MANAGEMENT OF MEGASITES IN THE UNITED STATES: REMEDIATION STRATEGIES, TECHNOLOGY SELECTION, AND CLEANUP COSTS

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Introduction

The European Union (EU) project on Water, Environment and Landscape management at COntaminated MEgasites (WELCOME) defined the term *megasite* as "a large (5 - 500 km^2) area with multiple contaminant sources related to (former) industrial activities, with a considerable impact on the environment, through groundwater, surface water and/or air migration." Megasites in Europe typically occur at sea ports, large scale chemistry industry complexes, metal mining areas, and military complexes. The EU has recognized that comprehensive remediation and redevelopment of megasites within the short-term (e.g., 25 years) is often impossible technically and economically, and therefore megasites represent long-term potential sources of regional contamination of groundwater, surface water and sediments. The WELCOME project developed an Integrated Management Strategy (IMS) guidance manual for megasites that provides a system for ranking site-specific risks and prioritizing remediation expenditures to address the greatest risks first.

In contrast to the EU, the United States (U.S.) Environmental Protection Agency (USEPA) has only developed a monetary definition of the term *megasite*. The USEPA defines a *megasite* as any hazardous waste site where the total cost of investigation and cleanup, excluding long-term care, equals or exceeds $50 million (USEPA 2003). This definition was primarily developed as a budgeting designation that refers to those sites regulated under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA, or Superfund) program that consume the greatest portion of the Superfund budget; however, the definition also effectively serves as a surrogate that conveys the size and complexity of megasites. In 2003 it was estimated that funding needs for eight large, complex sites (out of a total of 94 sites funded by the Superfund program) accounted for nearly 50% of the money available that year for Superfund cleanups (OIG, 2004).

USEPA has not yet issued written guidance regarding strategic approaches for management or cleanup at megasites. However, in 2004 USEPA commissioned an independent panel of experts to provide recommendations regarding the future of the Superfund program, including how best to manage megasites. The panel recognized that megasites present the same types of risk and technical challenges posed by smaller Superfund sites, except that decisions regarding megasite cleanup have a greater impact on government budgets (NACEPT 2004). Indeed, many industrial waste sites in the U.S. encompass large areas and include multiple contaminant source areas, but are not classified as megasites. The panel provided a series of recommendations to USEPA, but did not reach consensus on the question of whether a new cleanup approach or different cleanup criteria were necessary for megasites.

Absent specific guidance for megasites, risk assessment and remedy selection decisions at most megasites in the U.S. are made within context of the Superfund cleanup process. This paper presents an overview of how the Superfund program is applied to cleanup of soil and groundwater megasites in the U.S., and focuses on the risk management and remedy selection process in Superfund. An estimated 85% of all Superfund sites include significant groundwater contamination problems. In addition, this paper summarizes some of the limitations of the Superfund process when it is applied to management and cleanup of megasites in the U.S. Although many megasites in the U.S. and Europe involve restoration of contaminated surface water (e.g., within harbors or estuaries), this paper focuses primarily on soil and groundwater restoration, as these media are the primary target for remediation efforts at the Kærgård Plantage and Høfde 42 megasites.

A Brief Tour of the Megasites in the U.S.

A contaminated site in the U.S. is classified as a Superfund site when the USEPA has evaluated the site and (1) determined that the site is not eligible for cleanup under the Resource Conservation and Recovery Action (RCRA) program; (2) determined that the human and ecological hazards at the site exceed a specific hazard ranking threshold; and (3) solicited and responded to public input regarding potential classification of the property as a Superfund site. Sites that qualify as Superfund sites are put on the National Priorities List (NPL), a management tool that identifies federal (i.e., U.S. government) and non-federal (i.e., private sector) sites that are believed to present the greatest risk to human health and the environment across the U.S. The universe of megasites in the U.S., as in Europe, includes industrial, mining, and military facilities. USEPA distinguishes federal from non-federal sites, because the Superfund program generally funds cleanups for non-federal sites, but not federal sites.

As noted above, remediation cost (i.e. > $50 million) is the primary determinant of a megasite in the U.S. Cost estimates for Superfund site cleanup are often presented in terms of costs per “operable unit” or “OU”. Superfund sites, and megasites in particular, are typically far too large to address in a single response action. For this reason, Superfund sites are often divided into operable units (OUs) early in the Superfund process, and then are characterized both individually and as part of the whole site.

