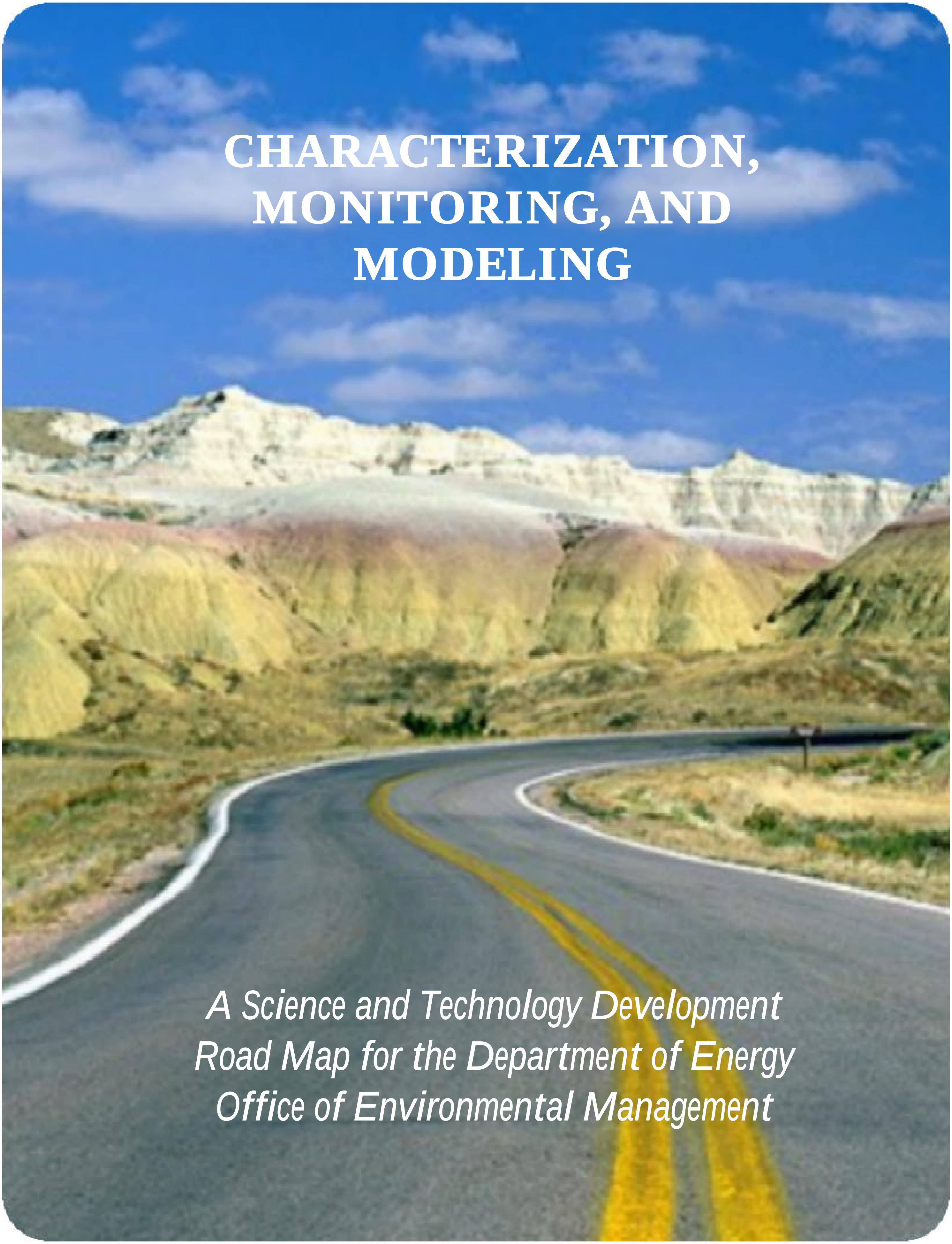
CHARACTERIZATION, MONITORING, AND MODELING



A Science and Technology Development Road Map for the Department of Energy Office of Environmental Management

CHARACTERIZATION, MONITORING, AND MODELING

A SCIENCE AND TECHNOLOGY DEVELOPMENT ROAD MAP FOR THE DEPARTMENT OF ENERGY OFFICE OF ENVIRONMENTAL MANAGEMENT

Prepared by the
DEPARTMENT OF ENERGY
OFFICE OF ENVIRONMENTAL MANAGEMENT
OFFICE OF SCIENCE AND TECHNOLOGY
CHARACTERIZATION, MONITORING, AND
SENSOR TECHNOLOGY
CROSSCUTTING PROGRAM

July 31, 2002

FOREWORD

Characterization, Monitoring, and Modeling: A Science and Technology Development Road Map for the Department of Energy Office of Environmental Management was prepared at the request of senior management of the Department of Energy Office of Environmental Management (DOE-EM) Office of Science and Technology (OST). The purpose of this ***CMM ROAD MAP for DOE-EM*** is to assemble information on technology development, needs, and gaps within DOE-EM and use this information to indicate directions in which further development is warranted.

This ***ROAD MAP*** was prepared by the DOE-EM OST Characterization, Monitoring, and Sensor Technology Crosscutting Program (CMST-CP). The initial source for identifying technology needs and gaps was the formal Site Needs identification process carried out by the OST Site Technology Coordinating Groups (STCGs). In recent years the primary role of CMST-CP has been to support the OST Focus Areas (FAs). In implementing this role CMST-CP personnel have assisted the FAs in compiling these STCG-expressed Needs, forming Technical Responses to those Needs, and performing technology gap analyses. These gap analyses, provided by the CMST-CP liaisons to the five FAs, are the foundation of this document. Additional sources of information include strategic needs assessments and other documents compiled by FAs, Sites, and other OST programs. Focus Areas and other OST programs have been invited to provide review comments; comments received have been incorporated into the document.

At the present time DOE-EM is reorganizing its Office of Science and Technology to provide better and more direct support to closure sites (Thrust 1) and to develop alternatives for high-cost, high-risk baselines (Thrust 2). Advances in Characterization, Monitoring, and Modeling remain critical for success in both of these thrust areas. In particular, many current environmental monitoring practices designed for active regulated facilities will be both prohibitively expensive and inadequately informative to provide scientifically defensible and regulatorily acceptable post-closure monitoring appropriate for DOE-EM sites. Consequently, the relevance of this ***CMM ROAD MAP for DOE-EM*** and the continuing research and development it describes remain as great as originally envisioned.

United States Department of Energy
Office of Environmental Management
Office of Science and Technology
Characterization, Monitoring, and Sensor Technology Crosscutting Program

John Jones, Field Program Manager
Ker-Chi Chang, Headquarters Program Manager

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TechID* 1514: Rapid Liquid Sampler

* TechID numbers refer to the DOE-EM OST Technology Management System database, http://ost.em.doe.gov/tms.

A CMM ROAD MAP FOR DOE-EM

The U.S. Department of Energy Office of Environmental Management (DOE-EM) embarked on environmental management technology development in 1989 with the formation of the Office of Technology Development, later known as the Office of Science and Technology (OST), and began aggressively supporting characterization, monitoring, and sensor technology development for environmental management and cleanup. Numerous EM challenges have been addressed by OST. Many successful technologies have been created and deployed at DOE sites and have become commercial successes as a result of OST investments over the years.

Nonetheless, challenges remain which need to be solved to support the DOE environmental mission. This ***CHARACTERIZATION, MONITORING, AND MODELING SCIENCE AND TECHNOLOGY DEVELOPMENT ROAD MAP*** enumerates these needs and the impact which their solutions can have, describes proven solution paths and their application to several of the challenges currently visible within DOE-EM, and outlines tested programmatic strategies that can be used in bringing about solutions to these problems. The **Visions for 2012** foresee a potential for even greater advances in characterization and monitoring practice during the next decade than have been achieved already. DOE-EM can help to realize these visions by building on its past accomplishments and broad expertise and resources in characterization, monitoring, and modeling (CMM) science and technology development.

The purpose of this ***ROAD MAP*** is to assemble information on the current state of DOE-EM CMM development and to identify directions toward which further development is needed. No distinction is made in this document between research and development (R&D) areas traditionally identified with OST Characterization, Monitoring, and Sensor Technology Crosscutting Program (CMST-CP) and areas identified with other DOE-EM programs.

There are five major parts:

- **INTRODUCTION** provides a concise overview of the document, focusing on the process used to identify the site environmental management and cleanup needs that generate the science and technology development challenges it presents. The challenges fall into two major categories: **Waste, Source, and Nuclear Materials Characterization** and **Process and Product Monitoring**. In addition, three areas are identified for special emphasis: **Long-Term Monitoring**; **Nondestructive Methods**; and **Improved Scientific Understandings**. The general nature of the challenges faced in each area is discussed; broadly stated targets for DOE are suggested (see the boxes on pages 4-8); and a number of currently **Visible and Important Problems** (**VIPs**) are recognized. Selected **VIPs**, with solution paths, are highlighted in sections beginning on page 12 and again on page 34; more detailed discussion is reserved for **APPENDIX B**. Finally, the **INTRODUCTION** closes with a brief discussion of programmatic strategies DOE-EM has used successfully in addressing these and similar science and technology development challenges.

- **PROBLEM AND OPPORTUNITY AREA HIGHLIGHTS** provides a more detailed breakdown of the two major categories and three special emphasis areas. A general description of baseline technologies and their deficiencies with respect to meeting DOE-EM needs is given, along with an enumeration of the objectives which further science and technology development could accomplish. Sub-areas (groups of similar technology development needs) are identified and described in greater technical detail. Finally, for each area a **Vision for 2012** describes an attractive future state of affairs that can be attained through following the recommendations in this ***ROAD MAP***.

- **SOLUTION PATHS** describes proven ways that DOE-EM can use to identify R&D providers, convey funding to them, monitor their progress, and test and demonstrate their projects. Brief examples are based on two **VIPs**; more detail is provided in **APPENDIX B**.

- **APPENDIX A: PROBLEM AND OPPORTUNITY AREAS** returns to the major categories and special emphasis areas. Needed technology development is described in detail within larger, crosscutting groups of needs. DOE-EM **Critical Application Areas** (**CAA**s) related to each challenge are identified. Few of these challenges are identified by specific site, as nearly all are common to at least a few sites. **Near-Term Goals** and **Far-Term Goals** are suggested in each section. These are listed at the close of this summary, beginning on page ix. Also included in **APPENDIX A** are listings of **OST CMM R&D Successes** and **Recent R&D Projects**. Although one cannot foresee all needs that might arise while environmental management and cleanup activities are proceeding, **APPENDIX A** provides a comprehensive vision of goals that DOE-EM should consider pursuing during the coming decade.

- **APPENDIX B: SELECTED VISIBLE AND IMPORTANT PROBLEMS** describes several **VIPs** in substantial detail, including both technical aspects of each challenge and proposed response strategy and a programmatic approach for solving the problem. The purposes of **APPENDIX B** are to provide greater detail about the **VIPs** and to illustrate successful strategies which have been employed by DOE-EM, utilizing the resources of the CMST-CP in many cases. It would be beyond the scope of any single document of manageable size to provide individual solution strategies for each of the many CMM R&D challenges presented by DOE-EM's environmental management and cleanup mandate.

Each **APPENDIX** has its own Table of Contents. Readers desiring a very concise enumeration of the many CMM science and technology development challenges facing DOE-EM may wish to begin by scanning the **APPENDIX A** Table of Contents (pages A.i - A.iii) before turning to the **INTRODUCTION**.

A few elements typically found in Technology Development Road Maps and Programmatic Road Maps are not included in this document. In particular, the variety of specific goals is quite broad, and there is little or no programmatic or technical dependence among goals in most cases, so it makes little sense to develop critical path displays for the document as a whole. Moreover, details about what technology is needed when and by whom involve prioritizations and funding decisions not in the purview of CMST-CP and therefore beyond the scope of this document. Hence specific timetables are not provided, beyond those implied by the terms "Near-Term Goals" and "Far-Term Goals". Similarly, each "Vision for 2012" is not so much a statement about actions required by a specific future date as about a new way of approaching characterization and monitoring which will be feasible once a certain amount of development work has been accomplished. It is viewed that the R&D needed to bring about these advances is an ambitious but achievable ten-year goal.

Hence, this ***ROAD MAP*** serves not so much as a trip map to a specific goal, as would be expected of a technology development or program road map, but rather as a traveller's guidebook identifying and describing numerous highly desirable goals, many of which are potentially quite important for DOE-EM success, along with paths to take and strategies to employ in addressing and attaining those goals.

In summary, this ***CHARACTERIZATION, MONITORING, AND MODELING ROAD MAP FOR DOE-EM*** provides

! broad **Visions** for DOE-EM to strive toward during the next decade, outlined in boxes on pages 4-8 with more detailed discussions in **PROBLEM AND OPPORTUNITY AREA HIGHLIGHTS**;

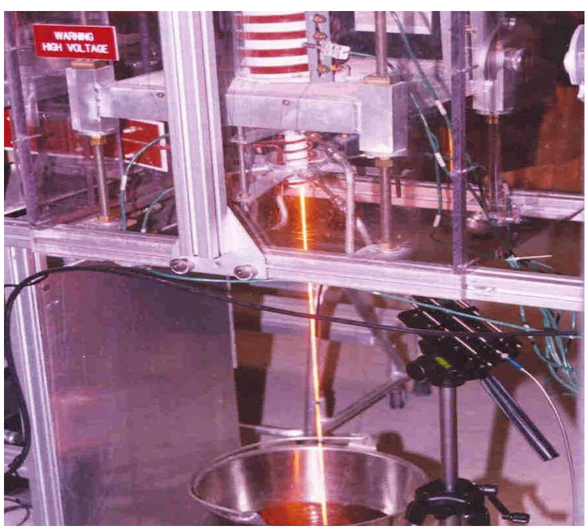
! selected **Visible and Important Problems** (**VIPs**) of current interest, highlighted on pages 12-19 and 34-41 with in-depth discussions in **APPENDIX B**;

! identification of broad, cross-cutting **Problem and Opportunity Areas** that emphasize the commonality of challenges in the various critical application areas that DOE-EM should consider addressing, described in highlight form in pages 21-33 and in greater detail in **APPENDIX A**;

! delineation of **Near-Term Goals** and **Far-Term Goals** for DOE-EM Science and Technology Development, discussed in **APPENDIX A** with a summary listing following immediately on pages ix-xiii;

! discussions of tested **Strategies** to identify projects to be undertaken (pages 9-11) and proven **Solution Paths** for those projects (pages 43-44 and **APPENDIX B**); and

! listings of **OST CMM R&D Successes** and **Recent R&D Projects** for each of the Problem and Opportunity Areas.



TechID 2004: Monitor for TRU in Molten Glass

SUMMARY OF DOE-EM CMM R&D GOALS

These pages provide a concise listing of the **Near-Term** and **Far-Term Goals** identified in **APPENDIX A**, along with an indication of which CAAs will be the primary beneficiaries of that Goal. A more detailed evaluation of these **Goals** and their relationships with needs groups may be found in *FY 2001 Office of Science and Technology Investments in Characterization, Monitoring, and Sensor Technology: A Cross-cutting Analysis* (CMST-CP, June 2001). That document also links each of the **Goals** to one or more DOE-EM OST programs.

Critical Application Areas (CAAs) are identified as follows:

SCR	Subsurface Characterization and Remediation
FDD	Facility Deactivation and Decommissioning
LTM	Long-Term Monitoring
WNMC	Waste and Nuclear Material Characterization
WTC	Waste Tank Closure
WTI	Waste Tank Integrity
TWP	Tank Waste Processing
MWP	Mixed Waste Processing

Many of these goals are shared among CAAs. These crosscutting aspects make it possible in many cases to leverage technology development accomplished previously for one CAA to meet needs of another. The document cited in the previous paragraph examines these crosscutting relationships in detail.

WASTE, SOURCE, AND NUCLEAR MATERIALS CHARACTERIZATION

Near-Term Goals

- Expand direct push capabilities to minimize the need for drilling during subsurface characterization (**SCR**).
- Improve methods for determining the subsurface distribution of dense non-aqueous phase liquids (DNAPLs), radionuclides, heavy metals, high explosives, and pyrophoric compounds (**SCR**, **FDD**).
- Expand capabilities for characterization beneath structures (**FDD**).
- Improve sampling technology for characterizing deep plumes (**SCR**, **LTM**).
- Improve methods for hydrogeological characterization of flow and transport (**LTM**, **SCR**).
- Improve and validate geophysical methods for determining the spatial distribution of contaminants in the subsurface (**SCR**, **LTM**).
- Improve tomographic nondestructive assay and nondestructive evaluation (NDA/NDE) and other characterization systems for containerized wastes (**WNMC**).
- Develop *in situ* methods for detecting contamination on surfaces and in inaccessible areas (**FDD**, **WTC**).
- Develop robotic platforms for characterization sensors (**FDD**, **WTC**).
- Supplant slow, costly, inaccurate laboratory methods; develop *in situ* characterization techniques for high-level waste (HLW) applications; obtain regulatory approval for innovative technologies (**all**).
- Develop better methods for evaluating and monitoring HLW tank integrity (**WTI**).

- ! Develop better methods for evaluating final and/or immobilized waste form content, durability, and degradation (**WNMC**).

- ! Develop *in situ*, real-time sensors for lead, low energy gamma-emitters, polychlorinated biphenyls (PCBs), and other constituents of concern in facilities slated for deactivation and decommissioning (**FDD**, **LTM**).

Far-Term Goals

- ! Improve methods for characterizing the subsurface, particularly in deep, complex, and heterogeneous settings, using direct observation as well as indirect geophysical techniques (**SCR**, **LTM**).

- ! Develop more flexible data integration methods (**SCR**, **LTM**).

- ! In general, develop the capability to characterize and quantify any residual waste which remains in any DOE facility after cleanup activities have been completed (**FDD**, **WTC**, **LTM**).

PROCESS AND PRODUCT MONITORING

Near-Term Goals

- ! Improve tank waste slurry monitoring capability (**TWP**).

- ! Improve capability to monitor tank waste liquid/solid separation processes (**TWP**).

- ! Develop on-line process control monitors for tank wastes as well as mixed waste, mixed transuranic (TRU) waste, and nuclear materials immobilization and stabilization (**TWP**, **MWP**, **WNMC**).

- ! Develop improved methods for HLW and low-level waste (LLW) process monitoring at the basic science level (**TWP**, **MWP**).

- ! Complete the development of continuous emissions monitors for constituents including mercury and dioxins/furans (**TWP**, **MWP**).

- ! Identify and address issues arising in emissions monitoring for mixed waste alternative oxidation treatments (**MWP**).

- ! Develop an improved understanding of dioxin and furan formation and control (**MWP**).

- ! Improve capabilities for real-time monitoring of subsurface remediation (**SCR**).

- ! Develop real-time portable beryllium monitors for surface and airborne contamination (**FDD**).

Far-Term Goals

- ! Develop monitors for tank waste slurrying and pretreatment processes yet to be developed (**TWP**).

- ! Nurture promising *in situ* HLW and LLW immobilization monitoring technologies (**TWP**, **MWP**).

- ! Develop acceptable methods for verifying waste tank closure risk analyses (**WNMC**, **LTM**).

- ! Develop/negotiate more flexible regulatory paradigms allowing the use of less expensive measurements (**several**).

- ! Develop effluent monitoring and control methods that can facilitate continuously documented regulatory compliance (**several**).
- ! Develop monitoring techniques for bioremediation processes to track process functioning as well as contaminant concentration (**LTM**).
- ! In general, develop waste remediation process monitoring, control, and automation to the level of reliability and acceptability expected of normal industrial production processes (**several**).

LONG-TERM MONITORING

Near-Term Goals

- ! Develop better, carefully validated geophysical monitors and data integration methods for subsurface DNAPLs (**SCR**, **LTM**).
- ! Identify well-characterized test areas for modeling methods (**LTM**).
- ! Adapt available monitoring systems for long-term, unattended, self-calibrating and testing operation with minimal maintenance and automated, remote data reporting (**SCR**, **LTM**).
- ! Develop remote systems for monitoring large areas such as landfill covers (**LTM**).
- ! Develop automated systems for remote monitoring of long-term *ex situ* treatment processes (**LTM**).

Far-Term Goals

- ! Develop systems for unattended long-term monitoring of closed structures, waste repositories, and stabilized waste tank farms (**LTM**).
- ! Capitalize on government and academic research on micro electro-mechanical sensors (MEMS) and other innovative scientific development, and direct that development toward areas of importance to DOE-EM (**several**).
- ! Develop techniques for monitoring bioremediation. (**SCR**, **FDD**, **LTM**)
- ! Participate in collaborative efforts among DOE, Department of Defense (DoD), U.S. Environmental Protection Agency (EPA), and other stakeholder groups to enhance regulatory and public acceptance of innovative monitoring strategies, equipment, and practices (**several**).

NONDESTRUCTIVE METHODS

Near-Term Goals

- ! Continue development of NDA technologies for the assay of Resource Conservation and Recovery Act (RCRA) metals (**WNMC**, **TWP**, **MWP**).
- ! Continue development of NDE and NDA methods for complex contact handled drum wastes (**WNMC**).
- ! Develop technologies for non-intrusive tomographic NDA and NDE of boxed wastes (**WNMC**).
- ! Develop multi-detector NDA technologies for characterization of remote handled wastes (**WNMC**).
- ! Advance the NDE of HLW tank wall, knuckle, bottom, and piping integrity (**WTI**).

! Develop NDA techniques for inventory verification of containerized SNF (**WNMC**, **LTM**).

! Develop remote technologies for monitoring containerized SNF in extended dry interim storage (**LTM**, **WNMC**).

! Develop sensors for determining moisture in spent nuclear fuel prior to encapsulation (**WNMC**).

