Integrated Program for Department of Energy Environmental Management Office of Soil and Groundwater Remediation – 15426

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ABSTRACT

The subsurface problems that remain at the U.S. Department of Energy (DOE) Office of Environmental Management (EM) sites are technically complex and the costs to complete the cleanup mission are expected to range from $17 billion to $21 billion. There is growing recognition that conventional remedies will not meet regulatory goals at a number of sites and alternative approaches will be required. To address the challenge, the EM Office of Soil and Groundwater Remediation created an integrated program to develop innovative scientific and technical in conjunction with engagement of stakeholders, regulators, and the public. The integrated program provides a holistic approach to assess the risk associated with the remaining challenges facing EM and develop solutions that achieve remediation goals and protect human health and the environment.

The integrated program uses a systems-based framework for achieving environmental remediation goals. The framework is based on developing and updating a site conceptual model and includes steps to 1) provide the technical basis for remedial actions, 2) assessments of potential remedies, and 3) implementation and management of remedies to achieve site restoration goals. The Office of Soil and Groundwater remediation defines research and development needed to successfully define and apply the framework. Research opportunities and targets are identified in characterization and conceptual model development, predictions of site conditions, remediation, monitoring, and remediation decision support. Characterization and quantification of key subsurface uncertainties is needed to support conceptual model development, identify contaminant source zones, quantify the flux of contaminants from source terms to points of compliance, and characterize controlling processes for remediation approaches including natural attenuation. Predictive analyses are needed to support development of remediation endpoints, select and design active and in situ or passive remedies, assess remedy performance, and predict long-term contaminant behavior for design of monitoring systems. Advancements are needed to support adaptive remediation approaches and to develop long-term contaminant management strategies for complex sites, such as effective in situ treatment methods for long-lived contaminants (^{99}Tc, ^{129}I, U, Hg, etc.). Monitoring tools and approaches are needed to evaluate remedy performance and plume behavior and decision support methods are needed to quantitatively evaluate remediation alternatives.

The Office of Soil and Groundwater Remediation leverages scientific understanding provided through partnerships with the DOE Office of Science, the Department of Defense, and Environmental Protection Agency. These partnerships are helping EM develop scientific understanding and technologies for implementing the assessment framework.

INTRODUCTION

The subsurface problems that remain at the U.S. Department of Energy (DOE) Office of Environmental Management (EM) sites are technically complex and the costs to complete the cleanup mission are expected to range from $17 billion to $21 billion. Cleanup of remaining EM sites represents one of the largest, most complex, and formidable environmental restoration challenges in the world [1]. There is growing recognition that conventional remedies will not meet regulatory goals at a number of sites that are considered complex and alternative approaches will be required. Complex sites are those

- With physical or chemical properties (e.g., heterogeneous conditions, unsaturated flow conditions, or challenging source terms) that render remediation difficult
- With multiple commingled contaminant plumes in different geologic formations
- That have significant uncertainty with respect to understanding contaminant location and behavior and estimating how the contamination will respond to a remedial action
- Where long-term processes will be needed to address the contamination (e.g., due to presence of long-lived sources or large size).

To address the challenge of remediating complex sites, the Office of Soil and Groundwater Remediation manages an integrated program based on a framework that provides a structured, systems-based technical approach applied to remediation processes. The framework is consistent with the remediation approaches established under the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) and the *Resource Conservation and Recovery Act* (RCRA). The framework facilitates remedy decisions and implementation at complex sites where complete restoration may be uncertain, require long time frames, or involve progressive and adaptive management approaches. A foundation of the framework is a "systems-based" conceptual model of a site describing the features, events, and processes that collectively describe contaminant behavior, remedy performance, and control of exposure pathways, especially those attributes that control contaminant behavior during remediation.

The framework (Fig. 1) is based on defining appropriate remediation endpoints, which are risk-informed remediation goals or scenarios that facilitate management of a progressive remedy path that protects human health and the environment, are acceptable under current regulations and guidelines, and most importantly are agreed upon or negotiated with stakeholders and regulatory agencies. The framework includes steps to 1) provide the technical basis for remedial actions by assembling site characterization and source-term information into an initial site conceptual model, 2) systems-based assessments to identify potential remedies and refine the conceptual model within the context of resource use, and 3) remedy implementation and management to achieve remediation endpoints.