Non-Federal Megasites in the Superfund Program

As of September of 2003, there were 1298 sites on the NPL (including 54 proposed sites), and USEPA estimated that approximately 142 of these sites are or are likely to become megasites. It is noteworthy that cleanup costs at Superfund sites not classified as megasites are typically very significant. The USEPA (2004) estimated that the average cost of investigation and cleanup at a non-federal Superfund OU is $1.4 million for remedial investigations/feasibility studies (RI/FS), $1.4 million for remedy design, $11.9 million for remedy implementation, and $10.3 million for long-term remedial action for sites that require long-term treatment to restore groundwater or surface water (2003 dollars).

Federal Megasites in the Superfund Program

One hundred sixty five (165) federal facilities were listed on the NPL in September 2005 (including 6 proposed facilities). Those facilities include abandoned mines, nuclear, biological, chemical and conventional weapons productions plants; military base industrial sites, such as aircraft and naval ship maintenance facilities; and landfills. Approximately 80% of these facilities are owned by the Department of Defense and 12% are owned by the Department of Energy. While federal facility Superfund sites represent only 11% of the NPL (2005 data), 67% (110) of those federal facilities are considered megasites (OMB 2005). The average number of OUs on a federal Superfund site (10) is more than 5 times the average number of OUs on a non-federal Superfund site, a fact that illustrates the difference in size and scope of contamination at federal government hazardous waste sites (OMB 2005).

A significant portion of federal megasites are owned by the U.S. Department of the Navy (DON). As of September 2004, there were 43 U.S. Navy installations listed on the NPL. U.S. taxpayers have spent over $2 billion on environmental cleanup at those 43 sites, with an estimated additional $1.4 billion needed to complete the expected cleanup program (DON 2005). The average estimated cleanup cost at each Navy site on the NPL is $80 million, and ranges from $10 - $280 million.

Overview of the Superfund Remedy Evaluation and Selection Process

After a site is listed on the NPL (i.e., entered into the Superfund program), a remedial investigation/feasibility study (RI/FS) is performed to characterize the type, concentration, and extent of waste impacts; assess risk to human health and the environment; and conduct treatability testing to evaluate the potential performance and cost of the treatment technologies that are being considered. The RI/FS is performed in five phases: (1) scoping; (2) site characterization and risk assessment; (3) development and screening of remedial alternatives; (4) treatability tests; and (5) detailed analysis. The RI/FS process is illustrated in Figure 1, and each of the five phases are discussed in more detail below.

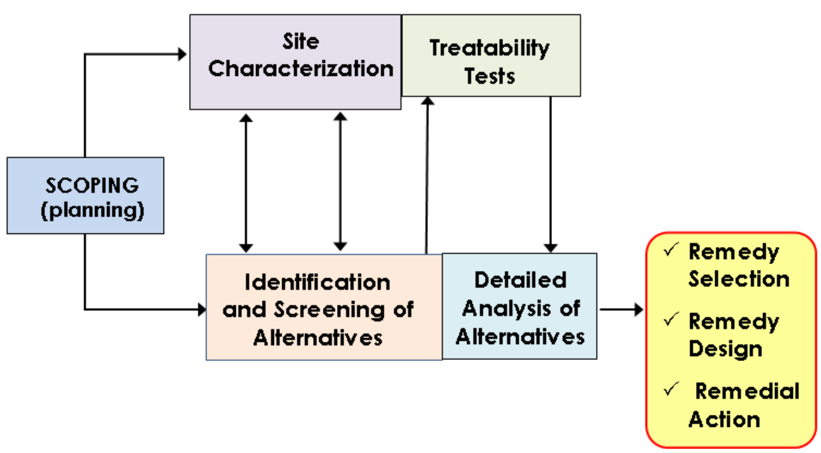

Figure 1. Flowchart of RI/FS process (modified from USEPA 1988).

The RI/FS process gives significant decision-making authority to the regulatory agencies, and also provides opportunity for public participation before the final remedy is selected. For more detailed information on this process, readers are referred to USEPA (1988) and http://www.epa.gov/superfund/whatissf/sfproces/rifs.htm.