Far-Term Goals

! Continue development of NDE methods for monitoring safety of aging HLW tanks (**WTI**).

IMPROVED SCIENTIFIC UNDERSTANDINGS

Near-Term Goals

! Improve basic understandings of subsurface structures and their relationship with contaminant fate and transport (**SCR**, **LTM**).

! Improve basic understandings of contaminant fate and transport processes and their relationships with geology, hydrogeology, and geochemistry (**LTM**).

! Develop acceptable remote data acquisition, screening, and reporting models (**LTM**).

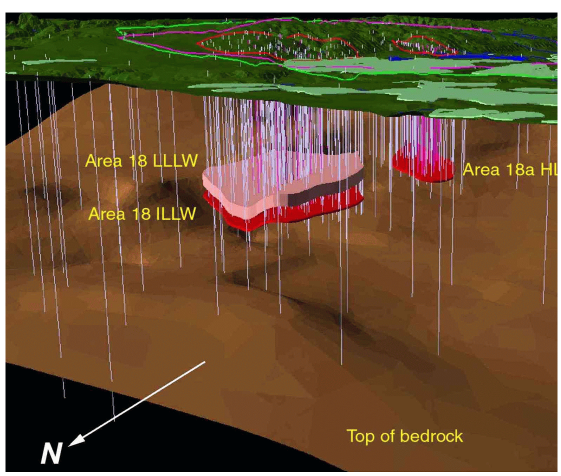
Far-Term Goals

! Develop better fundamental understanding of subsurface processes and characteristics critical for determining contaminant fate and transport (**LTM**, **SCR**).

! Improve capability to evaluate critical subsurface processes, particularly at large sites with heterogeneous geological and hydrogeological conditions (**SCR**, **LTM**).

! Develop automated, self-testing, self-reporting, self-calibrating sensors for long-term monitoring (**LTM**).

! Develop secure, redundant, automated data collection, storage, retrieval, evaluation, and reporting systems for long-term monitoring data (**LTM**).



TechID 775: Modeling the Subsurface in the Tomsk Region

TechID 70: BetaScint™

INTRODUCTION

OVERVIEW

The U.S. Department of Energy Office of Environmental Management (DOE-EM) relies on measurements to provide a scientific basis for its decisions and actions. The DOE-EM environmental management and cleanup mission has generated unprecedented characterization and monitoring challenges due to the uniqueness and magnitude of the situations faced at DOE sites. Since its creation in 1989, the DOE-EM Office of Science and Technology (OST), originally known as the Office of Technology Development, has developed many improved and innovative technologies to meet these challenges. This Characterization, Monitoring, and Modeling (CMM) Science and Technology Development Road Map for DOE-EM outlines further science and technology development that will assist DOE-EM in achieving its long-term cleanup goals efficiently and safely, confident that the results will be effective, safe, and recognized as protective of human health and the environment.

OST immediately recognized the critical importance of measurement technology and established the Characterization, Monitoring, and Sensor Technology Integrated Program (CMST-IP). This program evolved into the Characterization, Monitoring, and Sensor Technology Crosscutting Program (CMST-CP) when OST created its five Focus Areas[1] (FAs) in 1995. These CMST programs have guided DOE-EM in finding and implementing technology solutions for numerous challenges throughout the past decade. Many of these successes are cited in **APPENDIX A**; a detailed history of these programs is included in the *Characterization, Monitoring, and Sensor Technology Crosscutting Program Technology Summary, Fiscal Year 2000*, available at http://www.cmst.org.

A CMM Science and Technology Development *ROAD MAP for DOE-EM*

Gerald Boyd, then Deputy Assistant Secretary for OST (EM-50), and Mark Gilbertson, Director of the OST Office of Basic and Applied Research (EM-52), requested that the CMST-CP take the lead in developing a CMST Science and Technology Development Road Map. The purpose of the Road Map would be to guide DOE-EM in developing the new and improved measurement technologies which will assist DOE in achieving its site-specific EM and cleanup goals. The need for this science and technology development is widely recognized; see, e.g., *Research Needs in Subsurface Science* (National Research Council 2000), *DOE Research and Development Portfolio for Environmental Quality* (U.S. DOE 2000), *Long-Term Stewardship: Operational Roadmap and Strategic Plan* (OST 2000), and *A Strategic Vision for Department of Energy Environmental Quality Research and Development* (National Research Council 2001) among other documents.

At the present time DOE-EM is reorganizing its Science and Technology Program to provide better and more direct support to closure sites (Thrust 1) and to develop alternatives for high-cost, high-risk baselines (Thrust 2). Advances in Characterization, Monitoring, and Modeling remain critical for success in both of these thrust areas. In particular, many current environmental monitoring practices designed for active regulated facilities will be both prohibitively expensive and inadequately informative to provide scientifically defensible and regulatorily acceptable post-closure monitoring appropriate for DOE-EM sites. Consequently, the relevance of this ***CMM ROAD MAP*** and the continuing research and development it describes remain as great as originally envisioned.

This ***ROAD MAP*** identifies specific research and development (R&D) targets related to these overall goals, details the range of problems to be solved and similarities among those problems, and suggests time-tested strategies for achieving these goals. Specific technical and tactical approaches are suggested for several

[1]DOE-EM OST Programs include ***TMFA*** (TRU and Mixed Waste Focus Area), ***TFA*** (Tanks Focus Area), ***SCFA*** (Subsurface Contaminants Focus Area); ***DDFA*** (Deactivation and Decommissioning Focus Area), and ***NMFA*** (Nuclear Materials Focus Area), along with ***ESP-CP*** (Efficient Separations Crosscutting Program), ***RBX-CP*** (Robotics Crosscutting Program), ***INDP*** (Industry and University Programs), ***EMSP*** (Environmental Management Science Program), and ***CMST-CP***.

Visible and Important Problems (**VIPs**); these are highlighted in sections beginning on pages12 and 34 and discussed in greater detail in **APPENDIX B**.

Identification of Goals

Both Near-Term and Far-Term R&D Goals are identified. Near-Term Goals represent technology advances that are being pursued now or should be within the next few years; this R&D is generally already in progress. Far-Term Goals include technology development needs that are equally important, but not so pressing, as well as scientific research needs whose solutions may be anticipated to take longer to realize. It is not the role of the CMST-CP to establish timetables and priorities for these Goals; therefore timetables are not suggested in this Road Map, beyond those implied by the broad "Near-" and "Far-" suggestions.

The CMM needs and goals presented in this ***ROAD MAP*** were identified in several ways:

- **Site needs delineation.** Annually for the past several years the FAs, assisted by CMST-CP and other Crosscutting Programs, collaborated with OST Site Technology Coordinating Groups (STCGs) in identifying site technology needs. STCG needs for which solutions were not currently available became science and technology development needs. Previously identified R&D needs are incorporated into this ***ROAD MAP***.

- **Strategic needs.** CMST-CP and other crosscutting programs further collaborated with the FAs and other groups and reviewed other sources in identifying technology development needs not formally elicited through the STCG process. These are sometimes called strategic needs to distinguish them from the STCG-identified site needs that tend to be more immediately pressing. These were supplied by the CMST-CP liaisons to the FA; they also appear in documents such as the FA *Multi-Year Program Plans*.

- **Document review.** Numerous DOE and other documents and publications were reviewed, including the FA *Multi-Year Performance Plans*, the draft *DOE Complex-Wide Vadose Zone Science and Technology Roadmap*, and *Hanford Site Cleanup Challenges and Opportunities for Science and Technology: A Strategic Assessment* (DOE-RL, 2001) as well as documents cited previously and numerous conference and workshop presentations.

- **CMST-CP team expertise.** Additional strategic needs have been extrapolated by the CMST-CP team, drawing on over 100 years of collective association with DOE-EM CMM R&D and over 300 years total relevant professional experience with more than 18 advanced degrees in areas pertaining to environmental monitoring and sensor and technology development.

These means were used to identify the broad array of R&D goals presented in this document. Implicit in all of them are the overriding programmatic needs to perform the DOE-EM mission safely and to achieve stakeholder acceptance. Many, if not most, of the challenges and goals described in this document are fundamentally related to these overriding programmatic needs.

Organization of this *CMM ROAD MAP for DOE-EM*

The remainder of this **INTRODUCTION** presents a **Vision** for DOE-EM CMM R&D, followed by a discussion of programmatic **Strategies** by which this vision can be accomplished. The CMM Vision presents broad groups of science and technology development needs arising from DOE-EM mandates. Within each group several **VIPs** are identified. These **VIPs**, which are only a subset of the totality of needs to be addressed, are specific concerns already identified and prominent within DOE-EM. Selected **VIPs** are highlighted on pages 12-19 and 34-41, with greater detail in **APPENDIX B**. The **Strategies** section describes the primary selection process used by DOE-EM through OST in the past, and then discusses other mechanisms through which valuable R&D work has been accomplished.

PROBLEM & OPPORTUNITY AREA HIGHLIGHTS discusses groups of needs more broadly. Attention is not limited to **VIPs**; rather, this part surveys the broad range of CMM challenges to be faced by DOE-EM in its mission through site closure and long-term stewardship. The problem and opportunity areas emphasize step-change solutions (developing necessary new capabilities where none exist, or substantially reducing costs and/or schedules) and acquiring the new scientific understandings needed to support further technology development and innovative technology deployment. This part presents highlights; expanded detail is given in **APPENDIX A**, including the delineation of broad **Near-Term Goals** and **Far-Term Goals**. Past **OST CMM R&D Successes** and **Recent R&D Projects** for each area are listed in **APPENDIX A**.

SOLUTION PATHS complements the **Strategies** section, focusing on selecting R&D providers to undertake desired research as well as funding and project management avenues DOE-EM has found useful in the past; brief examples are included. **APPENDIX B** presents certain **VIPs** in detail, describing their technical aspects and providing suggestions about solution strategies including R&D provider selection. It includes a summary of provider and project management strategies keyed to these **VIPs**.

SUMMARY recaps the presentations of the previous parts.

A CMM R&D VISION FOR DOE-EM

DOE-EM CMM R&D needs fall into two major categories.

- **Waste, Source, and Nuclear Materials Characterization**
- **Process and Product Monitoring**

In addition, there are areas of special emphasis relevant to DOE's environmental management needs.

- **Long-Term Monitoring**
- **Nondestructive Methods**
- **Improved Scientific Understandings**

These areas are not distinct from the major categories, but rather identify areas deserving special emphasis because of the distinctive nature of the challenges facing DOE in achieving its environmental management and cleanup goals.

Science and Technology Development Visions; VIPs

A concise overall objective is announced here for each area. A more detailed **Vision for 2012** is provided subsequently for each; these **Visions for 2012** represent ambitious but achievable targets whose attainment within the next ten years will be highly desirable in order for DOE-EM to satisfy its environmental management and cleanup mandates and responsibilities. The year 2012 is nominal; actual progress along this ***CMM ROAD MAP*** will be determined by overall DOE-EM technical and fiscal priorities.

Also listed in these sections are the **VIPs** mentioned previously; solutions for at least portions of most of these are currently under development. Each **VIP** is related to at least one of the following Critical Application Areas (CAAs).

SCR	Subsurface Characterization and Remediation
FDD	Facility Deactivation and Decommissioning
LTM	Long-Term Monitoring
WNMC	Waste and Nuclear Material Characterization
WTC	Waste Tank Closure
WTI	Waste Tank Integrity
TWP	Tank Waste Processing
MWP	Mixed Waste Processing

Waste, Source, and
Nuclear Materials Characterization

By 2012 DOE should

- **be able to characterize any non-negligible contamination efficiently, exploiting wherever possible real-time measurement technologies generating no secondary wastes;**
- **understand subsurface contaminant fate and transport in all media, enabling credible and reliable planning for site remediation, closure, and long-term stewardship;**
- **have developed waste stream characterization to a routine operation; and**
- **be implementing next-generation decision models making efficient use of site-specific data for site-specific purposes.**

The legacy of defense and civilian nuclear industries is a well-known, politically sensitive challenge for DOE. Wastes and nuclear materials must be characterized before treatment, long-term storage, or disposal. The unique nature of DOE wastes and materials requires specialized characterization methods. Wastes and materials in storage pending treatment or disposal need to be evaluated for safety as well.

Significant surface and subsurface contamination exists at most DOE sites. The extent and magnitude of soil and groundwater contamination must be characterized as the first step of efficient and reliable remediation. Once site cleanup operations have been completed, DOE must verify that its intended final disposition has been achieved and present a defensible and acceptable plan for long-term post-closure monitoring.

To demonstrate that proposed DOE cleanup objectives will indeed be protective of human health and the environment, it is essential to understand the subsurface processes that affect past contamination or might affect future releases. This includes the development and use of groundwater flow modeling in complex hydrogeological settings, transport modeling of radionuclides, and natural attenuation processes for these and all additional constituents of concern (primarily organic compounds and toxic metals). Improved characterization of the subsurface geology at and around many DOE sites will also be required.

VIPs include the following:

- Residual tank waste characterization (**WTC**, **LTM**).
- Improved real-time, *in situ* characterization for soil and groundwater remediation (**SCR**).
- Non-destructive analysis and evaluation (NDA/NDE) particularly for remote-handled waste and materials (**WNMC**, **TWP**).
- *In situ* detection to free release goals on surfaces (**FDD**).

Process and Product Monitoring

By 2012 DOE should

- **be able to process most wastes and nuclear materials on a production-line basis, using real-time sensors and monitors for simultaneous regulatory compliance and process control;**

- **be able to monitor containment structures and long-term remediation processes efficiently with nearly universal end-user and stakeholder approval; and**

- **be using integrated monitors capable of minimizing or eliminating any risk or perceived risk to human health or the environment resulting from DOE environmental management activities.**

This area includes monitoring waste and nuclear material treatment and stabilization processes to ensure quality control, safety, and attainment of treatment objectives. It also includes monitoring remediation efforts in facilities to be decommissioned as well as in subsurface soil and groundwater.

The baseline technologies for such monitoring generally consist of sampling and off-site destructive analysis with attendant time delays prohibiting effective process control, sampling and transportation costs, high analytical costs, and secondary waste generation.

VIPs include the following:

- High-level waste transport and process monitoring, including monitoring of salt-cake dissolution processes, effluents from waste vitrification and other waste treatment processes, and two-phase liquid (liquid sulfur or organic phase layer) detection (**TWP**, **MWP**).

- Continuous *in situ* process, product, and effluent monitoring for thermal and nonthermal treatment technologies for mixed and mixed transuranic (TRU) waste (**MWP**).

- Improved real-time monitoring of and feed-back control for waste and nuclear material stabilization (**TWP**, **MWP**).

- Improved real-time monitoring for *in situ* soil and groundwater remediation (**SCR**, **LTM**).

- Improved real-time monitoring for decontamination of facilities, particularly using robotic interfaces (**FDD**).

Long-Term Monitoring

By 2012 DOE should

- **be using next-generation sensors and monitoring systems capable of unattended operation, self-validation, autonomous remote reporting, and automated data recording and screening with minimal maintenance;**

- **have acquired an understanding of contaminant fate and transport sufficiently advanced to support the judicious selection of monitoring systems and programs, monitoring parameters, and decision strategies; and**

- **have nurtured the evolution and acceptance of regulatory paradigms geared to these systems and understandings.**

This area includes monitoring the integrity of containment structures such as high-level waste tanks and subsurface barriers as well as long-term monitoring at facilities or parts of facilities that will not be released for unrestricted use. In particular, monitored natural attenuation using natural chemical and radiological processes may be the treatment of choice for long-term stewardship in appropriate situations.

As cleanup activities at DOE sites draw to a close not all sites will be free-released; long-term monitoring will be required at these sites. This will necessitate the development of monitoring systems that can meet new challenges. Sensors that will require minimal maintenance and will be self-evaluating and self-calibrating will be instrumental in reducing long-term stewardship costs. Currently available sensors will need to be evaluated and improved for long-term monitoring.

At a more fundamental level, the evolution in CMM technology must be taken into consideration in developing and negotiating appropriate monitoring Data/Decision Quality Objectives (DQOs) for long-term stewardship and, where appropriate, lobbying for regulatory advances. It will likewise be important to develop characterization methodologies and understandings which will support the validation of long-term stewardship decisions and their consequent acceptance by the broad array of stakeholders.

VIPs include the following:

- Post-closure monitoring of tank farms (**WTC**, **LTM**).

- Long-term monitoring for verifying the performance of waste disposal vaults, burial grounds, repositories, and long-duration remediation activities (**SCR**, **FDD**, **WTC**, **LTM**).

- Long-term monitoring for verifying the post-closure integrity and performance of end-state solutions for facilities which cannot be cleaned up to free-release standards (**FDD**, **LTM**).

Nondestructive Methods

By 2012 DOE should

- **have adopted nondestructive (including robotic) methods as the baseline for routine characterization and monitoring in many situations, particularly treatment and processing of mixed, mixed transuranic (TRU), and high-level waste and nuclear materials; and**

- **be relying on nondestructive methods for the routine verification of the continued integrity of waste tanks and other containment structures.**

NDA/NDE methods based on imaging, transmission, and emission measurements are considered nondestructive because they alter the chemical or physical states of the target virtually imperceptibly. They can do away with the need for sampling, reduce operator exposure, and provide quicker and cheaper results than conventional chemical analyses while producing no secondary waste. While individual measurements may be less accurate than those of conventional assay in some situations, the overall results may actually be more accurate where accuracy depends on representative sampling of heterogeneous materials as well as where more data points may be obtained due to the on-site availability and reduced cost of individual measurements.

The original impetus for NDA method development was for inventory control of nuclear materials for both defense and civilian purposes, particularly for nuclear safeguards. That need remains, including inventory control of spent nuclear fuel (SNF). An additional pressing need is in the evaluation and assay of containerized transuranic (TRU) waste. The development of NDA and NDE reflects a trend toward automation and workforce reduction that can be applied at all waste-owning facilities for material accounting, process control, criticality control, and perimeter monitoring.

Recent events have increased the interest in NDA/NDE methods related to national security as well. These two critical areas will be able to leverage advances made by the other.

VIPs include the following:

- Assay and evaluation of remote-handled wastes and materials (**MWP**, **WNMC**).

- Assay of contact-handled and remote-handled wastes in boxes and larger containers (**MWP**, **WNMC**).

Improved Scientific Understandings

By 2012 DOE should

- **have acquired an improved understanding of the relevance of subsurface structures and media to contaminant fate and transport in order to provide superior predictive models for long-term planning;**

- **be making full use of next-generation sensors and monitoring systems, having contributed significantly toward their development; and**

- **be leading the use and acceptance of sophisticated data acquisition, validating, screening, storage, and decision-making systems.**

Fundamental advances are needed in a variety of areas: developing innovative measurement technologies (including sampling and data analysis) for better understanding of subsurface contaminant transport mechanisms; modeling; multivariate data relationships; pollutant formation and destruction mechanisms in waste treatment and remediation processes; representative sampling and contaminant concentration concepts; and materials and containment stability. A prominent example is the need for better understanding the mechanisms involved and identifying the data that would be most useful in transport modeling, particularly of dense non-aqueous phase liquids (DNAPLs) in complex hydrogeological settings, of natural and enhanced degradation of DNAPLs in the subsurface, and of radiological decay of wastes. These better understandings are required for remediation, treatment, storage, and disposal planning, and are critical for modeling in support of decision-making and negotiating for long-term monitoring. These understandings are among the objectives of the Hanford Groundwater/Vadose Zone Initiative, for example.

Current policies and practices in monitoring at regulated facilities often produce great quantities of data, much of which is often irrelevant for making monitoring decisions at that facility. Research aimed at identifying and validating streamlined monitoring strategies with regard to key indicator parameter identification, monitoring network design, and decision paradigms (and the modeling to support them) that can satisfy stakeholder concerns can help in reducing the cost of long-term monitoring. More efficient ways of handling, reporting, and interpreting data are needed to support the necessary decision-making.

VIPs include the following:

- Better understandings of geological, hydrogeological, geochemical, and biological processes affecting contaminant fate and transport in the saturated and vadose zones (**SCR**, **LTM**).

- Improved, automated process and effluent monitoring metholodogies (**WTC**, **TWP**, **MWP**)

- Improved ways of collecting, managing, and interpreting long-term monitoring data (**LTM**).

STRATEGIES

Immediate responsibility for environmental management resides with individual DOE sites. Accordingly, the most important avenue toward accomplishing R&D goals is through aiding the sites in recognizing the value of CMM R&D toward achieving their objectives. Technology identification, adaptation, or development can begin at various levels of maturity, appropriate to the situation. Regardless of initial level, site engineering and operations personnel must be included in all stages of development, from need identification through documentation of functional and design requirements, technology selection, design, and safety reviews to ultimate demonstration, acceptance testing, and deployment.

The Role of the OST CMST-CP

CMST-CP and its predecessors have been championing the development of technologies to meet DOE-EM challenges for more than a decade. CMST-CP team members are affiliated with several DOE laboratories (Ames Laboratory in Ames, IA; the Bechtel Nevada Special Technologies Laboratory in Santa Barbara, CA; the Environmental Measurements Laboratory in New York, NY; and the National Environmental Technology Laboratory in Morgantown, WV), as well as Florida International University's Hemispheric Center for Environmental Technology (Miami, FL), Concurrent Technologies Corporation (Pittsburgh, PA), and PAI Corporation (Oak Ridge, TN). They have interacted directly with DOE sites to address pressing site characterization and monitoring needs and have sponsored, managed, and contributed to numerous successful technology development projects within DOE-EM. Under Focus Area-centered approach of the past few years, CMST-CP has functioned as a technical resource within OST similar to a corporate in-house technical support group.