This paper describes the Soil and Groundwater Remediation Program and outlines research and development that can lead to successful definition and application of risk-informed remediation approaches for complex sites. The outcomes of the proposed research and development investments will help DOE implement effective, adaptive systems-based approaches for remediation and/or will provide technical justification for exit strategies from remediation processes.

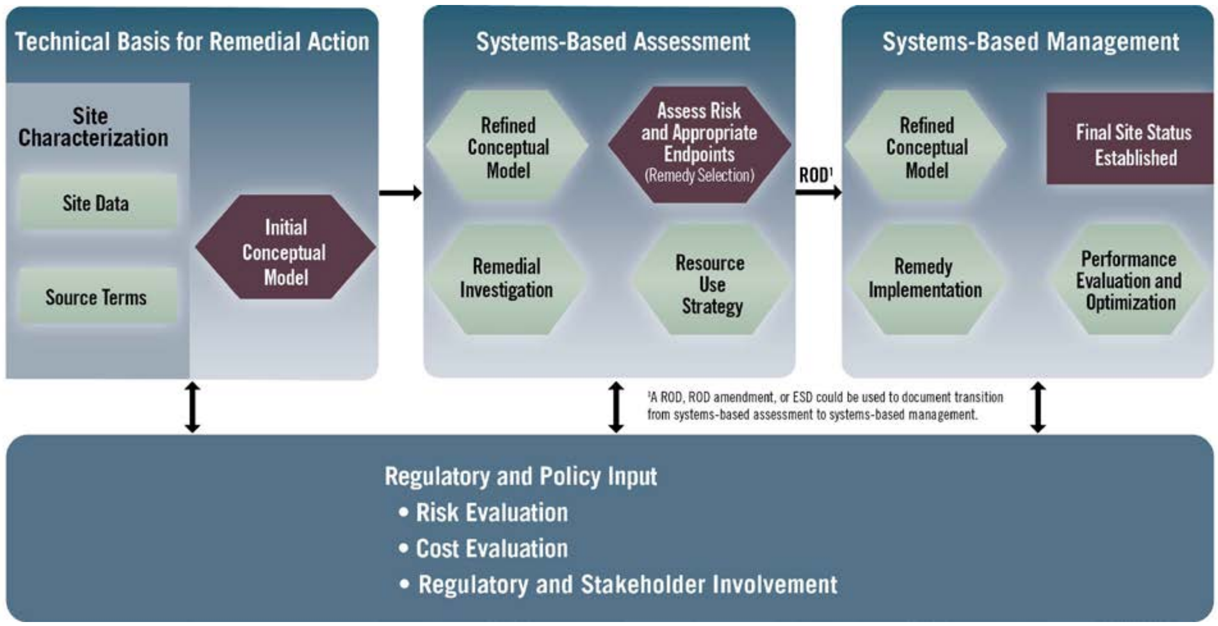

Fig. 1. Systems-based framework overview.

SOIL AND GROUNDWATER REMEDIATION PROGRAM

To address the challenge facing DOE EM completing the cleanup mission, the Office of Soil and Groundwater Remediation manages an integrated program that develops solutions to achieve remediation goals and protect human health and the environment. The program develops solutions through collaborations between Applied Field Research Initiatives (AFRIs) for the Deep Vadose Zone (DVZ), Attenuation-Based Remedies for the Subsurface (ABRS), and Remediation of Mercury and Industrial Contaminants (ROMIC), as well as the Advanced Simulation Capability for Environmental Management (ASCEM). The AFRIs conduct work within each part of the framework using DOE EM sites as test beds. Specifically, the ABRS-AFRI conducts their work at the Savannah River Site in collaboration with DOE Savannah River, the DVZ-AFRI operates at the Hanford Site in collaboration with the DOE Richland Operations Office and the Office of River Protection, and the ROMIC-AFRI conducts their work at the Oak Ridge Reservation in collaboration with the DOE Oak Ridge Office. Together, the program seeks to develop and implement systems-based approaches to provide the scientific and technical understanding for technology development and maturation as well as implementation of advanced scientific approaches in subsurface characterization, monitoring, and remediation to achieve alternate endpoints and meet cleanup and closure goals of DOE sites. To enable implementation of the framework, the Office of Soil and Groundwater Remediation has identified research opportunities and targets in characterization and conceptual model development, predictions of site conditions, remediation, monitoring, and remediation decision support [2].