Phase 1: Scoping

The primary purpose of the scoping phase is to: develop a preliminary conceptual model of contaminant impacts at the site; identify data gaps in that conceptual model; determine cleanup objectives; identify what interim (near-term) remedial actions might be appropriate; and prepare work plans for implementation of the RI/FS. A critical step in this phase that is especially integral to megasites is defining the spatial extent of contaminated areas, identifying contaminant source areas, and establishing OUs. As noted above, Superfund sites are typically too large to address in a single response action, and the actions selected often require a longer time frame to undertake than is common for other smaller or more contained sites. Human and ecological exposure risk is an important factor in designating units, and where appropriate, units that pose a human health risk are separated from units that pose an ecological risk. OUs come in a variety of different shapes and sizes, and many are quite large. For example, the El Monte OU at the San Gabriel Valley (Area 1) Superfund Site in California is an area of contaminated groundwater that covers approximately 29 km^2. The entire San Gabriel Valley (Area 1) Superfund Site includes eight OUs over an area of 78 km^2.

While there are no definitive criteria for designating units, many area-specific factors are used: (1) similar contamination of waste material or environmental media (e.g., soils, ground water, or surface water); (2) similar geographic locations; (3) similar potential cleanup techniques; (4) potentially similar cleanup time frames; and (5) sites that are amenable to being managed and addressed in a single decision making process (NRC 2005). Often, contaminant source areas and groundwater plumes are designated as separate OUs, and separate cleanup actions are used to address separate units. Once units have been designated, they are typically ranked to determine the order in which they will be addressed for remediation. Standardized criteria have not been established for determining unit priorities; however, exposure is typically a significant factor in assigning priority to sites based on the degree of risk they pose to human health and the environment.

Phase 2 – Site Characterization & Risk Assessment

At most contaminated sites, remediation systems cannot be designed effectively until the nature and extent of the contaminant impact have been properly investigated and delineated. During the second phase of the RI/FS, soil and groundwater are investigated extensively to determine the type, concentration, and distribution of contaminants in environmental media. As part of this process, a baseline risk assessment is typically performed to further investigate the extent to which the environmental impacts threaten human health and the environment. The risk assessment may evaluate a variety of contaminant exposure routes, including ingestion (soil, groundwater), inhalation (soil, vapors), and dermal contact (soil, groundwater, and surface water). The results of the site characterization and risk assessment affect the choice of remedial action, the required cleanup level, and the priority sequence for site-wide cleanup. USEPA has a significant portfolio of guidance documents for conducting ecological and human health risk assessment, much of which is available for free on the world-wide web at: http://www.epa.gov/oswer/riskassessment/risk_superfund.htm#.

Phase 3 – Screening of Remedial Alternatives

The purpose of this phase of the FS is to develop an appropriate range of response actions and remediation alternatives that will be analyzed more fully in the detailed analysis phase of the RI/FS. In Phase 3, the results of the site characterization and risk assessment are used to determine remedial action objectives (RAOs), identify general response actions (GRAs), and identify and screen viable remedial alternatives. RAOs specify the target contaminants and media requiring treatment, as well as short-term (preliminary) and final remediation goals. Preliminary remediation criteria are often determined on a site-specific basis, and incorporate site-specific risk-factors. During this process, the volume and/or mass of contaminated material subject to treatment is estimated for the given RAOs. GRAs describe broad categories of responses for each environmental medium requiring cleanup. Example GRAs include land-use controls, groundwater use controls, containment, mass removal (e.g., excavation or pumping), in situ treatment, and monitored natural attenuation/long-term monitoring.

Once the RAOs and GRAs have been developed, alternative remedial technologies and process options applicable to each GRA are identified and screened to eliminate alternatives that are not technically feasible at the site. Process options are specific treatment options within a broader technology category (e.g., permanganate, Fenton's reagent, and persulfate are alternative process options for in situ chemical oxidation). "No Action" is typically included as an alternative, as a baseline point of reference. Alternatives are screened based on three factors: effectiveness, implementability, and relative cost (i.e., high/medium/low). The evaluation of effectiveness focuses not only on treatment performance, but also on potential risks to human and ecological receptors during remedy implementation, and technology maturity. Only those alternatives that are judged as the best or most promising are retained for further consideration and analysis. Selection of alternatives for detailed analysis is typically made with the participation of all primary stakeholders (e.g., site owners, regulators, and contractors).

It should be recognized that a single remedial alternative for a given OU often consists of a combination of technologies. For example, a remedial alternative may consist of: excavation of unsaturated soils in the source area; in situ chemical oxidation of heavily contaminated saturated aquifer materials in the source area; and groundwater pump-and-treat in the downgradient plume. The number of technologies employed typically increases in proportion to the size and/or complexity of the OU.