To carry out its role within the Focus Area-centered OST structure, a CMST-CP liaison was assigned to each FA. These liaisons collaborated with the FAs in assisting sites in recognizing and documenting science and technology needs and developing technical responses to those needs, in identifying science and technology gaps arising from those needs, and in developing and implementing CMM R&D. CMST-CP team members collaborated with FAs in providing direct technical assistance to sites. They have also worked with the FAs and other organizations in and out of DOE, including interagency working groups with the U.S. Department of Defense (DoD), the EPA, the U.S. Geological Survey (USGS), and the U.S. Department of Agriculture (USDA). In these ways CMST-CP has served as a crosscutting source of expertise as well as a champion of CMM innovation and development for all of DOE-EM as well as other agencies and the scientific and environmental communities at large.

Site Needs-Based Science and Technology Development

The processes through which DOE-EM has selected and managed R&D projects have evolved since the inception of OST. During recent years that process has focused on responding to site-expressed needs. Under this scenario, the technology development process has involved the following steps.

- Site needs identification has been facilitated by collaboration between site end users (personnel with environmental management and cleanup responsibilities) and OST personnel. The CMST-CP team has participated to bring its collective experience and expertise to the table. OST then prepared technical responses to those site needs. Some needs could be met using technologies already available, whereas others involved technology gaps requiring further R&D.

- Needs were collated and compared across sites; where possible, commonalities of needs and technical responses were identified. CMST-CP assisted at this stage as well. True commonalities of needs groups among Focus Areas were infrequent. More often, a basic technology component or scientific principle used in one situation could be efficiently adapted for another, effecting cost and schedule savings by leveraging previous science and technology development efforts.

- The FAs proposed work packages which were then prioritized across OST. Following initial funding allocations, Program Execution Guidance (PEG) including costs, scope of work, and schedule was prepared. CMST-CP liaisons participated in these steps, particularly in PEG preparation on behalf of the FAs.

! After the PEG and funding levels were accepted, Technical Task Plans (TTPs) were developed. These generally involved one or more projects of interest to a given site, and served as contracts between the principal investigators (PIs) and OST. PIs were selected based on experience, interest, and availability. Depending on the nature of the science or technology development project, PIs were industry researchers responding to Requests For Proposal (RFPs), national laboratory affiliates, university researchers, and so on. CMST-CP members have served as PIs on selected projects.

! Project management was then a joint responsibility of the sponsoring FA and the site Technical Program Officer (TPO). As the time for technology demonstration and deployment neared, the FA once again involved the site end users, with CMST-CP team support as appropriate, in order to ensure successful demonstrations and deployments.

Alternatively, some needs were designated as Science or Applied Research needs, requiring more basic R&D than is typical for FA projects. In such cases, research and initial development of non-commercially available methods was advanced through the OST Environmental Management Science Program (EMSP) or Applied Research Program.

Other OST Strategies

In addition to the process outlined in the previous section, other opportunities have existed for promoting CMST development within OST.

! In strategic planning sessions and documents, such as their *Multi-Year Program Plans* (*MYPPs*), the FAs considered both site-expressed and strategic needs. CMST-CP members were typically invited to participate in these sessions and to provide review comments on draft documents, which presented opportunities to champion the goals expressed in this ***ROAD MAP***.

! The FAs have frequently been asked to provide input to other OST programs involved in science and technology development, particularly the EMSP. Site needs requiring basic scientific research are prime candidates for EMSP consideration; CMST-CP team members have often participated in evaluating such candidates. As EMSP projects approached completion, the FAs assisted by CMST-CP evaluated their potential contributions to the DOE-EM mission.

! OST personnel are also involved in working groups and joint development efforts involving other government agencies, including the National Technology Workgroup for emissions monitoring (DOE, EPA), the DNAPL Consortium (DoD, EPA, National Aeronautics and Space Administration, DOE), and the Memorandum of Understanding for Cooperation on Research on Multimedia Environmental Models (USGS, Nuclear Regulatory Commission, EPA, DOA, DOE). DOE-EM should continue to champion these efforts and accomplishments.

! Prior to the ascendance of the Focus Area-centered approach, the crosscutting programs (CMST, Efficient Separations, and Robotics) administered their own budgets for strategic research and development in their respective areas of expertise.

Other Avenues

The activities outlined previously have been the prime routes for championing the goals of this ***CMM ROAD MAP***. Other opportunities may arise from time to time, such as the following:

! Participating in other strategic planning sessions or groups, such as the Long-Term Groundwater Monitoring Task Committee of the Environmental & Water Resources Institute of the American Society of Civil Engineers and the DOE/EPA Workshop on Emerging Regulation.

- Reviewing drafts of other documents under preparation, such as Road Maps and program plans prepared by other DOE groups and regulation and guidance proposed by EPA.

OST has utilized all of these avenues over the past decade in the cause of advancing CMM R&D within DOE-EM. A number of past successes are featured in **PROBLEM AND OPPORTUNITY AREA HIGHLIGHTS** and **APPENDIX A**. Implementation strategies are discussed again in **SOLUTION PATHS** and particularly in **APPENDIX B**, in the context of developing plans for addressing several of the **VIPs**.

TechID 2238: Ribbon NAPL Sampler

VIP

Real-Time Monitoring And Characterization of Soils And Groundwater
Evolving Technologies, Concepts, and Strategies

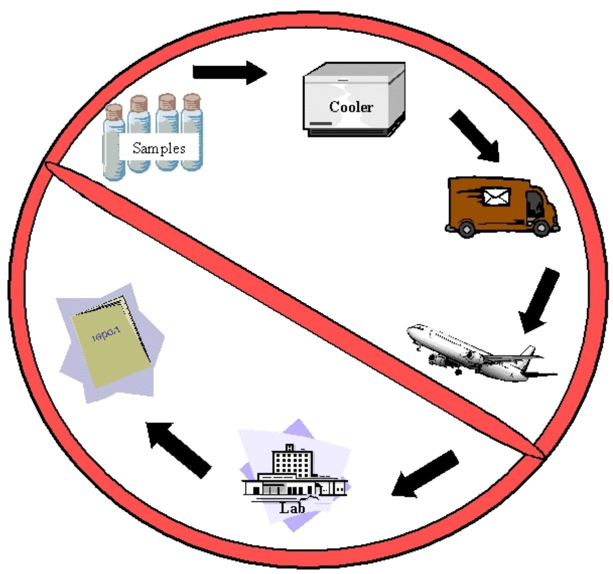
Early advances

Among its first activities OST focused on developing field analytical instruments which have proven invaluable for characterizing soils for Volatile Organic Compounds (VOCs), heavy metals, and radionuclides as well as for well-head groundwater analyses.

Expedited Site Characterization

These were then combined with the cone penetrometer and GeoProbe™ to facilitate subsurface characterization, and supplied with innovative decision support tools, culminating in Expedited Site Characterization (ESC). ESC emphasizes minimally intrusive technologies and optimized sampling. On-site analyses allow daily sampling location selection, reducing characterization time from months to weeks. The Argonne group instrumental in its development used ESC in characterizing the perched water zone at Pantex in 1995. ESC is now an ASTM standard practice.

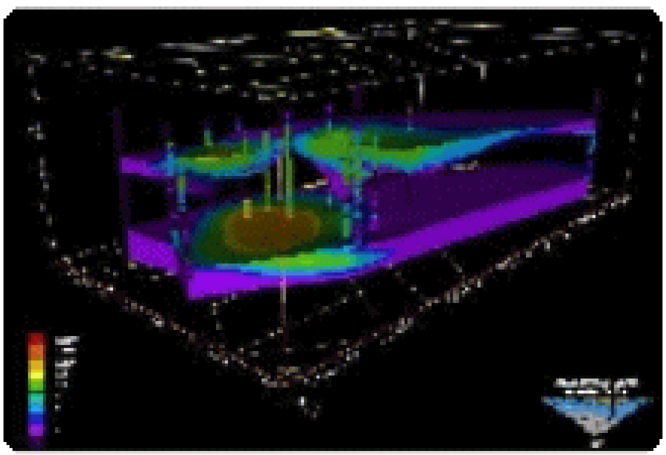
A related Ames Lab project focused on accelerating technology transfer. Contaminated sites were characterized using both current and new technologies; conclusions are given in the Innovative Technology Summary Report *Expedited Site Characterization* (TechID 77).



ERT and EIT

Electrical Resistance Tomography (ERT) and Electrical Impedance Tomography (EIT) are also aimed at improving subsurface characterization and monitoring. Projects have targeted subsurface imaging, tank leak detection, barrier validation, and DNAPL remediation monitoring, with an ultimate goal of non-invasive DNAPL mapping.

Next generation technologies



DOE sites continue to express high priority needs for improved characterization; these needs have evolved from initial field screening to final assessment applications. For example, several sites have expressed a need for real-time radionuclide and heavy metal characterization during soil excavation to determine when it is appropriate to stop. Similar needs involve waste sorting and separation based on radionuclide and/or heavy metal content.

Improved real-time subsurface characterization and monitoring techniques will be needed by 2006. The out-year focus will involve providing needed solutions for technology gaps identified in **APPENDIX A**. Prominent among these gaps is subsurface characterization of deep, hard-to-access areas beyond the reach of existing platforms. Integration of real-time characterization tools with excavation platforms and conveyor belt operations will be pursued as well to enable real-time differentiation of soil based on contamination by VOCs, heavy metals, and radionuclides.

Advanced characterization and monitoring research being conducted by EMSP and elsewhere will need to transition into full implementation. Promising sensing technologies under EMSP development include LIBS and electrochemical techniques for subsurface characterization of heavy metals and radionuclides; micro-electro-mechanical sensors (MEMs) with applicability for many contaminants of concern; and other new schemes for detecting radionuclides and heavy metals.

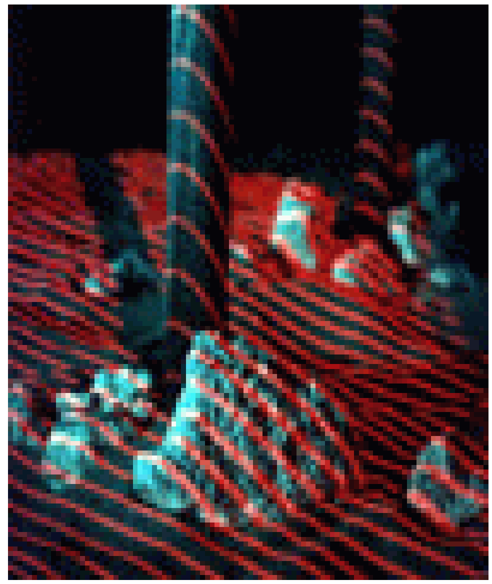
Alternative High-Level Waste Tank Disposition

New disposition approaches present characterization and monitoring challenges

VIP

Alternatives to HLW removal and processing

Removal, pre-processing, stabilizing, and shipping high-level tank wastes to long-term storage repositories present both substantial cost and technical risk. Accordingly, at this time DOE-EM is evaluating alternative scenarios for HLW tank disposition, including addressing the inherent risks associated with the waste residuals that may remain after the conclusion of retrieval operations. Aspects of these closure scenarios include assaying residual wastes for volume and composition, stabilizing residual inventory *in situ*, verifying and monitoring tank integrity, and leak prevention, detection, and mitigation.



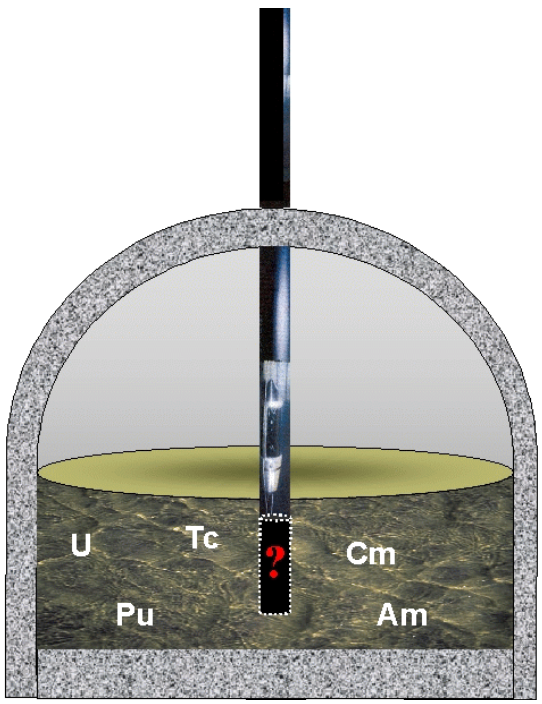
Characterization challenges

The total volume of any remaining wastes must be ascertained reasonably accurately as a start; techniques exist already, but refinement is needed. Estimates of inventories of radionuclides and other constituents will be required to support risk analysis modeling and to identify indicator species or parameters for long-term monitoring. This inventory estimation will be technically challenging due to waste heterogeneity, sampling access, and self-absorption. The physical integrity of the tanks themselves must also be determined. The nature and extent of any prior contamination outside of the tank may also be need to be determined.

Monitoring challenges

In the *in situ* stabilization scenario, improved methods for monitoring tank integrity will be needed for both single-shell and double-shell tanks. Current methods are cumbersome and time-consuming, and yet monitor only a small portion of tank wall surfaces.

Sensitive sensors and monitoring systems will be needed to provide early-warning detection of possible leaks from the tanks or migration of contaminants that may already have leaked. Moreover, as discussed elsewhere, sophisticated and credible modeling will be needed to support even a temporary *in situ* closure.



Topographic Measurement System

The Topographic Measurement System for measuring tank waste volume uses triangulated images of laser light to generate a map of the waste surface. This system is currently in use, although some further development is needed.

Pipe Explorer™ and robots

One approach to the inventory problem may involve further development of an existing OST-sponsored technology. In the Pipe Explorer™ system (TechID 74) an everted membrane is blown into a pipeline or duct. Gamma and beta radiation sensors are introduced directly; alpha radiation is detected by incorporating scintillating material into the membrane. Several strategies may be used to adapt this technology. The membrane can be blown through and beyond an opening into wider spaces where the gamma camera can be used. If the pipe opening is in a high radiation environment, added pipe lengths can reach a shielded location. Membranes and detectors can be extended into tanks when top access through risers or other penetrations is available. Sludge layers can be probed using everted membranes inside pipes with end slots or windows which can penetrate limited distances.

ERT

Electrical resistivity tomography has been developed for monitoring changes in subsurface conductance in tank farms (TechID 140). This could be coupled with the introduction of mobile ionic indicators into the grouts used for *in situ* waste stabilization.

VIP

Emissions Monitoring For High-Level Waste Processing

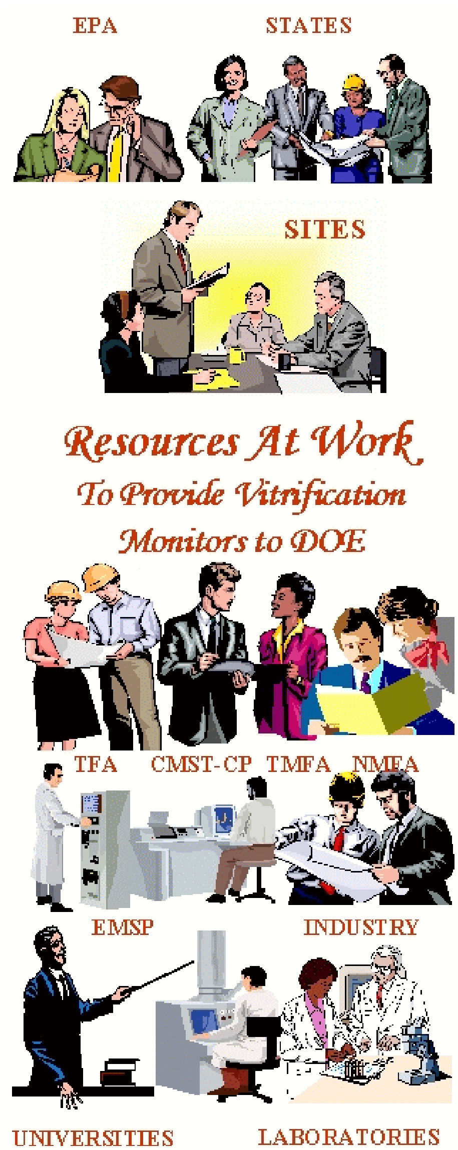
Crosscutting Leveraging at Work

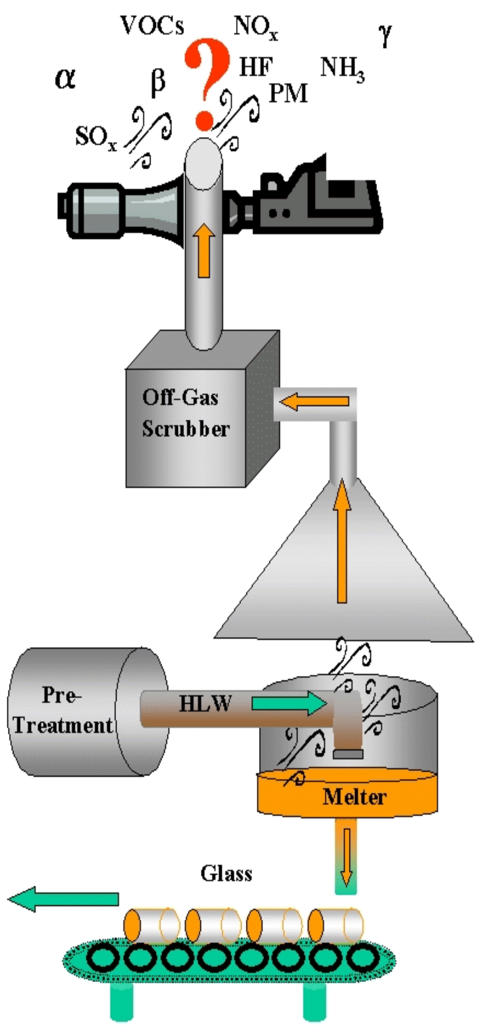
Off-gas monitoring for NO_x and other constituents during High-Level Waste (HLW) processing

Direct vitrification is a candidate treatment for sodium-bearing liquid wastes remaining in tanks at the Idaho National Engineering and Environmental laboratory (INEEL). As with other thermal treatment processes, an off-gas treatment system would be required for regulatory compliance; monitoring would be required for NO_x (NO and NO_2) and possibly also NH_3, CO, and/or H_2, depending on the NO_x removal process selected. Other thermal waste treatment processes at INEEL and other sites will require effluent monitoring for several hazardous constituents (radionuclides, toxic heavy metals, hydrocarbons, halogenated organics, and priority pollutants) for regulatory compliance. On-line monitoring of Hg, CO, NO_X, total hydrocarbons, particulate matter (PM), and other species will facilitate compliant operation and provide independent verification of process off-gas samples.

Technology development in DOE and beyond

The need for effluent monitoring extends beyond DOE tank waste concerns to other areas and, outside of DOE, to areas such as incineration, power generation, petroleum and metal refining, and chemical processing. Substantial technology development has been targeted at this wider need; commercial instrumentation is available for a number of applications. EPA sponsors the Environmental Technology Verification (ETV) program to expedite the acceptance and use of such instrumentation. The ETV program has verified technologies to monitor HF, NO, NH_3, and other compounds under simulated test conditions.





A pilot test of six commercial Hg monitors has been completed in collaboration with TMFA; the most successful will undergo Phase II testing at a commercial test facility. A TMFA program to test Continuous Emissions Monitoring (CEM) technologies supplements EPA efforts. Three commercial PM CEMs have been tested, and the development of dioxin/furan (D/F) monitors is part of a larger TMFA/EPA study of D/F formation and prevention.

Meeting the Site Needs

Given the advanced state of development and verification of CEMs, these INEEL needs are best addressed by adapting available technologies to site-specific functions, requirements, and conditions. Most relevant to HLW tank closure concerns is monitoring volatile off-gases produced when wastes are introduced into a melter. Adaptations of commercial instruments for use with off-gas systems should be given the highest priority, since such measurements are needed to design and qualify HLW vitrification processes.

A path forward previously identified is for DOE-EM to work with INEEL to develop function and design (F&D) requirements specifying the gases to be monitored, concentrations, and data and engineering requirements. Using these F&D requirements, INEEL would proceed to select a commercial monitor and identify a technology provider to install and demonstrate the technology in its planned pilot vitrification facility. DOE-EM could take the lead in developing and deploying both new and commercial technologies for these and additional constituents of concern; this would of course require keeping abreast of new developments in the CEM arena.