Characterization and Conceptual Model Development

Conceptual models define the important processes and features relevant to contaminant behavior in the environment and determining contaminant exposure. Quantitative descriptions of important processes reduce uncertainties in conceptual models and predictions of contaminant fate and transport. Conceptual models are widely used as defined in EPA guidance [3]. However, developing conceptual models that directly relate to the regulatory remedy and endpoint selection process (e.g., in the way the monitored natural attenuation (MNA) protocol directly supports the regulatory process for evaluation of MNA as a remedy) will enhance the effectiveness of the approaches in the endpoint framework.

The key issue in conceptual model development is that characterization and quantification of subsurface uncertainties that control remediation processes in complex subsurface environments is incomplete. Strategic opportunities and research topics in characterization and conceptual model development include:

- Quantification of source zones for EM-related contaminants (e.g. Hg, ^{129}I, ^{99}Tc, and Cr(VI)) around complex infrastructure using high-resolution geophysics and other methods
- Characterization of biogeochemical processes in and around low-permeability zones that serve as persistent sources including matrix diffusion, sorption, and biogeochemical reactions and transformation
- Characterization of physical processes including fractured-rock characteristics and fine-scale heterogeneities that control contaminant behavior and fate in complex subsurface settings
- Quantification of controlling geochemical conditions for commingled contaminant plumes vadose zone systems to develop remediation processes and descriptions of long-term contaminant behavior and risk
- Measurement and quantification of mass flux across interfaces including the vadose zone and groundwater, groundwater and river, and other system boundaries to characterize exposure pathways and reduce risk
- Quantifying the assimilative capacity of the subsurface to support design of enhanced remediation and natural attenuation approaches.

Prediction of Site Conditions

An interactive and graded approach for predictive assessments is needed to translate site characterization data into analytical or numerical models, model calibration, predictions of risk, and assessment of uncertainty. Conceptual models and predictive models are ineffective if they do not capture sufficient understanding of the system to be able to represent observed behavior (e.g., contaminant transport, response to remedial actions). An iterative approach to modeling and data collection can provide powerful insights into the behavior of an environmental system and the basis for site remediation and monitoring. The strategic opportunities and research targets associated with simulation and prediction include:

- Development and integration of toolsets with characterization and monitoring to quantify reaction pathways at the appropriate level to evaluate the impact on remediation decisions and approaches

- Enhancements of predictive approaches and toolsets for assessments and monitoring (e.g. ecosystem, biological, indicator parameters, and flux-based approaches)
- Adaptation or development of integrated toolsets that account for the interaction of remediation processes with the subsurface environment, including heterogeneities, changing biogeochemical conditions, and changing physical characteristics of the subsurface
- Development of predictive approaches that enable cost-effective and scientifically defensible long-term site management.

Holistic Remediation Approaches

Many of the sites still requiring cleanup including those being addressed by DOE EM, have characteristics that render remediation difficult [4]. Technical issues can include difficult subsurface access, deep and/or thick zones of contamination, large areal extent, recalcitrant contaminants, and subsurface heterogeneities that limit treatment effectiveness. Site remediation may also be complex because of significant uncertainty with respect to understanding contaminant behavior and estimating how the contaminant will respond to a remedial action. It may also be difficult to implement remedy selection and management at sites where long-term processes are needed to address the contamination (e.g., due to presence of long-term sources or large plume size). Due to these issues, it is recognized that remediation of subsurface contamination remains a significant challenge facing the nation [1], [4], [5], [6], [7]. Recent efforts by the Nuclear Regulatory Commission, Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program, Interstate Technology Regulatory Council, and DOE EM point to the need for improved remediation management strategies that include adaptive remedy approaches and methods to facilitate remediation decisions and associated transitions between the stages of a remedy. The strategic opportunities and research targets for site remediation include:

- Development of effective adaptive remediation approaches including integration with monitoring and diagnostic indicators (e.g. geophysics, isotopic, master variable, and microbial signatures) to measure remedy performance in terms of contaminant flux or other parameters that estimate performance of follow-on remedies such as MNA
- Development of remedies that can be applied for a finite amount of time that are consistent with site geochemical conditions and that address source issues such as matrix diffusion and heterogeneities
- Development of approaches that address long-term contaminant migration over the short term (e.g. “tipping points” in geochemical or biological activities)
- Quantification of the effects of hydraulic boundary manipulation (e.g. surface barriers for the vadose zone, trenches or outfalls in groundwater systems) on plume behavior for recalcitrant contaminants
- Quantification of the role of reactive facies and physical processes limiting the flux of contaminants through the vadose zone and groundwater to inform evaluation of MNA or enhanced attenuation.