Phase 4 – Treatability Testing

The fourth phase in the RI/FS process consists of bench- and/or pilot-scale treatability testing. In this phase, technologies that are retained in the preliminary screening in Phase 3 are tested to measure their performance under site-specific conditions. Treatability tests are a standard component of process engineering scale-up, and are used to identify successful treatment options and optimal operational modes at a limited scale, before monetary resources are invested in full-scale implementation. With this approach, treatability tests can avoid wasteful expenditures on full-scale designs that would otherwise fail to meet remediation objectives. Treatability tests (i.e., jar tests) are routinely used, for example, to optimize treatment performance at municipal waste water treatment plants.

Treatability tests are especially valuable for innovative treatment technologies (e.g., persulfate, or nano-scale zero valent iron) or for application of more conventional technologies at sites with unique or complex contaminant mixtures. Given the unique contaminants present, the Høfde 42 and Kærgård Plantage sites are excellent examples of cases where treatability tests have been necessary to assess performance of treatment options. Bench-scale treatability tests often are not necessary for application of proven technologies under typical conditions (e.g., air stripping or carbon adsorption for groundwater treatment). Similarly, field pilot tests are not always necessary for sites where proven technologies are applied under "average" conditions. Nevertheless, a properly designed pilot test offers the opportunity to optimize performance at a relatively small scale, thereby minimizing costs during full-scale application. To the extent possible, pilot test systems should be designed with the potential to incorporate the infrastructure of the pilot system into the final full-scale remedy.

Phase 5 - Detailed Evaluation of Remedial Alternatives

The detailed analysis of remedial alternatives consists of the analysis and presentation of the pertinent information needed to support final selection of a remedy for a site. The Superfund program specifies that each of remedial alternatives be evaluated and compared with regard to nine criteria for remedy selection: overall protectiveness; compliance with all relevant environmental laws and regulations; long-term effectiveness and permanence; short-term effectiveness; implementability; cost; reduction of toxicity, mobility, or volume of wastes; state acceptance; and community acceptance (see Figure 2). Relative to Phase 3, the level of evaluation and analysis for each alternative is significantly more detailed in this phase. For example, the estimate of remedy cost in Phase 5 should include a calculation of capital costs (design, construction, equipment, and infrastructure) and operation & maintenance costs (operating labor, reagents/materials, parts, and services). Typically, these "study estimate" costs made during the FS provide a +50/-30 % level of accuracy, and are presented in terms of present worth (i.e., are discounted for time-value of money) for those remedial alternatives that are expected to require long-term operation.

The end-product of the RI/FS process is a report providing a comparative analysis of remedial alternatives in relation to each of the nine evaluation criteria. The comparative analysis effectively serves to highlight the relative advantages and disadvantages of each alternative so that key tradeoffs can be identified. The report provides a basis for the regulatory agency to select a preferred final remedy for the site.

Establishing Achievable Cleanup Goals at Megasites: What does Superfund Allow?

Cleanup goals for Superfund sites are generally established with the short term goal of eliminating immediate risks to human health and the environment, and the long-term goal of returning soil and useable groundwater to beneficial uses. The Superfund

Figure 2. Nine criteria used in detailed evaluation of remedial alternatives in process for remedy selection under the USEPA Superfund program.

program allows use of risk assessments to determine whether site-specific risk-based cleanup goals for soil are appropriate. In many cases, cleanup goals for soil are established with a recognition of the future use of the property (e.g., residential use vs. industrial use). Cleanup levels for industrial use scenarios are typically higher than levels for residential scenarios (see: http://www.epa.gov/region09/waste/sfund/prg/index.html). The allowance for risk-based remediation goals, and higher cleanup levels for industrial use properties, can be particularly relevant to remediation of megasites, where the extent and concentration of contaminant impacts may make it technically and/or economically infeasible to completely eliminate contamination a site.

The Superfund program also allows some consideration of contaminant bioavailability when performing risk assessments to establish site-specific soil cleanup levels (see: http://www.epa.gov/superfund/health/exposure/bioavailability/). A variety of inorganic and organic contaminants, when mixed and aged in saturated sediments, will precipitate or sorb to the sediment and cease to be available for biological uptake. In this case, only a portion of the original contaminant mass in the sediment is bioavailable. Recognition of bioavailability – and the role of irreversible sorption and precipitation in controlling the fate of contaminants – can offer potential economic benefits in that it will help focus remediation goals (and expenditures) only on the fraction of contaminant that poses a risk to ecological or human receptors. Unfortunately, the question of bioavailability of contamination is not uniformly recognized throughout the U.S., and the majority of USEPA regional offices conservatively assume that all contamination in soil is bioavailable – regardless of whether the contamination is sorbed or precipitated.

