHER CAPPING CONSIDERATIONS

In preparing a feasibility study to evaluate in-situ capping for a site, project managers should consider the following:

- Identifying candidate capping materials physically and chemically compatible with the environment in which they will be placed;
- Evaluating geotechnical considerations including consolidation of compressible materials and potential interactions and compatibility among cap components;
- Assessing placement methods that will minimize short-term risk from release of contaminated pore water and resuspension of contaminated sediment during cap placement; and
- Identifying performance objectives and monitoring methods for cap placement and long-term assessment of cap integrity and biota effects.

In addition to evaluation during the feasibility study, these aspects should be addressed in more detail during design. These topics are discussed briefly below. In addition, project managers should refer to Chapter 8, Section 8.4.2 for a discussion of general monitoring considerations for in-situ capping, and to Chapter 3, Section 3.6 for a discussion of ICs that may relate to caps.

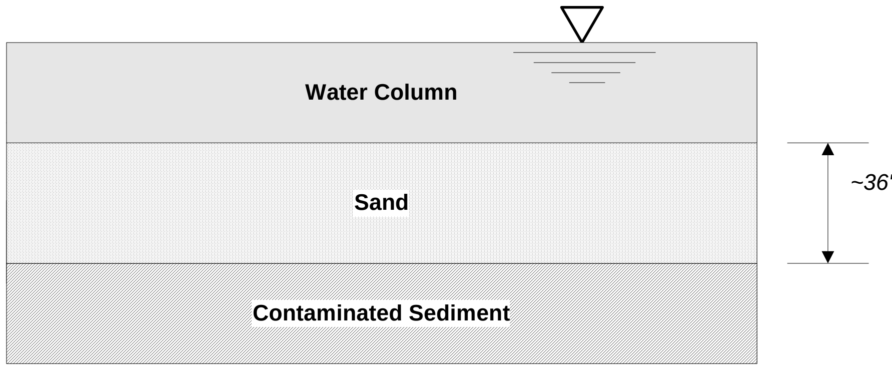
5.5.1 Identification of Capping Materials

Caps are generally composed of clean granular materials, such as upland sand-rich soils or sandy sediment; however, more complex cap designs could be required to meet site-specific RAOs. The project manager should take into consideration the expected effects of bioturbation, consolidation, erosion, and other related processes on the short- and long-term exposure and risk associated with contaminants. For example, if the potential for erosion of the cap is significant, the level of protection could be raised by increasing cap thickness or by engineering the cap to be more erosion-resistant through use of cap material with larger grain size, or by using an armor layer. Porous geotextiles do not contribute to contaminant isolation, but serve to reduce the potential for mixing and displacement of the underlying sediment with the cap material. A cap composed of naturally occurring sand is generally preferred over processed sand because the associated fine fraction and organic carbon content found in natural sands are more effective in providing chemical isolation by sequestering contaminants migrating through the cap. However, sand containing a significant fraction of finer material may also increase turbidity during placement.

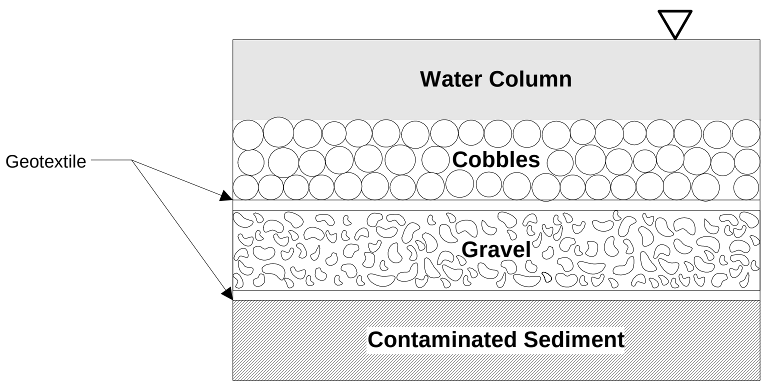
Specialized materials may be used to enhance the chemical isolation capacity or otherwise decrease the thickness of caps compared to sand caps. Examples include engineered clay aggregate materials (e.g., AquaBlok™), and reactive/adsorptive materials such as activated carbon, apatite, coke, organoclay, zero-valent iron and zeolite. Composite geotextile mats containing one or more of these materials (i.e., reactive core mats) are becoming available commercially.