Systems-Based Monitoring

A team of multidisciplinary experts identified the following specific opportunities for systems-based monitoring approaches to provide more effective performance assessment and contaminant management with respect to applying adaptive remediation [8]: 1) use conceptual site models to improve understanding of the system as a whole in order to improve monitoring design and interpretation; 2) use lines-of-evidence approaches and flux-based approaches as alternatives to point measurements; and 3) develop and apply innovative monitoring tools, including surrogates, early indicator parameters, bioassessment, geophysics/remote sensing, predictive analyses/models, and information management to supplement standard well measurements that can reduce the costs while simultaneously improving the quality of monitoring. The development of innovative approaches that use surrogates and alternative approaches that identify deviations from predicted behavior are especially applicable to the later stages of residual contamination monitoring because the residual plume is presumably well characterized, stable or shrinking, and behaving predictably. In this case, efficient and effective monitoring should focus on early warning of deviations from predicted plume behavior. The strategic opportunities and research targets for systems-based monitoring include:

- Adaptation of lines of evidence approaches/tools that are less expensive than point-based monitoring and provide better information about plume dynamics and factors controlling plume behavior
- Development of monitoring approaches that link monitoring surrogates (e.g. master variables, other indicators, or properties) to contaminant transport and fate
- Development of approaches for monitoring thresholds, measure deviations from predicted behavior, and larger-scale or boundary condition changes that can be used for long-term management of contaminant plumes
- Development of new tools and methods for monitoring based on mass flux of contaminants including predictive analyses for interpretation of flux data, characterization approaches, and geophysics coupled with other approaches for estimation of flux.

Remediation Decision Support

Decision analysis support systems provide a technical basis for remediation and other site management decisions [9]. These systems are based on Bayesian statistical decision theory applied in a technically defensible manner that can operationalize risk-informed decision-making. Currently, EPA is building decision analysis support systems based on value-focused thinking, and based on the three pillars of sustainability: economic, environmental, and social. Sustainability is included to bring in costs or values associated not only with the environment, but also economic and societal issues. Applying the ideas of value-based decision-making to complex environmental management problems requires a conceptual framework or formalized process to ensure that a decision is consistent with stakeholder values, is cognizant of tradeoffs among alternatives, and accounts for associated uncertainties and risks. Structured decision analysis approaches that facilitate decision-making through the integration of science and facts with stakeholder-derived values in an analytic-deliberative structure [10] can be applied to identify potential data- and conceptual-model gaps, requiring additional data acquisition to refine remedy selection and evaluate decision uncertainties [11]. This process can be dynamic and applied to a sequence of remediation alternatives and endpoints. The strategic opportunities and research targets associated with decision support include:

- Development of approaches for identifying and evaluating key data and assumptions that drive risk to prioritize refinements of remedial actions using simulation models and tools of sufficient complexity and resolution to adequately characterize uncertainties
- Development of decision-support approaches using laboratory and field-scale measurements with muli-scale models to evaluate sustainable remedial actions
- Development of methods to identify and estimate impacts resulting from remediation endpoints.

CONCLUSIONS

The Office of Soil and Groundwater Remediation is executing an integrated program to provide innovative tools, approaches, and guidance to support effective, sustainable, lower-cost remedies for soil and groundwater remediation. The success of the program strategy relies on existing and emerging scientific knowledge regarding natural and enhanced attenuation processes and the evolution of geochemical conditions at subsurface waste sites. The program is integrated with EM sites as test beds for technology development and maturation, and is focused on resolving the scientific and technical gaps presented in this paper. The program is advancing the application of holistic approaches necessary for defining and achieving alternative remediation endpoints at EM sites in a technically defensible manner. The outcomes will enable EM to implement effective, adaptive systems-based approaches for remediation; provide technical justification for exit strategies from remediation processes; achieve technically defensible, risk-informed, and adaptive endpoints; and fully realize a projected $10 billion cost saving in remediation of contaminated soil and groundwater at the remaining complex sites.

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ACKNOWLEDGEMENTS

This paper was developed through a series of discussions with EM Office of Soil and Groundwater Remediation staff and contributors from DOE national laboratories including Pacific Northwest National Laboratory, Los Alamos National Laboratory, Savannah River National Laboratory, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory. Input was also received from other federal agencies.