USEPA takes an even more conservative approach with regard to groundwater restoration: at the vast majority of Superfund sites, the RAO is to return impacted groundwater to drinking water quality, regardless of whether the aquifer beneath the site has been used for drinking water supply, or whether natural conditions (such as elevated sulfate concentration) render the groundwater unusable as a drinking water source. For most groundwater remediation programs at Superfund sites, preliminary remediation goals (PRGs) are established for the purpose of controlling human health and/or ecological risks from groundwater during the near-term. The long-term (typically 30-year horizon) goal is to reduce contaminant levels in groundwater to below the maximum contaminant limit (MCL), which equates to a 10^{-6} cancer risk threshold. PRGs are site-specific cleanup levels that recognize specific risk exposure scenarios, and are not typically higher than MCLs.

The U.S. government approach to valuing most groundwater as an existing drinking water resource has been a key factor contributing to the high cost of cleanup at Superfund sites. The question is whether this approach is sustainable in the decades to come, given the increasing cost burden for other environmental protection measures such as those associated with global warming.

One Option for the Worst Megasites: Technical Impracticability

In the early 1990s, USEPA recognized that certain Superfund sites contaminated with dense nonaqueous phase liquids (DNAPLs), including chlorinated solvents and coal tar creosote, pose a unique remediation challenge. Specifically, in 1993, USEPA issued a policy directive that recognized that the scale and type of contamination at certain sites was so problematic that complete remediation could be deemed technically impracticable (Technical Impracticability [TI] Guidance, USEPA 1993). The directive recognized that groundwater "restoration to drinking water levels may not be achievable due to the limitations of available remediation technologies", and noted that a variety of factors can contribute to conditions that make complete remediation impracticable, including (i) aquifers of very low permeability; (ii) certain types of fractured bedrock; (iii) and presence of DNAPLs which are "particularly difficult to locate and remove from the subsurface". The directive established a process for allowing a waiver from the requirement of remediating groundwater to drinking water levels and provided a decision framework for determining whether a site qualifies for TI status.

At the time the TI guidance was published, there were fewer technologies available for remediation of DNAPLs than there are today, and the guidance noted that limitations in available technologies was an important factor contributing to TI. Consequent to the issuance of the TI guidance, TI waivers were approved for a few sites, including those contaminated with creosote (i.e., wood treatment facilities) and coal tar creosote. At the same time, the effectiveness and success of technologies for treating DNAPLs has improved significantly over the last decade, and this has led to a decrease in the number of TI waivers that are approved. Nevertheless, the TI process is relevant and valuable model for megasites, where complete remediation of groundwater may not be technically or economically possible within any reasonable timeframe.

Conclusions and Recommendations

Cleanup of megasites is a long-term process involving numerous individual sub-sites or OUs where remediation expenditures must focus first on those OUs that pose the greatest risks to human health and the environment. In many ways, remediation of megasites in the U.S. is not significantly different from smaller Superfund sites, except that there are more OUs to address and the budget and timeframe for cleanup is larger. Remedy selection at most megasites in the U.S. follows the Superfund RI/FS process; however, given the scale and complexity of these sites, remediation megasites must be viewed as a long-term process with an uncertain outcome. Cleanup of megasites is quite expensive, and by definition in the United States, typically costs more than $50 million. Remedy implementation and remedy performance measures at megasites need to recognize that many remedies are not "final", and attainment of end-point cleanup levels may require decades to achieve. In general, multiple remediation technologies are required for cleanup of megasites, either concurrently (in parallel locations) or in sequence, and the number of technologies often increases in proportion to the size and complexity of the site.

Remediation goals (cleanup criteria) at megasites should integrate a realistic reflection of planned future uses for the site. In general, soil cleanup criteria for sites that have a planned industrial future use should be higher than for sites that have a planned residential future use. Careful consideration should be given to current and future groundwater use scenarios when establishing groundwater cleanup criteria. Soil and groundwater cleanup criteria can have a major impact on the total budget for megasite cleanup, and establishment of these criteria should be realistic with regard to future use scenarios. In addition, TI waivers in accordance with USEPA TI guidance should be considered where appropriate to ensure that site-specific cleanup goals for groundwater are realistic for the type, distribution, and complexity of contaminant impacts.

Currently, there are no Federal government programs in the U.S. specifically addressing megasites. Effective management of megasites requires the development of institutions with the capability to over-see engineering operations, minimize the impact of remediation on local communities, and maintain the institutional controls needed to maintain human exposures at acceptable levels (NRC, 2005).

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