VIP

Understanding Natural Processes Affecting Contaminant Fate And Transport

Basic Science Challenges

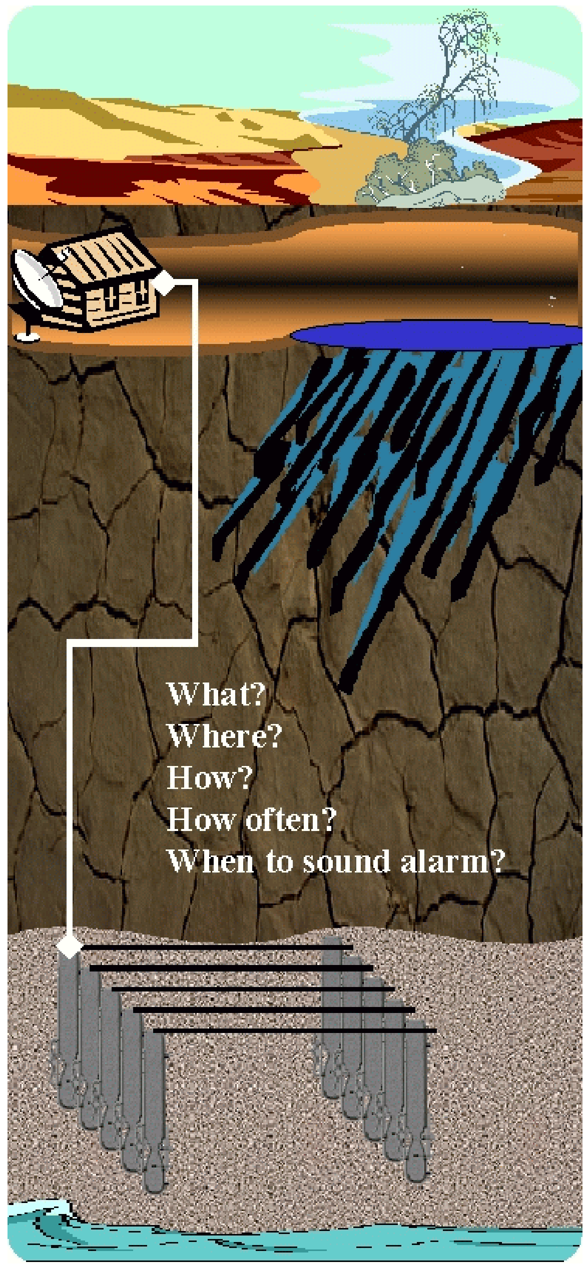
Reliable predictive models needed

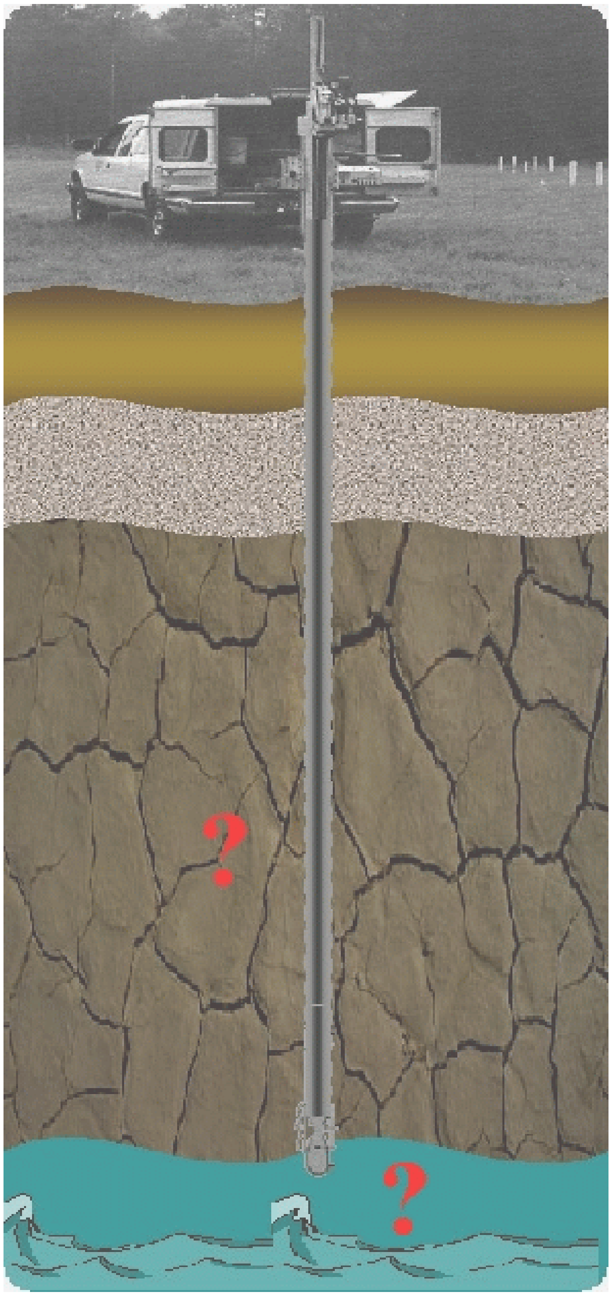
Reliable predictions of subsurface contaminant fate and transport are vital if DOE is to meet its Long-Term Stewardship obligations. Improved understandings of geological and geo-chemical processes, their relationship with contaminant fate and transport, and identification of key observables are critical; the National Research Council notes a current "inadequate understanding of ... characteristics that must be understood in order to make reliable predictions of fate and transport. ... little progress has been made on developing predictive models that incorporate the entire range of processes that may affect contaminant transport."

Every major DOE site identifies needs for defining the distribution of subsurface contaminants, quantifying their extent, and monitoring their movement. These needs were included by SCFA in its highest priority Work Package; related needs include improved understanding of permeability patterns, contaminant inventories, and vadose zone distribution and movement, along with better predictive models for groundwater flow and transport.

Previous studies

Previous OST projects have studied flow and transport in fractured rock, groundwater modeling, and data fusion for integrating diverse geophysical/hydrological sources. EMSP studies have addressed transport of specific contaminants and development of geophysical techniques for subsurface characterization. EMSP studies of transport and soil fixation respond to high-priority Hanford and Oak Ridge needs.





Geophysical characterization tools

Many improved geophysical characterization techniques are being developed by EMSP, including very early time-domain electromagnetic, seismic, and radar techniques, along with combinations of these to provide high resolution subsurface mapping.

Fate and transport

Numerous research projects involving contaminant fate and transport are underway. These include identifying site needs for better ways to characterize physical, chemical, and biological properties of the subsurface, particularly in deep and complex geologic settings, as well as to characterize physical, chemical, and biological heterogeneity and develop more reliable migration prediction models. Additional collaborations include developing ways to integrate data on different spatial and temporal scales to improve estimates of contaminant and subsurface properties; incorporating complexities such as colloid formation, biological activity, and fractured rock transport paths into transport models; and conducting experiments and modeling studies of the interacting chemical, physical, and biological processes that determine contaminant fate and transport.

DOE-EM has supported geophysical characterization development since the inception of OST; some of the earlier work was similar to basic and applied research efforts now being conducted by EMSP. An efficient path forward in this critical area will be to pool all present and past DOE-EM-sponsored research efforts with activities underway in other agencies and at universities.

TechID 2237: Induced Fluorescence Sensor for Cone Penetrometer

PROBLEM AND OPPORTUNITY AREA HIGHLIGHTS

Identification of Site Needs and Science and Technology Gaps

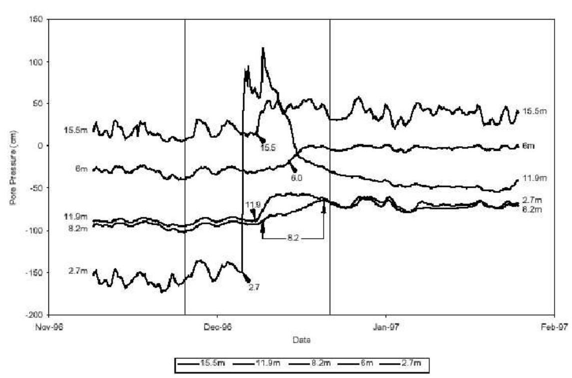
The major needs categories and special emphasis areas identified encompass numerous challenges including, but far from limited to, the **VIPs**. In this part these broad areas are examined further. It is impractical to discuss the multiplicity of individual site needs in detail within a document of manageable size. Rather, the FA approach is emulated. The FAs grouped similar needs into Needs Groups, with assistance from the crosscutting programs, and then prepared Technical Responses for the Needs Groups. Similarly, commonalities in technical approaches are often found among Needs Groups from different FAs, suggesting a crosscutting approach to meeting the needs. The Problem and Opportunity Areas presented here have been assembled using a crosscutting perspective that captures these commonalities of site needs.

In the road mapping process one typically strives to lay out a solution strategy and define a priority and a time line for each portion of the development process. This will not be attempted in this document; a major reason is the large number of science and technology development challenges and goals presented. Moreover, it is not the role of the CMST-CP to determine development priorities and schedules.

Rather than provide specific priorities and dates, therefore, this ***CMM ROAD MAP for DOE-EM*** provides simple statements that solutions will be needed or desirable in the Near-Term (within five years or so) or Far-Term (beyond five years). The benefits anticipated from developing technological solutions are stated; these implicitly delineate the consequences of failing to address the goals. Loosely speaking, the Near-Term challenges are more firmly rooted in pressing site-expressed technology development Needs, and the Far-Term challenges involve more strategic or science needs and may appear more visionary.

Nonetheless, this ***ROAD MAP*** provides a **Vision for 2012** for each of the **Problem and Opportunity Areas**. This is a vision of what capabilities could be developed and how baseline practices could change over the next ten years. The ten-year period is somewhat arbitrary, but does coincide with the target date envisioned in the Hanford 2012 Site Cleanup Vision.

APPENDIX A details specific science and technology development challenges; **Near-Term Goals** and **Far-Term Goals** associated with each of these **Problem and Opportunity Areas** are presented. Only a summary and overview of the **APPENDIX** discussions is presented here. In addition, **APPENDIX A** enumerates past OST CMM R&D successes in each area, and summarizes recent DOE-EM R&D projects.



TechID 2122: Advanced Tensiometer traces at several depths showing a precipitation event

WASTE, SOURCE, AND NUCLEAR MATERIALS CHARACTERIZATION

The long-term DOE goals of remediating environmental contamination, treating and disposing of radioactive and hazardous wastes, and decontaminating and decommissioning surplus facilities all require characterization as a first step and often as a final step as well. Accurate and thorough characterization of the nature, quantity, condition, physical extent, and hazards involved is needed for several reasons:

! to determine the scope of the remediation or treatment problem;

! to allow the selection of appropriate remediation or treatment strategies and technologies and to identify and estimate the resources needed to accomplish these tasks;

! to identify technology gaps to be closed and possible efficiencies to be obtained through the identification and development of innovative remediation and treatment methodologies;

! to ensure that remediation and treatment efforts themselves do not generate further problems;

! to provide baseline conditions from which to measure the progress of remediation and treatment efforts; and

! to foster confidence in proposed remediation and treatment programs on the part of responsible DOE site problem holders, DOE itself, Congress, and the Administration as well as regulatory and stakeholder communities and the general public.

The drawbacks of traditional characterization procedures affect all aspects of characterization in the DOE complex. These generally involve <u>sampling</u> materials according to a <u>predetermined plan</u>, <u>shipping</u> samples off-site for <u>later</u> and typically <u>costly</u> laboratory analysis, and disposing of <u>secondary wastes</u> generated in the process. These drawbacks include

! the difficulty of obtaining <u>representative samples</u> of heterogeneous materials such as those found in high-level waste tanks, certain types of subsurface regions, containerized wastes of unknown origin, and regions with restricted access such as small pipes and ducts;

! the inability to use results from recent samples incrementally in <u>dynamic planning</u> of the characterization effort, due to the <u>delay</u> incurred while awaiting off-site laboratory results;

! <u>costs</u> associated with the need to consider every sample as potentially hazardous while sampling and shipping and with the <u>post-analysis disposal</u> of potentially hazardous samples;

! the lack of <u>economies of scale</u> which might be obtained with the large numbers of analyses to be performed during the course of the DOE environmental management and cleanup effort; and

! the requirement that <u>every</u> sample be analyzed for the entire list of potential contaminants, even after the actual constituents of concern and their nature have become well understood.

Not each of these applies in every case, of course, but at least some apply in virtually every DOE-EM characterization task. Innovative characterization methodologies overcome these drawbacks in a number of ways, including

! the use of relatively <u>inexpensive *in situ* sensors</u> to generate a greater data density as one means of addressing the <u>heterogeneity</u> problem;

! the use of <u>autonomous real-time *in situ* sensors</u> to avoid delays between sampling and availability of analytical results, allowing <u>dynamic planning and control</u> with frequent on-site decision making for characterization, remediation, and treatment projects;

- the use of <u>on-site and *in situ* methods</u> to minimize or eliminate <u>secondary wastes</u> with their attendant risks of personnel exposure;

- the use of <u>holistic and tomographic</u> measurements to avoid the uncertainties associated with sampling <u>heterogeneous media</u>; and

- the use of minimally invasive and <u>non-invasive/nondestructive</u> methodologies which avoid personnel exposure and secondary waste generation.

These approaches and their underlying scientific and engineering principles are crosscutting foundations on which DOE-EM characterization science and technology advances can be based. These are applied to each of the Needs Groups.

Characterization of Contamination Sources

Contamination at DOE sites exists primarily in the subsurface and in contaminated facilities. Subsurface contamination sources include waste burial grounds, trenches, and pits along with previously contaminated soils and groundwater. The initial task involves locating these sources and delineating the nature and extent of contamination present. Non-invasive remote surface sensing and geophysical techniques have proven useful for identifying possibly contaminated areas for further investigation. Areas identified using such techniques must be investigated further while planning remediation activities. The variety of challenges faced results from the variety of modes of contamination present: undocumented waste drums buried in pits; leakage from production processes into the soils underneath buildings; seepage from unlined or leaking waste lagoons and underground storage tanks; leaching into the soils from surface contamination; and so on.

<u>Subsurface contamination</u>. Two prominent long-range goals in this regard are (a) developing improved understanding of the subsurface science involved in predicting contaminant transport and fate and (b) developing better ways of locating and characterizing distributions of Dense Non-Aqueous Phase Liquids (DNAPLs). The first of these involves developing satisfactory methods for modeling to predict contaminant flow toward, with, and sometimes contrary to groundwater in the subsurface; this is discussed further in **Improved Scientific Understandings**. The DNAPL problem deserves a separate category because DNAPLs (typically toxic chlorinated organic compounds) dissolve only sparingly in groundwater, so the usual groundwater flow models do not apply. Moreover, DNAPL contamination, once present, can remain in the subsurface for decades or longer.

Once the nature and extent of contamination have been determined and a remediation approach selected, the remediation process must be monitored; see the next section **Process and Product Monitoring**. When cleanup activities are complete, further characterization is typically required to determine or verify the end result of the cleanup operation: that the site can be released for unrestricted future use; or, alternatively, that the site satisfies the requirements placed upon it for entry into a long-term stewardship mode. Establishing and determining the adequacy of those long-term stewardship requirements again requires advances in understanding of contaminant fate and transport in many instances. These end-state characterization requirements apply as well when the decision is that no (further) remediation is warranted at a site.

<u>Contamination in and on facilities</u>. Contamination on surfaces and embedded within facilities slated for deactivation and decommissioning (D&D) presents similar challenges. In facility D&D there is the added challenge of performing characterization in difficult to access areas: inside walls, pipes, ducts, and equipment. In this setting great benefits may be realized by replacing conventional sampling and laboratory analysis with real-time, *in situ* measurement and mapping. Many past OST CMM R&D successes have involved technology development for non-invasive real-time radiation measurements; goals presented here include extending these capabilities with respect to both the variety of contaminants that can be measured and the ease with which the measurements can be made.

Characterization of Waste and Nuclear Materials

Another major characterization area is that of wastes and nuclear materials, including spent nuclear fuel. Whereas contaminant source characterization has previously been a major concern of only the Subsurface Contaminants Focus Area (SCFA) and the Deactivation and Decommissioning Focus Area (DDFA), waste and nuclear material issues cut across all DOE-EM operations and are a major concern for many. Characterization issues and methods can in many instances be quite similar to monitoring issues and methods; the operational distinction is that monitoring is generally an on-going activity, whereas characterization typically takes place during a few events of limited duration.

High-level waste tank remediation. Remediation of tanks containing high-level waste (HLW) is a critical DOE-EM technical and programmatic challenge. Prominent characterization needs arise at all stages of remediation: ensuring storage tank integrity while awaiting treatment; ensuring reliable, safe, and efficient waste retrieval; determining tank residues following waste retrieval; determining waste composition in order to plan stabilization into an appropriate final waste form; and characterizing the final waste forms to verify their intended composition and durability. Three related specific need areas have been identified: (1) sampling methodologies for tank residues, tank waste slurries, and stabilized waste forms; (2) improved laboratory analytical procedures for situations in which current methods are excessively slow or expensive or do not provide adequate sensitivity; and (3) *in situ* characterization for situations where sampling for laboratory analysis is not feasible because results are needed promptly or because representative sampling is not possible. A fourth need area is evaluation of the HLW tanks themselves to ensure maintenance of tank integrity.

An alternate approach to high-level waste tank disposition involves *in situ* stabilization and closure. The characterization needs associated with this approach are different from those involved with waste retrieval; major components include (1) waste volume determination; (2) characterization of the radionuclide inventory and identification of suitable indicator species or parameters for post-closure monitoring; and (3) evaluation of tank structural integrity.

Waste and nuclear material long-term storage. HLW, mixed waste, and certain nuclear materials are all stabilized and packaged for transportation and long-term storage. It is necessary to characterize the feedstock for these treatment and stabilization processes (e.g. incineration, calcination, or vitrification). The final waste form must be verified to meet transportation requirements and the Waste Acceptance Criteria (WAC) or Land Disposal Restrictions (LDR) of the repository sites. Moreover, methods are needed for monitoring the continued integrity of these waste forms; see **Process and Product Monitoring**.

Other waste characterization challenges. Additional specific challenges of note involve characterizing wastes generated by remediation processes themselves, characterizing waste sources (notably facilities slated for D&D) in order to effect volume reduction, and characterizing containerized wastes. The last of these is discussed further in **Nondestructive Methods**. Remediation and D&D efforts need to be closely coordinated with treatment, transportation, storage, and/or disposal planning.

The Deactivation and Decommissioning Free Release Goal

Several related challenges are identified in this area. The first set involves efficient real-time *in situ* characterization of facilities, equipment, and containerized materials to distinguish between contaminated and non-contaminated areas and materials and to identify contamination where it exists. The goal of these methods is to quickly and accurately determine whether a particular portion of a facility can be considered for reuse rather than dismantlement or demolition or, failing that, how the D&D project should proceed most efficiently with respect to volume reduction as well as worker and public safety concerns. Ideally such characterization would be done simultaneously with facility D&D activities, using sensors capable of reliably providing regulatorily acceptable measurements down to the D&D Free Release Goal. Such a capability would, of course, blur the distinction between facility characterization and D&D process monitoring.

Special challenges involve characterization of inaccessible areas inside pipes, cavities, ducts, and equipment as well as areas that present excessive hazards in terms of personnel exposure. One strategy involves expanding the use of robotic methods in the characterization of both inaccessible and hostile areas. In both of these one must develop real-time *in situ* sensors with adequate sensitivity, and obtain regulatory acceptance for their application.

Regulator and Stakeholder Concerns

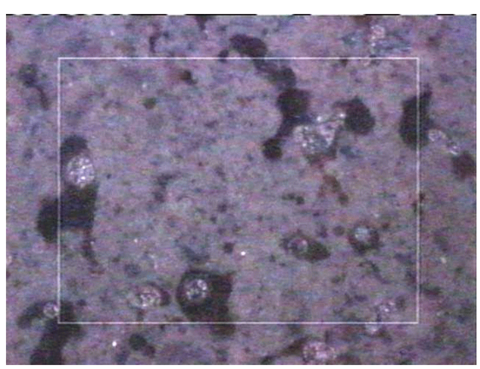
A common thread to all characterization and monitoring tasks is the need to secure regulatory and stakeholder acceptance of the methods used. This must be kept in mind while developing innovative approaches that depart from traditional baseline methods. A particular issue involves dealing with evolving regulatory standards. A particular useful technique for meeting these challenges is to collaborate with regulatory agencies in the development and validation of innovative methods.

A Vision for 2012

Within ten years DOE-EM should have developed the ability to characterize any non-negligible amount of contamination. *In situ* characterization of radionuclides will be enhanced through both incremental and step-change improvements in sensors coupled with innovative methods of deploying those sensors in limited access areas inside buildings, tanks, pipelines and ducts, building grounds, and landfills. *In situ* characterization of hazardous constituents will require major advances in field-deployable instrumentation; these should be achievable through improvements in sampling techniques and miniaturization of successful laboratory technologies. Robotics technologies will be necessary in some settings and very desirable in others.

Characterization of subsurface processes and contaminant distributions should enable credible long-term planning in support of site closure and long-term stewardship. Such planning will involve superior delineation of the nature and extent of subsurface contamination along with a better understanding of the natural processes affecting the fate and transport of that contamination and of ways to correlate anticipated fate and transport with available information about subsurface geology, geochemistry, and hydrogeology. Subsurface characterization will rely increasingly on non-invasive (geophysical) and minimally invasive (direct push) methods coupled with sophisticated analysis algorithms. Robotic and other remote and/or automated characterization methodologies will reduce risks to workers and increase efficiencies.

Improved data management and analysis models and protocols (data fusion) will replace current procedures centered around sample collection, laboratory analysis, and interpretation which often focus on individual constituents. Involvement of stakeholders and regulators should accompany these developments at each step to ensure that these improved capabilities are appreciated and employed. Regulator and stakeholder acceptance could be assisted by open, web-based reporting.



TechID 2399: GeoVis™ View of DNAPL in the subsurface

PROCESS AND PRODUCT MONITORING

Once the site or facility has been characterized and an environmental management or cleanup strategy decided upon, the task turns from characterization to monitoring, which is the systematic tracking of repeated measurements to detect and quantify changes. Monitoring is an integral part of environmental management and remediation activities for several reasons:

- to determine and document the evolution of the system being monitored;
- to warn of unanticipated or adverse events or trends occurring in the system; and
- to verify the effectiveness of remediation or treatment processes and, if necessary, to provide an alert when the processes are no longer performing as intended.