Highlight 5-2 illustrates some examples of cap designs.

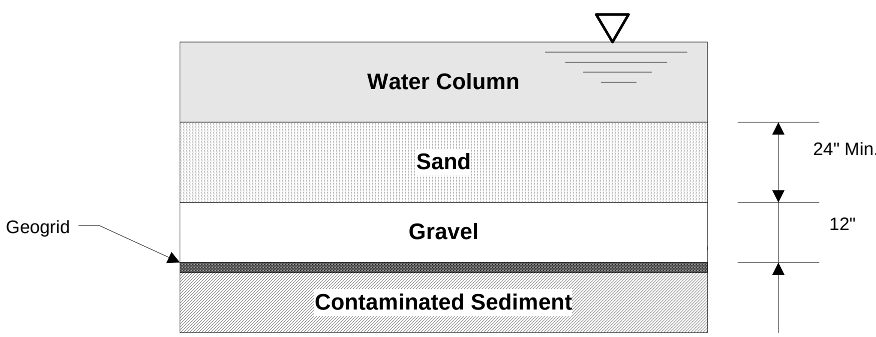
Highlight 5-2: Sample Cap Designs



A. Eagle Harbor, WA



B. Sheboygan, WI



C. Convair Lagoon, CA

Source: Modified from U.S. EPA 1998d

5.5.2 Geotechnical Considerations

Usually, contaminated sediment is predominately fine-grained, and often has high water content and low shear strength. These materials are generally compressible. Unless appropriate controls are implemented, contaminated sediment can be easily displaced or resuspended during cap placement. Following placement, cap stability and settlement due to consolidation can become two additional geotechnical issues that may be important for cap effectiveness.

As with any geotechnical problem of this nature, the shear strength of the underlying sediment will influence its resistance to localized bearing capacity or sliding failures, which could cause localized mixing of capping and contaminated materials. Cap stability immediately after placement is critical, before any excess pore water pressure due to the weight of the cap has dissipated. Usually, gradual placement of capping materials over a large area will reduce the potential for localized failures. Information on the behavior of soft deposits during and after placement of capping materials is limited, although some field monitoring data have shown successful sand capping of contaminated sediment with low shear strength. Conventional geotechnical design approaches should, therefore, be applied with caution (e.g., by building up a cap gradually over the entire area to be capped). Similarly, caps with flatter transition slopes at the edges are not generally subject to a sliding failure normally predicted by conventional slope stability analysis.

5.5.3 Placement Methods

Various equipment types and placement methods have been used for capping projects. The use of granular capping materials (i.e., sand, sediment, and soil), geosynthetic fabrics, and armored materials are all in-situ cap considerations discussed in this section. 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 mixing with the underlying contaminated sediment. Uncontrolled placement of the capping material can also result in the resuspension of contaminated material into the water column and the creation of a fluid mud wave that moves outside of the intended cap area.

Granular cap material can be handled and placed in a number of ways. Mechanically excavated materials and soils from an upland site or quarry usually have relatively little free water. Normally, these materials can be handled mechanically in a dry state until released into the water over the contaminated site. Mechanical methods (e.g., clamshells or release from a barge) rely on gravitational settling of cap materials in the water column, and could be limited by depth in their application. Granular cap materials can also be entrained in a water slurry and carried to the contaminated site wet, where they can be discharged by pipe into the water column at the water surface or at depth. These hydraulic methods offer the potential for a more precise placement, although the energy required for slurry transport could require dissipation to prevent resuspension of contaminated sediment. Armor layer materials can be placed from barges or from the shoreline using conventional equipment, such as clamshells. Placement of some cap components, such as geotextiles, could require special equipment. Examples of equipment types used for cap placement are shown in Highlight 5-3. The *Guidance for In-Situ Subaqueous Capping of Contaminated Sediments* (U.S. EPA 1998d) contains more detailed information about cap placement techniques.