Monitoring is required for virtually every environmental management activity. Past monitoring practices share many of the previously enumerated drawbacks of past characterization practices; indeed, some of those drawbacks are even more important for monitoring than for characterization. Moreover, the demands of real-time monitoring for some treatment processes go far beyond those imposed by initial or final characterization. These drawbacks include

- the virtual uselessness of off-site laboratory analyses in <u>treatment and remediation process control</u> due to the <u>inherent delay</u> between sampling and data availability, resulting in a need to rely on inefficient feed-forward process control when on-line feedback control would be preferable;
- the <u>costs</u> associated with <u>personnel protection</u> and disposal of <u>secondary wastes</u> when monitoring through sample collection, as well as those associated with using conventional methods in providing the <u>very large number of measurements</u> anticipated in the DOE environmental management and cleanup agenda rather than achieving economies of scale through the use of innovative technologies;
- the <u>risks</u> posed by potential <u>breakdowns</u> of treatment processes such as slurry pipeline blockages or emissions, which might be avoided if better monitoring procedures were available;
- the need to <u>rely solely on post-process sampling</u> of final waste forms or nuclear material forms to <u>verify process success</u> when continuous process monitoring is not available;
- a similar need to rely on <u>post-cleanup verification</u> of facility decontamination, possibly followed by further decontamination stages, when real-time verification of cleanup success would allow project completion in a single stage; and
- the difficulties with emerging requirements in <u>regulatory compliance</u> and <u>stakeholder acceptance</u> with regard to off-gas effluents from thermal treatment, alternative oxidation treatment, and other waste and nuclear material stabilization processes.

The purpose of CMM Science and Technology development for process monitoring is to overcome these drawbacks. Numerous specific goals are discussed in succeeding sections and especially in **APPENDIX A**. Several common threads run through these goals, including

- the use of <u>real-time, *in situ*</u> sensors to <u>minimize sample collection, time delays, exposure risk of personnel, and secondary waste generation</u>;
- the incorporation of <u>real-time sensors</u> into waste and nuclear material stabilization processes in order to provide <u>continuous process control and documentation</u> and to avoid the risk of <u>process breakdown</u>;
- the <u>improvement</u> of <u>laboratory analytical methods</u> with regard to cost, time, and sensitivity;

- cost reduction resulting from the large-scale use of inexpensive *in situ* sensors and on-site analyses in place of conventional laboratory analyses; and

- avoidance of costs in remediation verification due to the availability of reliable, acceptable data obtained during the remediation process.

High-Level Tank Waste Processing

Vitrification had been tentatively identified as a candidate treatment for high-level tank wastes, although the high cost and technical risks of the process continue to spur a search for viable alternatives. Process monitoring will be critical to tank waste vitrification or any other treatment. Safety, efficiency, and cost reduction can be enhanced by reliable real-time monitoring of the feed, intermediate products, and final products of each stage of the remediation process selected. Real-time monitors are needed to detect possible leaks during retrieval and to measure slurry properties to ensure mixing status and reliable pipeline transfer. After retrieval and possibly pretreatment, the HLW or its intermediate products will undergo further processing, such as stabilization. Existing stabilization processes depend on careful control of feedstock, which limits the production rate; feedback process control would allow considerable increases in efficiency. This area is at the basic science stage of development at present; development of real-time monitors is a far-term goal.

Mixed and Mixed Transuranic (TRU) Waste Treatment

Mixed wastes contain both hazardous and radioactive components. The hazardous components include toxic organic compounds and heavy metals. The organic constituents can be destroyed by oxidation or other treatments, after which the residue can be stabilized for long-term isolation.

Monitoring of treatment processes. The challenges here are to verify the completeness of the destruction of organic constituents and to ensure that any effluents from the treatment processes satisfy regulatory requirements. Emissions standards and protocols for incinerators are currently in place, although the EPA is beginning to encourage alternate protocols based on continuous emissions monitors (CEMs). CEMs for regulated constituents are becoming available, although further development work is needed in several areas. Protocols and standards for monitoring effluent emissions for treatment technology alternatives to incineration are being developed through joint research involving the EPA, DOE, and other participants. One aspect of this research involves studying the formation of certain toxic organic constituents (dioxins and furans) during the oxidation process itself for the purpose of limiting the creation of these constituents; see **Improved Scientific Understandings**.

Waste and Nuclear Material Stabilization

Once the organic component of mixed waste has been removed, or HLW has been pretreated to remove certain radioactive constituents, the wastes are stabilized for long-term storage through vitrification or another solidification process. There is an urgent need for *in situ* real-time monitoring of the vitrification or solidification process to provide feedback for process control. The goal of such process control is to ensure that the process product will meet the specifications for long-term storage. Lacking such on-line process control, the process operators must rely on careful characterization of feedstock materials and engineering controls on the vitrification process, followed by sampling and laboratory analysis of the product and possible reprocessing if long-term storage criteria are not met. As with other applications involving *in situ* real-time measurements, regulatory acceptance will be needed to achieve the benefits of the innovative technology.

These same needs apply for stabilization of nuclear materials for future use; indeed, the final product criteria may be stricter because of the intended final use. In addition, it will be desirable to develop nondestructive and automated methods for inventory control of the stabilized materials.

Monitoring of Soil and Groundwater Remediation

These monitoring needs complement those for soil and groundwater characterization. As with facility D&D, the anticipated benefits are greatest for real-time *in situ* measurements that can make reliable process control possible during remediation. Several specific challenges have been identified: real-time determination of radioactive and other contaminants in soils during excavation, to support precise and defensible control of the volumes of soils excavated; inexpensive *in situ* monitoring of the extent of DNAPL and other contaminant plumes during remediation, leaving more costly sampling and laboratory analyses to final verification, if indeed it is even needed at that stage; and real-time monitoring of remediation processes which do not remove contaminated materials (particularly DNAPLs) from the subsurface but rather treat them in place.

In addition to active remediation of the subsurface, DOE facilities will require long-term monitoring in certain situations: passive treatment systems such as natural attenuation or enhanced natural attenuation; containment systems such as landfills, subsurface barriers, and tanks; and post-cleanup monitoring once cleanup activities have been completed, if the facility cannot be returned to free-release status; see **Long-Term Monitoring** to follow.

Monitoring of Facility Deactivation and Decommissioning

Ideally these monitoring needs will become nearly identical with characterization needs in a future in which real-time *in situ* measurement systems allow dynamic process control and optimization of treatment systems, efficient waste segregation for volume reduction of HLW and LLW, more reliable worker protection, and cost savings resulting from both reduced analysis costs and waste volume reduction.

A Vision for 2012

By 2012 DOE-EM should be able to treat wastes and nuclear materials on a reasonably routine production basis, using data provided by *in situ* real-time sensors as nearly the sole means documenting regulatory compliance. Current challenges of avoiding pipeline slurry blockages, ensuring waste tank and container integrity as long as necessary, and controlling and avoiding effluent releases of hazardous materials will no longer be challenges; reliable autonomous, self-reporting alarm systems will be in place to accomplish this end.

Strategies for efficient monitoring of subsurface remediation processes will have been developed and will have met with broad, if not universal, end user and regulatory approval. These strategies will tend toward *in situ*, autonomous, self-reporting and self-testing sensors with appropriate data collection, screening, and event generation provisions. A new generation of sensors will be needed for this and particularly for the demands of long-term stewardship; see the following section.

TechID 2015: Integrated Raman-EN Sensor for Tank Corrosion Chemistry Monitoring

LONG-TERM MONITORING

In recent years the need for long-term stewardship has become increasingly apparent, due to the impossibility or impracticality of cleaning up many DOE sites adequately for release for unrestricted use. Such sites include engineered facilities and containment systems as well as sites with existing subsurface contamination. In addition, the treatment of choice for certain types of contaminants, notably organic constituents, may well be natural or enhanced natural attenuation, again requiring long-term monitoring to verify that the process is progressing as anticipated and to provide alerts if needed. The demands of long-term monitoring differ from those of traditional monitoring of waste management facilities in several significant ways:

- traditional monitoring is based on sample collection and shipment to on-site or off-site laboratories, whereas it would be highly desirable to minimize the logistical demands of actual sample collection and shipping during long-term monitoring;

- the record-keeping involved in traditional monitoring involves sampling logs, chain-of-custody forms, laboratory analysis records, and facility management reports to regulatory authorities, whereas during long-term monitoring using remote and automated systems it will be highly desirable to minimize the “paper-work” involved while maintaining legal defensibility;

- monitoring at active sites, particularly waste management sites, is typically designed to detect releases of any of a large suite of potential contaminants whose source concentrations may increase or decrease in time, whereas during long-term monitoring the source will have been well characterized so that the monitoring program can be more specifically targeted; and

- traditional monitoring is typically performed at or near sites or facilities with on-going activities and related personnel and other resources, whereas it will be highly desirable to limit the personnel and other on-site resource demands during long-term monitoring.

Conventional monitoring technologies and strategies could be used in long-term monitoring, but their use is expected to be inefficient and costly. Among the drawbacks of traditional monitoring approaches are the following:

- the need for routine periodic <u>hands-on</u> field sampling at many locations rarely if ever visited otherwise;

- the typical reliance on a <u>broad array</u> of indicator parameters and potential contaminants rather than a <u>short list of key indicators</u> based on <u>detailed knowledge of site-specific conditions</u> and processes;

- the need to <u>ship samples</u> to off-site laboratories, with attendant shipping costs and, in some cases, exposure risk;

- the cost savings lost by not taking advantage of potential <u>economies of scale</u> when dealing with the great numbers of similar measurements which will need to be made and processed during DOE long-term monitoring activities; and

- the need for <u>manual review</u> of laboratory reports and other documents.

Many advances in monitoring technology and procedures will be desirable to overcome these drawbacks and carry on long-term monitoring efficiently. General goals include the following:

- advancing the ability to <u>characterize</u> subsurface contamination, subsurface contaminant flow, and the site-specific processes which affect contaminant fate to identify defensible parsimonious lists of key indicators to monitor;

- ! developing remote, *in situ*, relatively low-unit-cost sensors capable of autonomous reporting, self-maintenance, and self-validation for selected parameters appearing on the short parameter lists;

- ! developing automated data collection, recording, storage, review, and event reporting capabilities which will minimize the logistical demands of dealing with long-term monitoring data; while

- ! encouraging the evolution of regulatory paradigms involving parameter selection, data and decision quality, data storage, and event reporting as appropriate for the advanced monitoring systems envisioned.

Long-Term Monitoring Challenges

The major science and technology innovation needed for efficient long-term monitoring is the invention of a new generation of sensors. The new sensors will be rugged, to withstand long deployments in possibly hostile environments; small, for *in situ* deployment using the cone penetrometer and GeoProbe^{TM} as well as for reduced energy demands; self-validating and self-maintaining, to minimize maintenance demands while assuring monitoring system and data integrity; and capable of remote autonomous reporting.

An additional demand is that of shifting the monitoring paradigm from active, hands-on monitoring to passive, remote monitoring. This will require better understanding and modeling of subsurface processes involved in contaminant fate and transport as well as careful site characterization in order to justify and validate efficient, parsimonious monitoring program designs. Advancing data recording storage, validation, retrieval, analysis, and event reporting are also needed. These advances will be needed to gain regulatory and stakeholder acceptance of the new and efficient monitoring systems.

A Vision for 2012

An optimistic vision for DOE-EM capabilities by the year 2012 has long-term monitoring in support of long-term stewardship and passive remediation using a new generation of robust sensors capable of unattended operation, autonomous reporting, self-calibration and testing (even self-repairing to some extent), and minimal or no reliance on consumable supplies or external power. These sensors will be linked to remote data acquisition systems; data will be recorded, validated, and screened nearly automatically; sophisticated decision rules will govern the generation of alarms for exceptional events that require human recognition and intervention.

Superior understandings of fate and transport processes will have enabled a substantial evolution of regulatory paradigms from the current practice of monitoring extended, general lists of parameters to the judicious, parsimonious selection and monitoring of key site-specific indicator parameters. All of these advances will have been accomplished on multiple fronts: challenges are faced in both the technical and the regulatory and stakeholder acceptance arenas.

TechID 3182: Chemiresistor for VOC monitoring

NONDESTRUCTIVE METHODS

Nondestructive Assay and Nondestructive Evaluation (NDA and NDE) techniques range from visual examination and calorimetric measurements to high-energy gamma-ray measurements. Typical NDA methods involve gamma and passive or active neutron spectroscopy for isotope determination and mass quantitation of nuclear materials and TRU/Mixed TRU waste. NDE is typically performed by digital radiography. Ultrasound NDE may be employed for characterization of tank integrity, for example.

Many NDA and NDE techniques measure radiation from a target in order to determine its physical and chemical properties. This radiation may be emitted spontaneously (passive NDA/NDE), as radioactive emissions from radionuclides or thermal emissions from heated materials, or in response to an external stimulus (active NDA/NDE), as with laser-induced fluorescence (LIF), laser-induced breakdown spectroscopy (LIBS), and pulsed gamma neutron activation analysis (PGNAA). X-ray or LIF imaging technologies may be used to examine inside pipes or survey facility walls, respectively. In some cases the radiation emitted uniquely identifies the isotope(s) present and can thereby be used in quantitation.

The baseline technology is typically conventional destructive analysis; i.e., sampling followed by laboratory chemical or radiological analysis. Reasons for preferring NDA/NDE over baseline technologies include

! the lack of material destruction, which is critical in applications involving inventory control of nuclear materials;

! the avoidance of sampling and the time delays and secondary wastes inherent in sampling followed by laboratory analysis;

! the reduction in radiation and hazardous material exposure for personnel;

! the availability of analytical results in real time or near-real time, making them useful for process control or real-time planning of process or remediation activities;

! the holistic analysis of heterogeneous materials, in situations where representative sampling might be challenging; and most significantly

! the ability to view inside materials or objects in certain circumstances, such as non-invasive examination of tank walls, pipes, and ductwork in facilities undergoing D&D, and waste in containers.

Many early OST CMM R&D successes involved spectral methods of various types, many of which can be considered as variants on the NDA/NDE theme; see **APPENDIX A**. Advances desired in this area include

! advancement of neutron capture and combined gamma-neutron interrogation techniques for evaluating containerized wastes for radionuclides and RCRA metals;

! fusion of NDA/NDE analysis results with acceptable knowledge from the facility operating record;

! fusion of tomographic X-ray evaluation and neutron-gamma NDA assay;

! development of NDA/NDE methods for monitoring HLW storage tanks;

! development of methods for verifying the continued safe storage and inventory of containerized nuclear materials, particular with regard to moisture content and hydrogen headspace gas concentration; and

! development of NDA methods for assay of contaminants in bulk materials such as concrete and in microscopic structures such as surface cracks in metals during facility D&D.

NDA and NDE for Mixed and Mixed TRU Wastes

Priorities in NDA/NDE method development include analyses of containerized wastes for radionuclides and RCRA metals and analyses of remote-handled wastes, combining direct measurements with acceptable knowledge. Cost effective radiological classification and disposal of TRU waste lacks simple and demonstrated *in situ* measurement and verification procedures. Overly restrictive classifications can be assigned in the absence of defensible measurements. The differences in disposal costs can vary substantially between TRU and LLW. A combination of process information (Acceptable Knowledge), simple measurements, and calculated predictions from radiation shielding models may readily resolve issues on many waste streams. Some RH waste streams may require developing advanced characterization methodology. NDA measurements are influenced by many variables, including type of radiation and energy, measurement distance, source size and shape, source distribution and matrix, and shielding. Since the signal depends on the elemental composition of the material interrogated, as well as a host of measurement geometry and shielding considerations, sophisticated matrix-correction algorithms are needed.

High-Level Waste Tank Integrity

Needs here focus on better understanding of corrosion and failure mechanisms of HLW tanks in order to prevent leaks in the future, and on monitoring aging in-use HLW tanks for years or decades until final closure.

Nuclear Materials and Spent Nuclear Fuels

Challenges here focus on assay of nuclear materials and spent nuclear fuel for inventory control and regulatory certification, as well as NDE of containerized materials to ensure their continued safe storage.

Non-Intrusive Techniques for Facility Deactivation and Decommissioning

The focus for NDA/NDE science and technology development for facility D&D is in developing methods for detecting radionuclides and hazardous materials inside materials in support of worker safety and volume reduction of HLW and LLW.

Vision for 2012

By 2012 DOE-EM attentions will have shifted largely from initial characterization to remediation, facility closure, and long-term stewardship. NDA/NDE and robotic methods should become the baseline for routine characterization and monitoring in many settings. NDA/NDE methods will be thoroughly embedded in the processes for treatment of mixed, mixed TRU, and high-level tank wastes and nuclear materials. Non-intrusive methods will have been developed to the point of facilitating reliable evaluation and assay of closed containers with regard to radionuclide as well as hydrogen and moisture content. The use of NDA/NDE methods for tank integrity monitoring and tank residual waste verification should be routine.

TechID 134: X-Ray K-Edge Heavy Metal Detector

IMPROVED SCIENTIFIC UNDERSTANDINGS

Three topics deserve special attention.

Subsurface Science

Long-term stewardship and site closure often require and depend on models of contaminant fate and transport in the subsurface. Research is needed to understand subsurface processes better, with an eye toward making reliable fate and transport predictions. With a better understanding of the processes will come an enhanced ability to determine the key predictive characteristics and parameters of those processes and how to better characterize them.

Emerging and Evolving Technologies

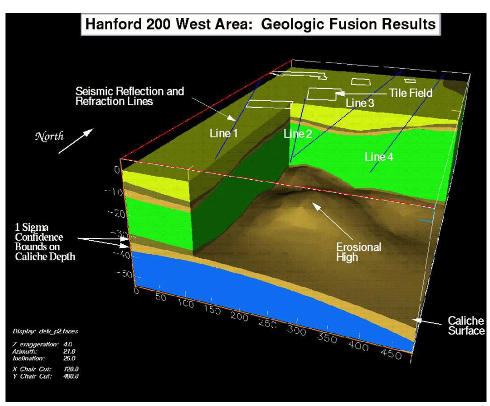
The year 2002 is an exciting time in sensor technology development, with advances in miniaturized sensors and biosensors among others being made in government, industry, and university laboratories. Many of these emerging technologies, along with evolutionary advances in currently available technologies, are of critical importance to DOE in pursuing its environmental management, cleanup, and long-term stewardship mandates. DOE-EM should remain aware of and encourage these developments and steer them toward DOE applications. In addition, DOE-EM should promote continual evolution in characterization and monitoring strategies and regulatory paradigms to parallel the technological advances.

Data Collection and Interpretation

Finally, the availability of the new breed of sensors, particularly those suited to **Long-Term Stewardship** applications, will demand new ways of dealing with data collection (remotely, autonomously), storage (automated, but with adequate data verification and authentication), validation (by remote sensors themselves and by the data access and storage system), and screening, analysis, and reporting (automated, using site-specific decision rules). New visualization systems will be of great benefit in some contexts. Along with these new ways of handling and reporting data will come need for a parallel evolution in regulatory requirements, which in turn will require adequate demonstration and validation of the proposed data collection and interpretation systems.

A Vision for 2012

By 2012 these specific special challenges will have been met, although improved sensor development will always continue. These three areas will have had major impacts on characterization and monitoring in general, and the knowledge gained by DOE and disseminated through collaboration with EPA, DoD, and other agencies will have had a substantial impact in streamlining regulatory and stakeholder acceptance.



TechID 2944: Hydrogeologic Data Fusion

VIP

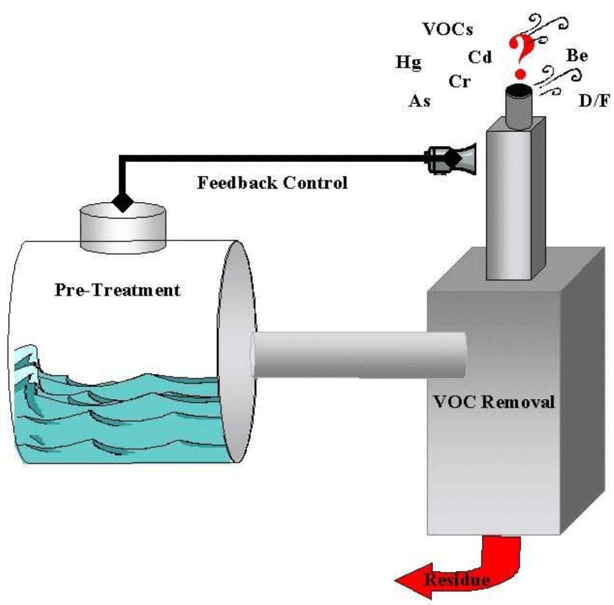
Monitoring Mixed Waste Treatment Processes and Effluents

Continuous Emission Monitors for Feedback and Compliance

CEMs: what, why and where?

DOE must employ continuous emission monitors (CEMs) in order to ensure proper operation of its mixed waste treatment facilities. CEMs enhance regulator and stakeholder confidence that emissions will remain within limits, hence reducing waste feed characterization and off-line testing requirements. Operating limits based on trial runs cannot ensure compliance during routine operation. CEMs are needed for mercury, multiple metals (MM), dioxins and furans (D/F), and particulate matter (PM) in order to provide both continuous emission records and real-time process control.

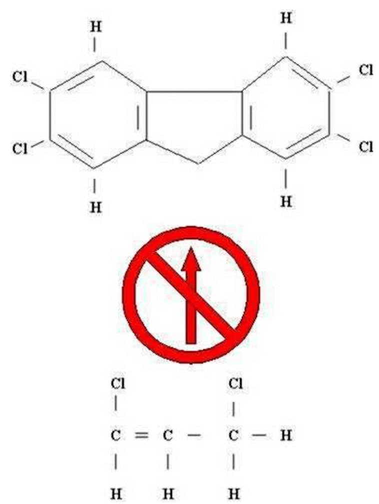
Treatment is needed for low-level and high-level radioactive waste, mixed transuranic waste, and nuclear materials as well as mixed waste. Treatment systems such as waste melters, incinerators, and plasma systems have been explored. Future processes may include steam reforming, thermal desorption, and chemical oxidation; developing CEMs for alternate treatments is a natural extension of current CEM development.



Particulate matter

High efficiency particulate air (HEPA) filters present a primary challenge to PM CEM development. PM levels down-stream of HEPA filters are orders of magnitude lower than both the emission limit and the levels of detection (LOD) for current PM CEMs and possibly below the LOD for the EPA Reference Method as well. A joint EPA/DOE National Technical Workgroup is addressing the resulting challenges.

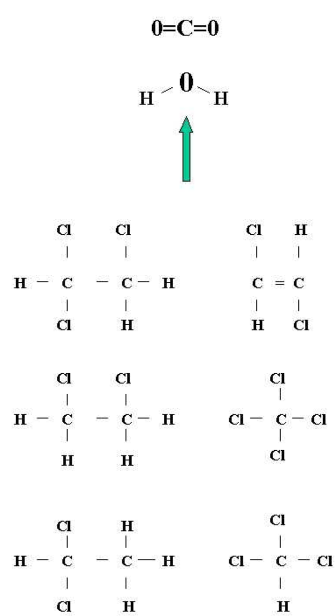
Mercury



Mercury (Hg) is present in many DOE waste streams. Few treatment facilities can suppress Hg emissions, so facility designs and permits assume that all Hg in the feed is emitted. The maximum waste feed concentration would need to be less than 10 ppm to comply with the current limit; sampling and analyzing to that level is costly and would greatly increase the potential for worker radiation exposure. Savings in waste characterization could easily offset the cost of Hg CEMs. DOE is involved in several collaborative efforts aimed at developing and gaining regulatory acceptance for Hg CEMs.

Multiple metals

Maximum Achievable Control Technology (MACT) Rule metals include mercury, cadmium, lead, arsenic, beryllium, and chromium. Except for mercury, DOE facilities readily meet MM emission limits, because they are present mostly in the particulate phase and DOE facilities have extensive PM control for radionuclides. The incentive to develop and deploy MM CEMs comes from stakeholder interests in assuring that hazardous metal emissions are monitored and communicated on a continuous basis, as well as from a desire to minimize waste feed analysis costs.



Dioxins and furans

The primary source of D/F is formation during combustion or thermal treatment, through mechanisms not yet totally understood. Regulatory levels are extremely low, not achievable by any "real-time" monitor, making the study of D/F formation laborious and costly. A coordinated industry-EPA-university program is developing a D/F CEM to aid this study. "Near real-time" data available within minutes rather than weeks will allow researchers to generate data much more efficiently over a much wider set of experimental conditions.

In Situ Detection of Surface Contamination to Free Release Goals

VIP

The Surface and Airborne Beryllium Monitor

D&D safety challenges

The decontamination and decommissioning (D&D) of excess DOE facilities involves potentially great hazards to workers and others. The varied nature of facilities undergoing D&D presents a wide range of characterization and resulting technology development challenges. One challenge at the Rocky Flats Environmental Technology Site (RFETS) and elsewhere arises during characterization and D&D of property and equipment contaminated with beryllium (Be). RFETS is concerned about potential exposure to airborne beryllium re-suspended from surfaces and the potential liability associated with property release. Epidemiologists believe that no safe exposure level exists for airborne beryllium and that dermal exposure may result in sensitization.

A Be surface and air monitor

DOE will benefit greatly from having a nearly instantaneous, continuous monitor for both surface and airborne beryllium contamination. Such a monitor will improve worker safety by providing an alarm for airborne beryllium. As a surface monitor, it will allow for more effective free release of property and aid in identifying contaminated areas prior to potential worker exposure. These safeguards will increase worker efficiency and accelerate site closure.

Such a monitor is being developed by private industry in a four-way collaboration with DDFA, INDP, and CMST-CP. To initiate the process INDP issued a Request For Proposal through DOE's National Energy Technology Laboratory (NETL). CMST-CP personnel canvassed the DOE

complex, including RFETS, to determine technical specifications. A technical evaluation committee was formed to evaluate the proposals received; this committee was comprised of INDP and CMST-CP personnel with advisors from RFETS, Los Alamos National Laboratory, and Lovelace Respiratory Research Institute. The company submitting the winning proposal is currently funded to develop the real-time Beryllium Surface and Air Monitor. Review comments on its draft engineering design were provided by RFETS end-user (D&D and Environmental Safety and Health), INDP, and CMST-CP personnel.

Experience and teamwork

The winning solution is based on extensive experience with laser induced breakdown spectroscopy (LIBS) instrumentation. An important part of the instrument design is proper consideration of aerosol behavior and properties, including size distribution. Lovelace Respiratory Research Institute will provide the world class aerosol science capabilities needed to ensure that the end result is a robust instrument ready to meet the required performance certifications.

Demonstration and delivery

A critical development step is an on-site demonstration including federal and state regulators at a RFETS D&D facility. Because of the critical importance of regulatory acceptance to the deployment of innovative technologies, every effort is being undertaken to involve regulatory bodies early in the development process to help them acquire confidence in the instrument. Two prototype monitors have been fabricated and tested; these are being demonstrated and deployed at Rocky Flats and Paducah (May 2002). Additional monitors will be fabricated according to market demand.

VIP

Long-Term Monitoring of Remedial Measures

Remedy Performance Verification

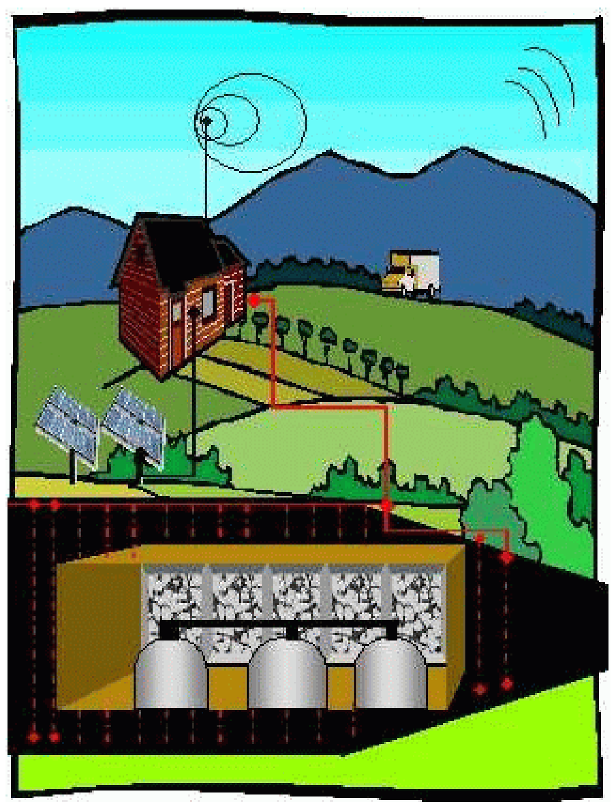
Remedial measures

All major DOE sites will require long-term monitoring of remedial measures including natural processes, containment, and stabilization. SCFA has identified a three-pronged approach: in situ sensors for VOCs, heavy metals, and radionuclides in groundwater; advanced geophysical tools for monitoring vadose zone contaminant fluxes and geostatistical techniques to validate them; and aerial monitoring to detect contaminant releases in large, difficult to access areas.

Containment and stabilization

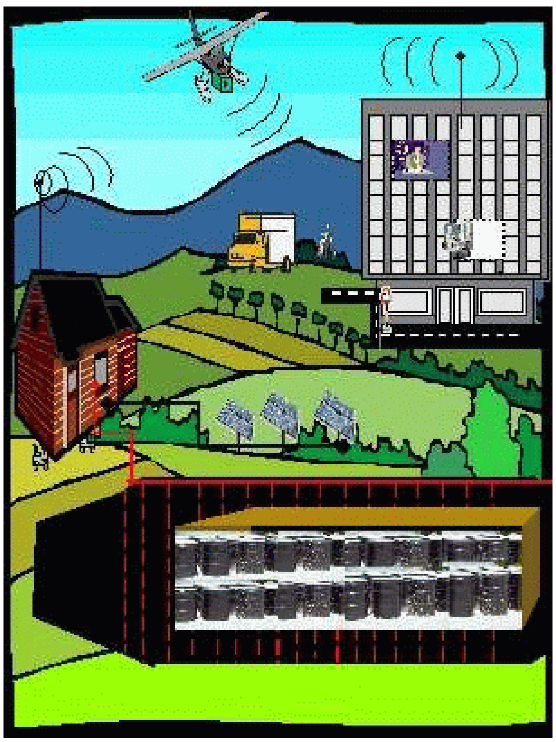
Since containment is often a preferred remedy, DOE-EM has sponsored several technology development projects for verification and monitoring of caps, covers, and barriers used with buried waste. These include remote sensing systems, subsurface barrier validation using the SEAtrace™ system, barrier monitors using ERT, the advanced tensiometer, and a remote real-time radiation tracking system for surface soils. The latter, although designed for day-by-day direction of remediation operations, includes remote reporting and data acquisition capabilities as well as analysis software potentially useful in long-term monitoring of remote areas.

Current and future technology development related to long-term monitoring should include autonomous in situ landfill cap, cover, and barrier sensors which are self-maintaining, self-calibrating, and self-validating. Parallel evolution in data transmission, recording, and integration along with advances in regulatory strategies are needed to enable DOE to benefit optimally from these advances.



Monitored natural attenuation

An important future focus will be on post-closure monitoring and natural remediation processes such as monitored natural attenuation and bioremediation. Monitoring will help determine the efficacy of these natural processes to aid in identifying measures for their enhancement.



Regulatory buy-in and EMSP research

Regulatory acceptance of natural attenuation and/or bioremediation for organic contaminants in the subsurface will require demonstrations that actual decontamination is occurring, rather than mere dilution of the contaminant by diffusion into a larger volume. Several EMSP projects are exploring potential techniques. One involves using ratios of carbon isotopes to determine whether or not biodegradation is occurring; other isotopic ratios have been used to study the exchange between aquifer layers. Another EMSP project explores the use of precise isotopic ratio measurements of chlorine and carbon to evaluate in situ bioremediation of chlorinated organic solvents. Other projects involve genetic engineering approaches to developing microorganisms for bioremediation of chlorinated organics in mixed wastes with high radiation levels as well as of a variety of other contaminants found at DOE sites.

Advanced Monitoring Systems Initiative

The Advanced Monitoring Systems Initiative (AMSI) has been created to establish a vertically integrated development and testing operation at the Nevada Test Site capable of taking promising new sensor and sensor system concepts from the research bench to field application demonstrations swiftly, keeping up with the ever-accelerating pace of innovation in micro- and nanosystems.

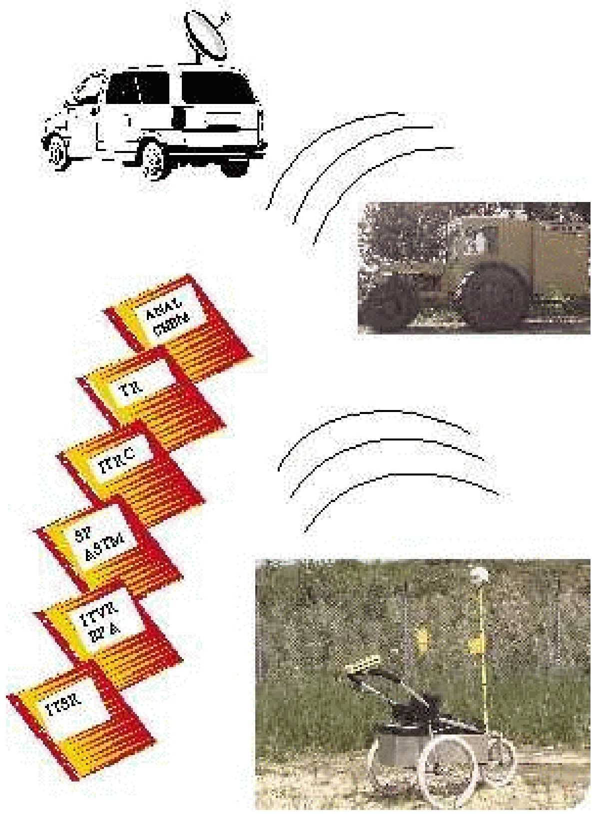
VIP

Improved Methods and Strategies for Managing and Interpreting Data

Regulatory and Stakeholder Involvement Critical

Novel technology yields novel data

Previous projects have yielded significant advances in the effective use of real-time data in characterization and remediation. These include Expedited Site Characterization (ESC), Geophysical and Hydrogeological Data Fusion, Adaptive Sampling and Analysis Programs (ASAPs), PLUME - Groundwater Modeling Software, and RSS Software for Soil Excavation Control. These provided ways of using data generated on-site by multiple sources in making reliable, accurate, timely, and defensible decisions. Three conceptual components are involved: data collection (both hardware and software); improved decision strategies and concepts (data fusion and other decision support tools); and methods to ensure acceptability of the resulting decisions.



Data collection systems

Previous advances include transmitting mobile sensor data along with global positioning system (GPS) location data by radio to a central on-site facility. This enables real-time mapping of radiation levels at Fernald and Oak Ridge in support of soil excavation and remediation decisions. The RSS Software provides the real-time mapping and decision support needed.

Decision models

Advances include using of Bayesian geostatistical analysis to combine prior information, such as historical records, modeling results, and institutional memory, with sampling data to update estimates of contamination likelihood or concentrations. ASAPs is a peer-reviewed procedure for performing such analyses.

$$f(x|a) = \frac{f(x)\,f(a|x)}{\int f(\xi)\,f(a|\xi)\,d\xi}$$

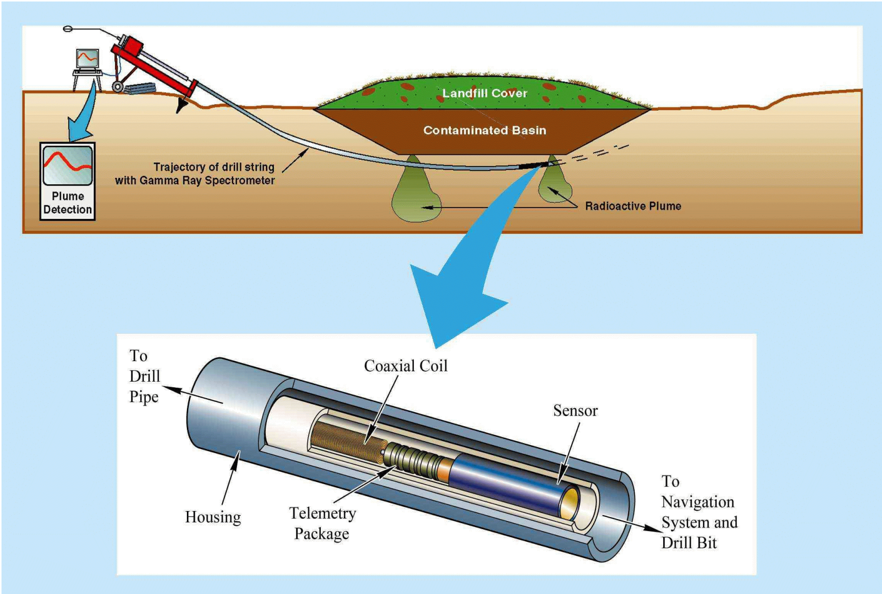
Regulatory acceptance

Peer review has aided the acceptance both ASAPs and ESC, the topic of an ASTM Standard Practice. Also, the goals of the EPA ETV Program and the Interstate Technology Regulatory Council are to foster and accelerate the regulatory acceptance of innovative technologies.

Future development

Commercial entities are developing networks to gather real-time data from in situ sensors; there is considerable interest in government and academic research communities as well. DOE-EM should promote the exchange of information about new developments, the state of the technology, and DOE, regulator, and stakeholder requirements through workshops, collaborative working groups, and other means. Particular concerns for long-term monitoring include sensor self-calibration and self-testing, data transmission and recording integrity comparable to current practice, and automated data screening algorithms.

Parallel development of design and decision strategies is needed, involving regulatory agencies, regulated parties, and ultimately stakeholder. One path forward is to continue presenting proposed innovative methodologies for peer review in professional publications as well as forums such as ASTM. Another is continued DOE-EM participation in inter-agency task groups; such participation both brings DOE expertise to the evolution of regulatory thinking and ensures representation of DOE concerns in that evolution. In addition, DOE-EM should collaborate with other government agencies in disseminating information on optimal monitoring and modeling designs, technologies, and software.



TechID 8: Environmental Measurement While Drilling

SOLUTION PATHS

The **Strategies** section of the **INTRODUCTION** outlined the process used recently for identifying and prioritizing needs, procuring funding, and managing science and technology development under the OST Focus Area-centered approach. **SOLUTION PATHS** complements **Strategies** by exploring pathways that can be used in identifying and recruiting qualified Principal Investigators (PIs) and contractors to carry out the desired research and development activity.

The first and most cost-effective tactic is to ensure that DOE site end users can easily become aware of readily available measurement technologies previously developed by DOE-EM, other federally funded organizations, and the private sector. Similarly, DOE characterization, monitoring, and modeling needs and gaps should be publicized to a broad range of potential solution developers and providers.

PATHWAYS TO R&D PROVIDERS

There are two related aspects to recruiting PIs: how the PI is identified and selected; and how the project is funded and managed. In the past PIs have been recruited through a variety of mechanisms.

- Broad competitive solicitations for proposals to perform research of interest to DOE-EM, such as Program Research and Development Announcements (PRDAs) targeted at industry and university researchers, invitations to DOE laboratories, and solicitations issued by EMSP
- Targeted competitive solicitations for proposals to provide solutions to specific needs, issued through INDP, the Small Business Innovative Research (SBIR) program by the DOE Office of Science, or by individual site organizations
- Sole source requests to uniquely qualified PIs for R&D needed to meet specific needs
- Inclusion of specific R&D tasks in larger work scopes such as Industry and University Programs research conducted at Mississippi State University's Diagnostic Instrumentation and Analysis Laboratory (DIAL), the Hemispheric Center for Environmental Technology (HCET) at Florida International University, and at National Laboratories

DOE site needs and priorities have traditionally been publicized through various means, including workshops and needs meetings ranging from site-specific to medium-specific to program-wide, conference exhibits and presentations, solicitations published in the *Commerce Business Daily*, and websites maintained by DOE sites and DOE-EM.

FUNDING AND PROJECT MANAGEMENT

Funding and project management mechanisms have likewise varied according to the nature and maturity of the R&D desired. Avenues have included the following.

- Research grants awarded by EMSP, typically for basic and applied research to be conducted at universities and/or government laboratories (occasionally elsewhere), with oversight by EMSP assisted by other OST programs
- Direct R&D contractor funding provided through a site, generally for site-specific development work, with oversight provided by the site Technical Program Officer (TPO) assisted by OST programs
- Deployment assistance provided to a DOE site contractor through the Accelerated Site Technology Deployment (ASTD) program, typically for mature technologies needing relatively minor site-specific modification or adjustment, with oversight provided by the TPO in conjunction with the ASTD program and the FA involved

- Funding channeled to industry or university research centers through INDP, generally for successful respondents to INDP or SBIR solicitations as well as DIAL and HCET, with oversight is provided by NETL along with other OST programs

- Research conducted under Interagency Agreements with U.S. EPA, DoD, and USGS, with funding contributed by DOE and others, monitored by an interested OST program

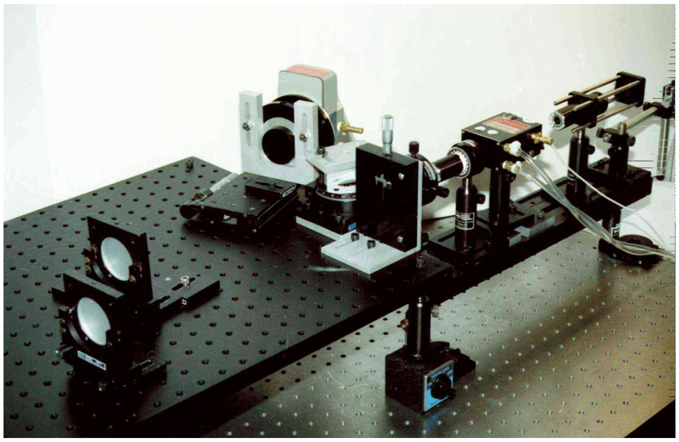
EXAMPLES

Two R&D procurement processes that were used for **VIPs** are sketched here. Expanded discussions for these and other **VIPs** are included in **APPENDIX B**.

- The FAs, assisted by Crosscutting Programs, developed detailed functional requirements responding to site-identified needs. These were published in Requests For Proposals in the *Commerce Business Daily*, the NETL website, and elsewhere. Responses from interested researchers were evaluated, refined, and ranked; one respondent was selected. Development was contracted through INDP and reviewed and monitored by INDP and the FA involved, assisted by the Crosscutting Program as appropriate. This path was followed for the SEAtrace™ Barrier Validation System and the Surface and Air Beryllium Monitor.

- DOE needs and technical requirements for previously unsolved problems were presented to DOE research communities including EMSP, DOE labs, DIAL, HCET, and other parties through workshops, conference presentations, website publication, and other means. Interested researchers then responded to broad calls for proposals; they could in some instances even initiate proposals. This path is particularly appropriate at more basic R&D levels. **VIPs** following this path include developing next generation sensors (robust, *in situ*, autonomous, self-calibrating, and self-maintaining) for long-term monitoring, devising data collection methods and protocols for such sensors, and providing *in situ* tank waste characterization technologies capable of providing data satisfying regulatory certification requirements currently attainable only with conventional laboratory analyses.

The strategy selected for a particular challenge depends on the nature and maturity of previous technology development for it and similar challenges. CMST-CP's familiarity with measurement technology relevant to DOE needs and the results of prior DOE efforts has been a major asset in responding to the challenges.