Monitoring sediment resuspension and contaminant releases during cap placement is important. Cap placement can resuspend some contaminated sediment. Contaminants can also be released to the water column from compaction or disruption of underlying sediment during cap placement. Both can lead to increased risks during and following cap placement. Applying cap material slowly and uniformly can minimize the amount of sediment disruption and resuspension. Therefore, designs should include plans to minimize and monitor impacts during and after construction.

5.5.4 Performance Monitoring

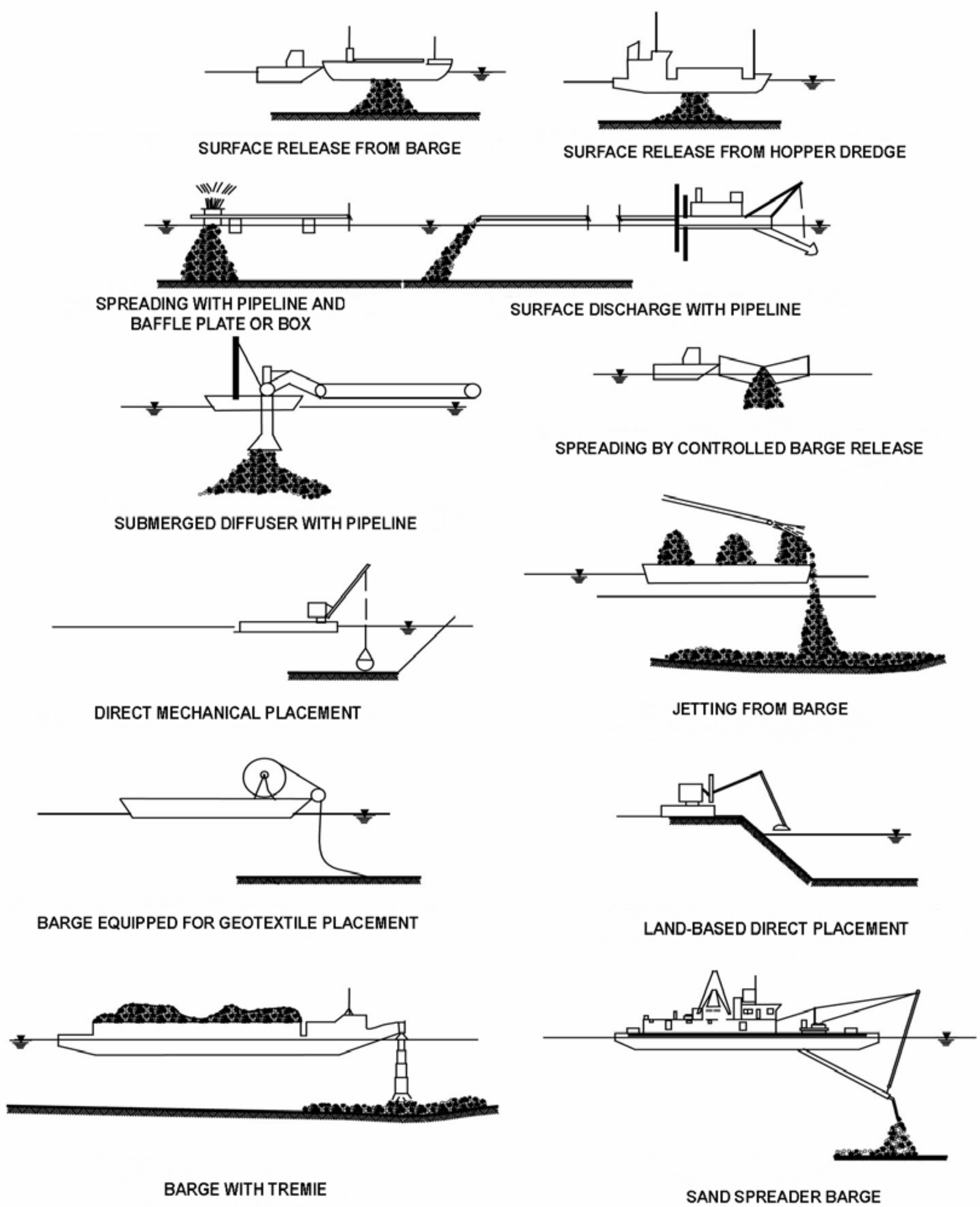
Performance objectives for an in-situ cap relate to its ability to provide sufficient physical and chemical isolation and stabilization of contaminated sediment to reduce exposure and risk to protective levels. Broader RAOs for the site such as decreases in contaminant concentrations in biota or reduced toxicity should be monitored when applicable. The following processes should be considered when evaluating the performance of a cap, and in developing a cap monitoring program:

- Erosion or other physical disturbance of cap;
- Contaminant flux into cap material and into the surface water from underlying contaminated sediment (e.g., ground water advection, molecular diffusion); and
- Recolonization of cap surface and resulting bioturbation.

General considerations related to monitoring caps and an example of cap monitoring elements are presented in Chapter 8, Remedial Action and Long-Term Monitoring.

Performance monitoring of a cap should be related to the design standards and remedial action objectives related to the site. Generally, physical monitoring is initially conducted on a more frequent schedule than chemical or biological monitoring because it is less expensive to perform. Some processes (i.e., contaminant flux) are not generally assessed directly because they are very difficult to measure, but are assessed by measuring contaminant concentrations in bulk samples from the cap surface, in shallow cores into the surface layer of a cap, and by bathymetric surveys and various photographic techniques. It is often desirable to establish several permanent locational benchmarks so that repeated surveys can be accurately compared. In some cases, contaminant flux and the resulting contaminant concentration in surface sediment, cap pore water, or overlying surface water can be compared to site-specific sediment cleanup levels or water quality standards (e.g., federal water quality criteria or state promulgated standards). In addition, the concentration of contaminants accumulating in the cap material as a function of time can be compared to site-specific target cleanup levels during long-term cap performance monitoring. Both analytical and numerical models exist to predict cap performance and have been compared and validated with laboratory tests and field results (e.g., Ruiz et al. 2000). However, project managers should be aware that representative chemical monitoring of caps is difficult, in part because of the need to distinguish between vertical migration into the cap and the mixing that occurs at the cap/sediment interface during placement. In some cases, physical measurement of cap integrity and water column chemical measurement may be sufficient for routine monitoring.

Highlight 5-3: Sample Capping Equipment and Placement Techniques



Source: U.S. EPA 1998d

Highlight 5-4 presents some general points to remember from this chapter.

Highlight 5-4: Some Key Points to Remember When Considering In-Situ Capping

- Source control generally should be implemented to prevent recontamination
- In-situ caps generally reduce risk through three primary functions: physical isolation, stabilization, and reduction of contaminant transport
- Caps may be most suitable where water depth is adequate, slopes are moderate, ground water flow gradients are low or contaminants are not mobile, substrates are capable of supporting a cap, and an adequate source of cap material is available
- Evaluation of capping alternatives and design of caps should consider buried infrastructure, such as water, sewer, electric and phone lines, and fuel pipelines
- Alteration of substrate and depth from capping should be evaluated for effects on aquatic biota
- Evaluation of a capping project in natural riverine environments, should include consideration of a fluvial system's inherent dynamics, especially the effects of channel migration, flow variability including extreme events, and ice scour
- Evaluation of capping alternatives should include consideration of cap disruption from human and natural sources, including at a minimum, the 100-year flood and other events such as seismic disturbances with a similar probability of occurrence
- Selection of cap placement methods should minimize the resuspension of contaminated sediment and releases of dissolved contaminants from compacted sediment
- Use of experienced contractors skilled in marine construction techniques is very important to placement of an effective cap
- Monitor in-situ caps during and after placement to evaluate long-term integrity of the cap, recolonization by biota, and evidence of recontamination
- Maintenance of in-situ caps is expected periodically