TechID 1564: Bench Prototype of Compact High Resolution Spectrometer

SUMMARY

This CMM Science and Technology Development Road Map for DOE-EM is based on a broad and thorough evaluation of DOE-EM characterization, monitoring, and modeling needs. The needs are first and foremost those identified by DOE sites through the formal Site Technology Coordinating Group (STCG) process. Although many of these needs can be met using existing or readily available technologies, numerous gaps (technology development needs) have emerged. DOE-EM OST programs have identified additional strategic needs which will surely arise, even though they may not yet have been expressed by the STCGs. Others have been identified in internal and external studies, such as the National Research Council's *Research Needs in Subsurface Science* and the *DOE Research and Development Portfolio for Environmental Quality*, both published during 2000.

This ***CMM ROAD MAP for DOE-EM*** outlines two major areas, **Waste, Source, and Nuclear Materials Characterization** and **Process and Product Monitoring**, along with three special emphasis areas, **Long-Term Monitoring**, **Nondestructive Methods**, and **Improved Scientific Understandings**. Summary descriptions and brief Vision Statements are given for each, and **Visible and Important Problems** are identified. A discussion of technology development **Strategies** successfully used by DOE-EM in the past to conquer these challenges completes the **INTRODUCTION**.

PROBLEM AND OPPORTUNITY AREA HIGHLIGHTS provides a more comprehensive description of each major and special emphasis area. These areas are collections of Needs Groups, which in turn are collections of specific Needs directed toward specific FAs. The discussion here presents the variety of challenges to be found in each area, along with a summary discussion of past accomplishments and present activities. Goals for future technology development are proposed as well, both **Near-Term Goals** for technology development needed in the next few years to meet pressing site needs and **Far-Term Goals** for science and technology development for which either the need or a reasonable delivery date will be further in the future.

This Part is augmented by **APPENDIX A: PROBLEM AND OPPORTUNITY AREAS**. This consists of a comprehensive breakdown of each area by type of problem, including a comprehensive listing of specific challenges for each. Although many of these challenges are specific to one Critical Application Area, many also are crosscutting challenges shared by several application areas and multiple DOE and other programs. A listing of near-term and far-term goals is given for each area. Moreover, in many cases a technology solution found for one problem will be adaptable for a related problem; the technology development effort expended in one area can be leveraged to provide solutions in another. Finally, lists of CMM Successes and current and recent DOE-EM R&D projects associated with each area are provided.

SOLUTION PATHS complements the **Strategies** section of the **INTRODUCTION** by discussing various routes which have been found successful over the years in recruiting R&D providers and in providing funding and project management to them. Examples are given using the **VIPs**. Further information is provided in **APPENDIX B: SELECTED VISIBLE AND IMPORTANT PROBLEMS**, in which detailed discussions including suggestions for solution strategies are presented. In some cases the solution strategies are more technically explicit, as where a clear path has been identified and development is already underway. In others the solution strategies are more programmatic; in particular, in some cases the nature of the solution or even of the challenge itself has not yet been fully established.

Funding, of course, is a major factor in addressing these technology development needs. A goal of this ***CMM ROAD MAP for DOE-EM*** is to help keep these R&D Goals and the potential benefits to be attained through achieving the goals visible within DOE-EM when priorities are determined and funding decisions made.

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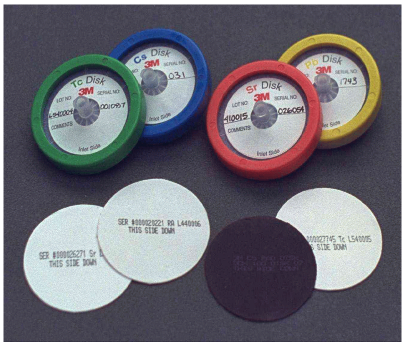

TechID 1514: Rapid Liquid Sampler

ACRONYMS and ABBREVIATIONS

AMSI	Advanced Monitoring Systems Initiative
ASAP	Adaptive Sampling and Analysis Program
ASTM	American Society of Testing Materials
Be	Beryllium
CAA	Critical Application Area
CEM	Continuous Emissions Monitor
CH	Contact-Handled
CMST	Characterization, Monitoring, and Sensor Technology
CMST-CP	Characterization, Monitoring, and Sensor Technology Crosscutting Program
D&D	Deactivation and Decommissioning
DDFA	Deactivation and Decommissioning Focus Area
D/F	Dioxin/Furan
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	(U.S.) Department of Defense
DOE-EM	Department of Energy Office of Environmental Management
DQO	Data/Decision Quality Objective
EIT	Electrical Impedance Tomography
EM-50	Deputy Assistant Secretary for OST
EM-52	Director of the OST Office of Basic and Applied Research
EMSP	Environmental Management Science Program
EN	Electrochemical Noise
EPA	(U.S.) Environmental Protection Agency
ERT	Electrical Resistance Tomography
ESC	Expedited Site Characterization
ESP-CP	Efficient Separations Crosscutting Program
ETV	(EPA) Environmental Technology Verification (Program)
F&D	Function and Design
FA	Focus Area
FDD	Facility Deactivation and Decommissioning
GPS	Global Positioning System
HEPA	High Efficiency Particulate Air (filters)
Hg	Mercury
HLW	High-Level Waste
INDP	Industry and University Programs
INEEL	Idaho National Engineering and Environmental Laboratory
LDR	Land Disposal Restrictions
LIF	Laser-Induced Fluorescence
LIBS	Laser-Induced Breakdown Sspectroscopy
LLW	Low-Level Waste
LOD	Limit Of Detection
LTM	Long-Term Monitoring

MACT	Maximum Achievable Control Technology
MEMS	Micro Electro-Mechanical Sensor
MM	Multiple Metal
MWP	Mixed Waste Processing
MYPP	Multi-Year Program Plan
NDA	Nondestructive Assay
NDE	Nondestructive Evaluation
NETL	National Energy Technology Laboratory
NIOSH	National Institute of Occupations Safety and Health
NO_x	Nitrogen Oxides (primarily Nitrite and Nitrate)
OST	Office of Science and Technology
PCB	Polychlorinated Biphenyl
PEG	Program Execution Guidance
PGNAA	Pulsed Gamma Neutron Activation Analysis
PI	Principal Investigator
PM	Particulate Matter
ppm	parts per million
R&D	Research and Development
RBX-CP	Robotics Crosscutting Program
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
RFP	Request For Proposal
RH	Remote-Handled
SCFA	Subsurface Contaminants Focus Area
SNF	Spent Nuclear Fuel
SRS	Savannah River Site
SSR	Subsurface Characterization and Remediation
STCG	Site Technology Coordinating Group
TFA	Tanks Focus Area
TMFA	TRU and Mixed Waste Focus Area
TPO	Technical Program Officer
TRU	Transuranic (waste)
TTP	Technical Task Plan
TWP	Tank Waste Processing
USGS	U.S. Geological Survey
USDA	U.S. Department of Agriculture
VIP	Visible and Important Problem
VOC	Volatile Organic Compound
WAC	Waste Acceptance Criteria
WNMC	Waste and Nuclear Material Characterization
WTC	Waste Tank Closure
WTI	Waste Tank Integrity
WVDP	West Valley Demonstration Project

APPENDIX A

PROBLEM AND OPPORTUNITY AREAS

Identification of Needs And Technology Gaps

TABLE OF CONTENTS

PROBLEM AND OPPORTUNITY AREAS

Identification of Needs And Technology Gaps

INTRODUCTION

This ***CMM ROAD MAP for DOE-EM*** has identified a number of **Problem and Opportunity Areas**. These have been discussed in general terms so far, with some detailed discussion for selected Visible and Important Problems (**VIPs**). **APPENDIX A** fills out the Problem and Opportunity Area descriptions by enumerating the large variety of challenges DOE-EM must expect to face and by establishing Goals related to those challenges. **Near-Term Goals** should be met within five years or so; **Far-Term Goals** are less urgent, though no less critical.

DOE-EM has already been addressing many of these challenges. Past achievements and current efforts are highlighted in this Appendix. **OST CMM R&D Successes** are associated with each Problem and Opportunity Area; these are technologies and projects previously supported by DOE-EM, many through CMST programs. Each technology has a TechID, which may be used to access information in the DOE-EM OST Technology Management System database (http://ost.em.doe.gov/tms/). **Recent R&D Projects** identify efforts funded recently, identified with the associated DOE-EM OST program or programs[1].

Near-Term Goals and **Far-Term Goals** are identified in this Appendix. These listings, though comprehensive, are not exhaustive. Many of these are fairly broad targets pertinent to several applications. Additional R&D challenges will surely arise in the future. Each Goal is associated with one or more Critical Application Areas[2] (CAAs), as are the challenges themselves; the crosscutting natures of these challenges are identified where appropriate.

One *caveat* is worth repeating. In 1989 DOE-EM set about developing technologies, and has done so with splendid technical success during the past decade. Only recently, however, have firm steps been taken to ensure that these efforts are firmly rooted in DOE site needs and to ensure the transfer of innovative technologies to the appropriate users. These steps, particularly the continuing involvement of site end users in project selection and review, promise to enhance the utilization of technical successes in meeting DOE environmental management and cleanup goals. Technology transfer and acceptance are as essential as technology development itself. One charter CMST program member puts it this way:

> **"Don't misunderstand, as a scientist I am involved with new and better technologies (in much the same way as a cowboy is involved with his horse) and we have been relatively good at developing them, but in terms of succeeding in cleaning up the DOE complex, we have been far less successful. We can work very hard and develop new technologies, but they will go unused unless we do a better job of communicating with the customers, stakeholders, and regulators."**

In recognition of this *caveat*, the Goals include not only challenges that are purely technical, but also some that address desirable achievements in terms of customer, regulator, and stakeholder relations.

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[1]DOE-EM OST Programs include ***TMFA*** (TRU and Mixed Waste Focus Area), ***TFA*** (Tanks Focus Area), ***SCFA*** (Subsurface Contaminants Focus Area); ***DDFA*** (Deactivation and Decommissioning Focus Area), ***NMFA*** (Nuclear Materials Focus Area), ***ESP-CP*** (Efficient Separations Crosscutting Program), ***RBX-CP*** (Robotics Crosscutting Program), ***INDP*** (Industry and University Programs), ***EMSP*** (Environmental Management Science Program), and ***CMST-CP***.

[2]CAAs include ***SCR*** (Subsurface Characterization and Remediation), ***FDD*** (Facility Deactivation and Decommissioning), ***LTM*** (Long-Term Monitoring), ***WNMC*** (Waste and Nuclear Material Characterization), ***WTC*** (Waste Tank Closure), ***WTI*** (Waste Tank Integrity), ***TWP*** (Tank Waste Processing), and ***MWP*** (Mixed Waste Processing).

WASTE, SOURCE, AND NUCLEAR MATERIALS CHARACTERIZATION

The SCFA has identified five steps in cleaning up contaminated areas:

1. **identify** the contaminant nature and extent;
2. **contain** the source to prevent further contamination;
3. **remediate** the problem, *in situ* where possible;
4. **remove** the contamination, otherwise; and
5. **validate** the success of the remediation effort.

Steps 1 and 5 involve challenges shared by all DOE-EM programs. The overall goal is that, once cleanup activities have been completed, DOE-EM should have a strong technical basis for claiming that free-release goals have been met and/or that the closure is complete and stable.

CHARACTERIZATION OF CONTAMINATION SOURCES

One set of specific challenges applies to characterizing contaminant sources and validating the remediation of those sources.

! **Buried wastes**. Waste burial grounds were used at all major DOE sites. Many of these have leaked, contaminating groundwater, soils, and surface water with metals, radionuclides, and hazardous chemicals. Approximately three million cubic meters of solid radioactive and hazardous wastes are located in these burial grounds. The first challenge is to locate and characterize these burial grounds to facilitate their safe and efficient remediation. (***SCR*** - see the listing of CAAs on page viii)

! **Soil contamination.** Facilities, waste disposal pits, storage tanks, and other sources have leaked into the soils at many sites; examples include the transuranics in soils at Rocky Flats and up to two hundred tons of mercury at Oak Ridge. The problem is widespread throughout the DOE complex, with around forty million cubic meters of contaminated soil in all. The challenges are to delineate the location and spatial distribution of contaminants, to estimate the amount of contamination, and to monitor the movement of contaminants in the subsurface, all with an eye to safe and efficient remediation as well as source term containment to prevent migration of contaminants into ground-water. (***SCR***, ***WTC***)

! **Vadose zone contamination.** The vadose zone is the unsaturated zone overlying the water table, ranging in depth from a few feet at humid eastern sites to around three hundred feet at Hanford and more at some arid sites. At Hanford, for example, over three hundred billion gallons of water contaminated with radionuclides were discharged into the ground through settling ponds and other drainage structures, and up to a million gallons of high-level waste is estimated to have leaked from underground storage tanks. Most other sites also have significant amounts of radionuclide, metal, and hazardous chemical vadose zone contamination, leaching downward from the surface as well as from injection wells. The characterization need is the same as with surface soil contamination, except that access to the subsurface soil is more problematic. (***SCR***; also ***WTC***, ***FDD***, ***LTM***)

! **Saturated zone and groundwater contamination.** Groundwater contamination is of particular concern since groundwater can carry contaminants off site. Prompt characterization and contain-ment are particularly important where groundwater contamination is present. The major sites all have contaminated groundwater plumes; some of these have already migrated off site or may be contaminating surface waters. Approximately 1.7 trillion gallons of contaminated groundwater may require remediation. A particularly pernicious problem is groundwater contamination involving DNAPLs; see the following entry. (***SCR***, ***FDD***, ***LTM***)

- **DNAPLs.** Dense Non-Aqueous Phase Liquids (DNAPLs) include man-made organic compounds, typically chlorinated solvents, commonly used in cleaning and degreasing operations. DNAPLs do not flow with groundwater, but tend to accumulate in discrete blobs and ganglia and to sink in water. Some of these are quite toxic and, since their solubility in water is low, can remain a source of contamination for decades or more. Characterization is particularly challenging in hydrogeologically heterogeneous vadose and saturated zones. (***SCR***, ***LTM***)

- **Hot spot removal from landfills and subsurface sources.** Technologies are needed to effectively characterize and remove highly radioactive, explosive, and pyrophoric wastes that pose unacceptable risks to workers during remediation. Technologies that allow on-site characterization of waste to be exhumed and remote retrieval of high-risk waste will reduce the risk to workers. (***SCR***; related to ***FDD*** as well)

- **Facility deactivation and decommissioning.** As surplus DOE facilities are deactivated additional hazardous and/or radioactive waste is generated. The characterization useful for volume reduction of this generated waste can be accomplished most efficiently before structures are demolished. In some cases, careful characterization can support the selective re-use of portions of sites or facilities. (***FDD***)

- **Contamination under buildings and facilities.** Contamination in the vadose zone beneath buildings can present unique characterization challenges. Directional drilling and direct push techniques can be developed in response. (***FDD***, ***SCR***)

- **Remediation verification.** Once remediation has been completed there is the challenge of verifying the cleanup. Alternately, where site characterization identifies portions of a site already meeting free-release standards, these determinations must be verified. haracterization techniques used must be deemed satisfactory for regulatory/legal/stakeholder acceptance. This can present challenges, particularly in the subsurface and in settings with complex geology. (***SCR***, ***WTC***, ***FDD***, ***LTM***)

- **Fate and transport.** There is today an inadequate, though growing, understanding of the characteristics essential to making reliable predictions of contaminant fate and transport in the subsurface and of the chemical, biological, and physical processes that determine the long-term behavior of contaminants. The challenge is to develop these understandings in order to more reliably make closure and long-term monitoring decisions. This challenge is discussed further in the **Improved Scientific Understandings** section to follow. (***SCR***, ***LTM***)

CHARACTERIZATION OF WASTE AND NUCLEAR MATERIALS

Complementary challenges exist in waste and nuclear materials characterization, particularly of high-level waste tank residues, containerized mixed and transuranic (TRU) wastes, nuclear materials, and spent nuclear fuel. Sites currently characterize waste to identify and quantify radioactive and hazardous constituents that may be present, along with other physical and chemical parameters, using a combination of process knowledge, destructive analysis, and nondestructive analysis. The typical baseline methodology is conventional sampling followed by destructive laboratory analysis These methods are often slow and expensive, increase environmental and worker exposure risks, require representative sampling of heterogeneous materials, and generate secondary waste. Hence *in situ* and nondestructive methods are preferred when available; nondestructive methods are discussed in a special emphasis section to follow.

Compliance and waste acceptance criteria require quality assurance (QA) programs. These programs combine waste characterization with process controls and restrictions on treatment and disposal. Performance demonstrations are intended to show that data obtained meet data quality objectives established by DOE to allow proper review of waste treatment and disposal.

The first set of specific challenges presented is motivated by characterizing high-level waste (HLW) in storage tanks at five DOE sites: Hanford, Idaho, Savannah River, Oak Ridge, and West Valley. HLW tank remediation is a major technical and programmatic challenge for DOE. Tank waste processing is accomplished in three steps:

1. waste **retrieval**;
2. waste **pretreatment**; and
3. waste **stabilization**.

Waste chemical and rheological (flow) properties must be characterized to ensure safe storage and retrieval, to reliably plan pretreatment strategies, and to determine appropriate final waste forms. After wastes have been retrieved, tank residues must also be characterized to determine whether final cleanup targets have been met or further treatment is needed. Finally, the stabilized waste forms must be characterized to ensure safe long-term storage. Alternative HLW tank disposition strategies are being considered as well; see the **VIP** "Alternate High-Level Waste Tank Disposition" discussed on pages 14-15 and B.2-4.

Specific challenges related to HLW characterization include the following; there are numerous commonalities with challenges arising in other Focus Areas.

! **High-level waste tank sampling methods.** Methods for characterizing high-level waste tank contents are needed, both for their complex chemical/radiological properties and for physical properties of tank waste slurries which will affect waste pumping and treatment . Sampling challenges arise in all three steps. Retrieval sampling challenges include sampling restricted areas and small staging tanks to see if further cleaning is needed. Pretreatment sampling of heterogeneous waste slurries is needed for immobilization process planning as well as contractual and regulatory compliance verification. Sampling of immobilized waste forms is necessary to verify that processing achieves the intended results. (***TWP***, ***WTC***; similar challenges exist for ***MFP***, ***WNMC***, etc.)

! ***In situ* characterization for HLW tanks.** A related set of challenges has to do with *in situ* characterization for real-time or near-real-time remediation planning or for situations where representative samples cannot be obtained. Gross beta and gamma radiation sensors currently available for surveying tank wastes do not allow determination of separate elements or isotopes and do not detect many transuranic elements. Chemical and rheological properties of tank waste slurries must be measured *in situ*, as these can be heterogeneous with respect to both time and location. (***TWP***, ***WTC***; similar challenges exist for ***FDD***)

! **Validation of analytical methods.** Although baseline laboratory methods exist for nearly all aspects of HLW assay, some are time-consuming, very costly, and/or are not accurate enough. A major need exists for a rapid, cost effective assay of the solids fraction of HLW samples obtained during waste retrieval; normal assay methods can require as long as two months for completion. Other characterization tasks requiring improved technologies are analysis of waste samples for ^{99}Tc and TRU and determination of the liquidus temperatures for waste and glass frit mixtures to support stabilization. (***TWP***; improvement of laboratory methods is a general need)

! **HLW tank integrity.** Final disposition of HLW tanks will take decades at some sites; hence improved methods of characterizing and monitoring storage tank integrity are needed. Single shell tanks (SSTs) at Hanford containing little or no waste should be examined by NDE methods for concrete dome cracks and leaks; if necessary, destructive metallurgical examination of small isolated sections of empty tanks destined for lay-up may provide understanding of the relevant corrosion mechanisms. Regulatory compliance requires life cycle integrity assessments of both the SSTs and double shell tanks (DSTs) at Hanford. Similar requirements and needs apply to HLW tanks at ORR, INEEL, and the WVDP. (***WTI***)

Another set of challenges is related to characterizing mixed low-level (MLL) and transuranic (TRU) waste. The current inventory, approximately 165,000 m^3 of MLL and TRU waste, is distributed among 36 sites. More than 2300 waste streams comprise this inventory, which is heterogeneous both physically and chemically. About 60% is categorized as TRU and packaged in containers ranging from 55-gal drums to larger crates. Most TRU waste is scheduled for disposal at the Waste Isolation Pilot Plant (WIPP).

Characterization of mixed and TRU waste is required to meet DOE site requirements for treatment, storage, transportation, and disposal. The Resource Conservation and Recovery Act (RCRA) and the Atomic Energy Act require that DOE facilities characterize mixed wastes for hazardous and radioactive content and that treatment and disposal facilities require data on their physical and chemical properties.

The current technical baseline for identifying and quantifying RCRA contaminants is sampling coupled with destructive and/or nondestructive analysis; this intrusive analysis serves as the “true value” for that waste stream. To avoid sampling variation, radioactivity contaminants are identified and quantified using a combination of nondestructive assay (NDA) and acceptable knowledge. Recent development of gamma-ray and neutron technologies have reduced total measurement uncertainties to acceptable levels. The gamma-ray technologies include the Segmented Gamma Scanner (SGS), Tomographic Gamma Scanner (TGS), and Active and Passive Computed Tomography (A&PCT); the neutron technologies include the Combined Thermal Epithermal Neutron (CTEN) scans, Imaging Passive and Active Neutron (IPAN) scans, and High Efficiency Neutron Counter (HENC).

These recently developed technologies have received full approval for disposal of contact handled waste at WIPP. While NDA does have uncertainties due to a combination of random and systematic errors, they have been reduced to manageable levels. The use of tomographic techniques, such as A&PCT and TGS, has significantly reduced errors due to matrix interferences and contaminant heterogeneity for both neutron and gamma-ray measurements. Compared with intrusive analysis, NDA reduces or avoids worker exposure, representative sampling problems, unavailability of qualified facilities, delayed analytical results, and high expense.

MLL and TRU waste characterization involves both hazardous and radioactive constituents. Hazardous constituent characterization will identify and quantify RCRA constituents and the physical and chemical properties potentially affecting treatment operations. Subdividing hazardous waste into debris and sludges leads to characterization of the former by alternative oxidation treatment acceptance criteria and the latter by WIPP acceptance criteria. Division of radioactive contaminants into contact-handled and remote-handled waste affects the manner in which the high background levels associated with the latter will affect the selection of measurement techniques. Further division into container size affects both handling techniques, where uncertainties tend to follow container size.

Work on contact-handled (CH) waste has focused on developing solutions for material contained in 55 and 83 gallon drums, where advanced gamma-ray (TGS, A&PCT) and neutron (CTEN, HENC) techniques have been shown to be very effective at reducing characterization uncertainties for most waste streams; dense sludges may still prove to be a problem. Assays of waste boxes have also been addressed by issuing a Request for Proposals (RFP) for the design and development of a mobile system that can be deployed to different DOE sites.

For remote-handled (RH) waste, work has focused on two solutions: gamma-ray spectroscopy combined with acceptable knowledge (GSAK) and multi-detector assay (MDAS). With GSAK, direct measurements of Pu and U are precluded by the presence of high intensity fission products such as ^{137}Cs. As a result, the analyses depend on measurements of fission products and relationships between them and the operating history of the reactor (the acceptable knowledge portion). MDAS is still in the research stage.

Additional challenges arise in characterizing wastes and nuclear materials now stored or to be generated by sources other than HLW tanks, including wastes to be generated during remediation activities and wastes to be subject to sorting for volume reduction. Specific challenges include the following; these inevitably overlap with characterization needs arising in HLW tank remediation.

- **Mixed and TRU waste characterization related to treatment, storage, transportation, and disposal requirements.** Site and other requirements for the handling of mixed and TRU wastes include stringent characterization. Technology and methodology development are needed to meet these requirements, particularly in the case of remote-handled wastes. (***MWP***, ***TWP***, ***WNMC***)

- **Wastes generated by remediation efforts.** New wastes will be generated during soil and groundwater remediation as well as facility deactivation and decommissioning. These wastes must be characterized, handled, and disposed of. The long-term consequences of remediation decisions with respect to the volume and types of wastes generated should be considered in planning remediation activities. (***FDD***, ***WTC***, ***SCR***)

- **Volume reduction.** More efficient methods can be developed for segregating wastes, including wastes generated during remediation activities, to reduce the volume destined for high-level and low-level waste disposal facilities. The characterization challenges are to determine the make-up and heterogeneity of the wastes to efficiently pursue this objective and to verify the successful segregation of the wastes once the process is complete. (***MWP***, ***FDD***, ***SCR***, ***TWP***)

- **Containerized wastes and nuclear materials, including spent nuclear fuel.** Better methods for characterizing containerized wastes should be developed, including non-intrusive methods which do not require opening containers as well as techniques suitable for remote-handled containerized wastes. Three specific challenges are the assay of amounts and types of nuclear materials present, the moisture content of the container (related to the hydrogen generation potential), and the in-container hydrogen generation activity itself. The latter two are critical to container safety determinations with respect to certain radionuclides. (***MWP***, ***WNMC***, ***LTM***)

- **Characterization of orphan wastes.** These wastes do not fall into standard categories. There may be relatively small quantities of orphan wastes at any individual site, but the total amount becomes non-negligible across the entire DOE complex. The challenges are to develop technically sound protocols acceptable to regulators for characterizing such wastes prior to stabilization and disposal. (***MWP***, ***WNMC***)

- **Waste characterization standards and sampling methods.** Standards and waste surrogates must be developed to support waste characterization. Remote sampling and analysis methods need to be developed to reduce hazards, such as those encountered in headspace gas analysis for containerized waste and exposure to radioactivity. (***MWP***, ***others***; closely related to ***WTC*** *in situ* characterization challenges)

- **Durability of waste forms.** Measurement methods are needed to enhance research aimed at fundamental understanding of waste form durability and degradation. This should be a collaborative effort with EPA, NRC, and the scientific community. Clear requirements for long-term performance testing of final waste forms for the disposal of mixed waste must be developed in consensus with EPA and NRC to minimize the risks associated with deploying technologies now which may later judged inadequate. (***MWP***, ***TWP***, ***others***)

- **Vitrified and calcined wastes and nuclear materials.** The ultimate disposal form for many wastes and other nuclear materials will be glasses and/or ceramics. Calcined wastes will be stabilized in a more stable form. More efficient methods for verifying the content of such vitrified and calcined materials should be developed, preferably on-site rapid turn-around methods that will also support real-time process control. (***MWP***, ***WNMC***, ***TWP***)

THE DEACTIVATION AND DECOMMISSIONING FREE RELEASE GOAL

The DOE has constructed over 20,000 facilities to support nuclear weapons production and other activities, many of which are contaminated with radioactive and hazardous materials. Many of these facilities no longer serve a mission for DOE. Monitoring and maintenance activities are required because of the potential for release of radioactive and hazardous materials and the risk of industrial safety accidents. DOE plans to deactivate and decommission excess facilities to reduce risks and costs.

Accurate characterization of the nature and extent of contaminants can dramatically reduce the amount of material ultimately subject to treatment before disposal. Moreover, treatment options depend on accurate representations of the distributions and concentrations of contaminants. Real-time control and optimization of waste treatment systems can be accomplished only if reliable, real-time monitors are available, enabling continuous monitoring and adjustments for changing waste conditions. Sensitive, reliable sensors and monitoring programs will be critical to protecting public health and assuring the necessary high confidence level in engineered solutions.

Off-site laboratory analysis of samples persists as the primary mode of analysis for site characterization, waste characterization, and process monitoring, because it is reliable and accepted by regulatory agencies in spite of its cost and inherent time delays. Real-time *in situ* characterization sensors and monitors, once accepted by regulators, promise to provide substantial cost and schedule savings compared to current practice. Moreover, characterization tools capable of detecting contaminants down to free release levels on facility materials, equipment, and containers, as well as during waste segregation, will provide dramatic cost savings from minimizing the amount of material to be disposed of and maximizing the material released for recycle or reuse. This application anticipates using these tools in an on-going fashion during facility D&D as well as for initial and final characterization.

During the next decade DOE-EM should develop the capability to quantitatively characterize any residual wastes that remain in any DOE facility once clean-up operations have been completed. The magnitude of this challenge alone demands the development of real-time *in situ* methods.

One set of specific challenges relates to facility, equipment, and container characterization.

! **Facility and equipment triage.** Improvements in characterization are needed to enable quick and easy differentiation between contaminated and non-contaminated concrete, metal structures, and process equipment in order to improve D&D efficiency. Characterization technologies are needed that can quickly and conclusively determine the type of contamination, the cross-sectional profile of the volumetric contamination, and the amount of contamination on and in concrete and metal. New characterization technologies should be able to measure contamination down to the site free-release levels on a contaminant-by-contaminant basis.

  Characterization and survey tasks will continue to be burdened by the need for outside assistance with their inevitable schedule delays, and excessive and destructive volumetric sampling will continue to be the standard practice, until reliable field-tested and field-verified methods are developed and become available. (***FDD***)

! **Containerized materials.** Improvements are needed also in waste characterization to quickly assay containerized materials in order to improve the overall efficiency of a D&D activity. Since there are a multitude of container sizes and geometries in use across the DOE complex, container assay technologies are needed that are adaptable to these requirements for widespread deployment. The new characterization technology should be able to determine the assay value of materials within differently shaped containers down to free-release limits. (***FDD***; also related to ***WNMC***)

Another set of specific challenges is associated with volume reduction during D&D activities.

- **Waste segregation.** Accurate characterization of radioactive contamination is needed to distinguish between low-level waste and free-release waste. Hazardous material (solvents, oils, etc.) characterization ties directly into meeting RCRA requirements, and toxic substance (PCBs, asbestos, etc.) characterization directly ties into meeting TSCA requirements.

  As buildings are emptied for demolition, cost-effective and certifiable techniques are desired to rapidly characterize and identify non-contaminated excess equipment so that it can be segregated for free release and ultimate property disposition. Ideally, new techniques will be capable of detecting contamination contained within interior spaces that are either inaccessible or difficult to access, in complex shaped equipment, and under painted surfaces. Significant cost savings are expected through disposal cost avoidance by recycling and reusing the radioactive fraction (e.g., waste containers and shielding) and through decontamination for reuse. (***FDD***)

Another set of specific challenges is related to the characterization of remote and difficult areas. Technologies are needed for remote access and deployment of equipment and tools throughout contaminated facilities at many DOE sites. Within the complex structures at DOE sites some areas cannot be reached using conventional methods or personnel. Remotely operated systems are needed for nearly every aspect of deactivation and decommissioning (D&D), including entry, sample collection, deployment of sensor packages and characterization tools, size reduction, dismantlement, void space filling, and waste emplacement.

Characterization technologies capable of verifying the existence or absence of contamination in process piping, drain lines, wall cavities, and ventilation ducts are needed. These should measure contamination to unrestricted release levels with field-deployable, real-time characterization and sampling equipment. Remote technologies will often need to function in a highly radioactive environment and in the presence of process chemicals, acids, and caustic solutions. Long-term deployments will be required in areas such as tunnels and drainpipes. Less lengthy deployments may be appropriate in highly congested areas such as hot cells.

Specific challenges in D&D characterization of remote and difficult areas include the following:

- **Characterization of inaccessible areas.** Presently this is usually effected through brute force: significant portions of a facility or system are dismantled in order to adequately sample, analyze, and verify the cleanliness of a pipe, drain line, cavity, or ventilation duct. Quickly and definitively determining the status of such areas could significantly reduce dismantlement. A non-intrusive, nondestructive approach could leave the inspected facility with enough of its piping and ventilation ducts in place to be considered for reuse. New methods of characterizing small bore pipes and ventilation ducts, if successful, will allow less dismantlement and decontamination work, fewer drain line pulls, less flushing, and less secondary waste generation.

  Of particular concern for many DOE buildings are drain lines that may have carried radioactive effluent. In order to abandon, continue using, remediate, or exhume these lines, it is necessary to know if they contain residual contamination above release levels and if the integrity of the lines has been compromised allowing radioactive contamination of surrounding soils before proceeding with remediation. This becomes extremely important with drain lines intended for continued use in an occupied building and/or impossible to access physically without extraordinary expense and loss of time. (***FDD***)

- **Robotic devices.** Robotic devices to traverse underground pipe lines for *in situ* characterization and observation are needed. They must be integrated with characterization technologies capable of providing quantitative or semi-quantitative radioactive isotopic analysis of contamination within and outside the buried drain, as well as visual observations to assess line integrity. The information obtained must be sufficient to support decisions on remediation necessity and methodology. (***FDD***)

REGULATOR AND STAKEHOLDER RELATIONS

This is an area of concern for CMST development that can have a major impact on DOE environmental management and cleanup decisions and strategies. It is not itself necessarily an area of technology development; nonetheless, the quality of communication between DOE problem solvers and the regulatory and stakeholder communities can have substantial effects either for or against deployment of efficient innovative technologies. It is important that communication among involved parties be maintained and continually improved in order to reap all of the benefits of which DOE-EM CMM R&D is capable.

- **Ensuring compliance with waste acceptance criteria.** A non-negligible aspect of DOE waste processing, stabilization, transportation, and storage is the need to ensure that wastes generated will meet waste acceptance criteria of repositories such as WIPP, and moreover to establish routine methods for demonstrating that wastes meet the criteria. (***All programs***)

- **Evolving regulatory standards.** There is a fundamental need to demonstrate the validity of proposed characterization and monitoring methods. Where characterization is for ultimate disposal, as with vitrified wastes, or involves significant safety or public policy issues, the validity demonstration should be developed with stakeholder and regulatory involvement. Regulatory requirements and stakeholder expectations can present a challenging moving target; DOE-EM must keep this in mind and develop strategies for meeting these requirements. (***All programs***)

Selected Near-Term Goals

Improve and expand direct push capabilities to minimize the need for drilling while characterizing contamination in the subsurface and in waste tank farms; benefits include lower costs, greater data density, accelerated schedules, and minimization of secondary wastes.

Improve methods and analytical devices for determining the distribution of DNAPLs, radionuclides, heavy metals, high explosives, and pyrophoric compounds in the subsurface; benefits include lower costs and schedule acceleration resulting from more precise contaminant characterization.

Improve and expand capabilities for characterization beneath structures; benefits include more reliable determination of safety and remediation requirements and long-term monitoring needs.

Improve sampling technology for characterizing deep plumes; benefits include cost reduction and schedule acceleration as well as improved information on which to base closure and long-term stewardship decisions.

Improve methods for hydrogeological characterization of flow and transport; benefits include cost reduction through efficiencies in the design of monitoring systems.

Improve and validate geophysical methods for determining the spatial distribution of contaminants in the subsurface, since borings and direct push measurements are inherently restricted in spatial density; benefits include more accurate remediation planning, reduced characterization costs, and more reliable planning for closure or long-term monitoring.

Improve tomographic NDA/NDE and other characterization systems for containerized wastes; benefits include reduction in cost and exposure risk associated with handling containerized materials and waste.

Develop methods for *in situ* detection of contamination on surfaces and in inaccessible areas down to free-release goals; benefits include cost and schedule savings as well as volume reduction.

Develop robotic deployment platforms for characterization sensors; benefits include cost savings, volume reduction, exposure risk reduction, schedule acceleration, and reduced dismantlement of potentially reusable facilities.

Develop improved analytical methods to supplant laboratory procedures that are too slow, costly, or inaccurate; adapt and engineer *in situ* characterization techniques for HLW tank applications; obtain regulatory approval for innovative technologies.

Develop better methods for evaluating waste tank integrity and monitoring corrosion control aspects of waste tank chemistry; benefits include avoidance of costs and exposure risks associated with potentially catastrophic events, avoidance of further leakage from tanks, and regulatory compliance.

Develop better methods for evaluating waste form content, durability, and degradation; benefits include greater confidence in long-term disposal methods and avoidance of costs associated with repeating remedial activities.

Develop *in situ*, real-time sensors for characterizing and monitoring distributions and concentrations of lead paint, low energy gamma-emitting radionuclides (thorium and plutonium), alloy constituency, PCBs, and general radioactive and hazardous materials in facilities slated for D&D; benefits include cost avoidance, schedule acceleration, and improved worker safety and efficiency.

Selected Far-Term Goals

Improve methods for characterizing physical, chemical, and biological properties of the subsurface, particularly in deep, complex, and heterogeneous geologic settings, using both direct observation as well as indirect geophysical techniques; benefits include improved ability to model subsurface processes in support of remediation method selection and long-term stewardship decisions.

Develop flexible data integration methods capable of utilizing data from various sensors obtained on different temporal and spatial scales to better estimate contaminant and subsurface properties and processes, along with ways of integrating such data into conceptual models; benefits include more efficient use of monitoring resources.

In general, develop the capability to characterize and quantify any residual waste which remains in any DOE facility after cleanup activities are completed; benefits include reliable accountability to regulators, stakeholders, and the public in general.

See also Goals in the **Long-Term Monitoring** and **Improved Scientific Understandings** sections.

OST CMM R&D Successes

Associated Particle Imaging (413) for nonintrusive characterization of sealed containers
Sol-Gel Indicators (634) for quick screening for uranium, mercury, and certain organics
Laser Ablation/Mass Spectroscopy for Tank Waste Core Samples (127)
Near-Infrared Spectroscopy for In-Tank Waste Characterization (86)
Topographic Mapping System (130) for estimating tank waste inventory
Electrochemical Noise Corrosion Monitor System (1985)
Raman Probe and neural net software for tank chemistry monitoring (189, 1544)
Vadose Zone Characterization System (2118) for tank farms
PLUME - Groundwater Modeling (733) software for groundwater modeling
Hydrogeologic Data Fusion (2944) software
Adaptive Sampling and Analysis Programs (ASAPs) (2946) for site investigations
Rapid Geophysical Surveyor (1995)
Electrical Resistance Tomography for Subsurface Imaging (17, 284, 2120)
Ground Penetrating Radar (1148) for nonintrusive geophysical investigations
Crosshole Seismic Imaging (588) for subsurface hydrological characterization
Cone Penetrometer with numerous enhancements and sensors (243, with 141, 307, 381, 489, 1723, 2364, 2399, etc.) for rapid efficient subsurface measurements
Wireline Cone Penetrometer (2222) for enhancing CPT flexibility
Rapid Liquid Samplers (1514) for groundwater measurements of Pb, Tc, Ra, Sr, Pu, U etc.
Beta-Scint Fiber-Optic Sensor (70) for real-time, *in situ* soil and facility beta measurements
RCRA Metals Analysis by LIB Spectroscopy (434) for real-time metals measurements in soils
X-Ray Fluorescence Spectroscopy (622) for downhole detection of metals and radionuclides
Long Range Alpha Detector (596, 681) for detecting uranium on soils and facilities
LIBS Sensors for Heavy Metals (319) for CPT screening for heavy metals
Miniaturized Chemical Flow Probe Sensors (218) for real-time measurements
Cold Wringer (2105) for on-site tritium analyses
Surface Acoustic Wave Array Detectors (16, 282) for incorporation into real-time portable measurement tools for VOCs and other constituents
Direct Sampling Ion Trap Mass Spectrometer (69) for near real-time GW and soil gas VOCs
Innovative DNAPL Characterization Toolbox (237 with 2237, 2238, 2949, 2950, etc.)
Field Raman Spectrograph (873) for downhole identification and quantitation of organics
HaloSnif^{TM} Fiber-Optic Spectrochemical Sensor (103) for vadose zone chlorinated organics
RCL Monitor (313) for on-site analyses of soil gases for chlorinated organics
Coherent Laser Vision System (94) for accurate topographic analysis and recording
Environmental Measurement While Drilling (8) for gamma, location, and other quantities
Directional Drilling Locating Device (POLO) (316)
Hybrid Directional Boring and Horizontal Logging (650)
ResonantSonic^{SM} Drilling (55)
StrataSampler^{TM} (3106) for multilevel sampling
Surface Towed Ordnance Locator System (548) for magnetically locating drums etc.
In Situ Permeable Flow Sensor (99) for determining subsurface characteristics
Advanced Tensiometer (2122; also 647) for vadose zone surface tension measurements
Integrated Suite for Delineating Soil Contamination (2157, 2361, 2362)
Portable X-Ray, K-Edge Heavy Metal Detector (134) for non-intrusive char. of pipes and ducts
Pipe Explore^{rTM} (74) for characterization of radioactive contamination inside pipes and ducts
Drain Line Characterization Robot (2328) for pipelines and inaccessible locations
Ground-Based Laser Induced Fluorescence Imaging (1999) for real-time rad measurements
X-Ray Fluorescence Metal Analyzer (2001) for real-time portable analysis of metal alloys
Three-Dimensional Integrated Characterization and Archival System (3D ICAS) (97)
In Situ Object Counting System (ISOCS) (2098) for remote gamma spectroscopy of regions

Recent R&D Projects

Combining Gamma Spectroscopy with Acceptable Knowledge (***TMFA***)
Multiple Detector Analysis System (MDAS) (***TMFA***)
Transuranic Optimized Measurement System (***TMFA***)
Microsensors for *In Situ* Chemical, Physical, and Radiological
Mixed Waste Characterization (***EMSP***)
Integrated Raman EN Sensor for In-Tank Corrosion Chemistry Monitoring (***TFA & CMST-CP***)
for ensuring storage tank integrity
Electrochemical Noise Corrosion Monitor System (***TFA***)
Non-Invasive Diagnostics for Measuring Physical Properties and Processes in HLW (***EMSP***)
Actinide-Aluminate Speciation in Alkaline Radioactive Waste (***EMSP***)
Detection and Characterization of Chemicals Present in Tank Waste (***EMSP***)
Optical and Microcantilever Sensors for Real-Time *In Situ* Characterization of HLW (***EMSP***)
The Effect of Temperature and Electrolytic Concentrations on Actinide Selection in HLW (***EMSP***)
Characterization of Actinides in Simulated Alkaline HLW Sludges and Leach Solutions (***EMSP***)
Mass Spectrometer Fingerprinting of HLW Using Tunable, Ultrafast Infrared Lasers (***EMSP***)
Hybrid MEM Systems for Highly Reliable, Selective HLW Characterization (***EMSP***)
Comparative Evaluation of Geophysical Methods (***SCFA & CMST-CP***) for DNAPL delineation
Basic Research into Electromagnetic Methods for Non-Intrusive Subsurface Imaging (***EMSP***)
Complex Electrical Resistivity for Monitoring DNAPL Contamination (***EMSP***)
Advanced High Resolution Seismic Imaging, Material Properties Estimation, and Full Wavelength
Inversion for the Shallow Subsurface (***EMSP***)
High Frequency Electromagnetic Impedence for Characterization, Monitoring, and Verification
Efforts and for Vadose Zone and Groundwater Characterization (***EMSP***)
DNAPL Detection at Depth and/or in Difficult Settings (***SCFA***)
Automating Shallow Seismic Imaging (***EMSP***)
DNAPL Characterization Method Development (***SCFA & CMST-CP***)
DNAPL Detection Using Integrated Ground-Penetrating Radar Analyses (***EMSP***)
Non-Invasive DNAPL Location by Seismic Reflection ***(INDP***)
Cone Penetrometer Off Surface Sensor (***SCFA***)
Novel Hotpoint DNAPL Detector for Subsurface Analyses (***SCFA***)
Sensitive Detection of Toxic Chlorinated Compounds (***INDP***)
Novel Optical Schemes for *In Situ* Mapping of CVOCs in the Vadose Zone (***EMSP***)
The Use of Radar Methods to Determine Moisture Content in the Vadose Zone (***EMSP***)
Gamma Ray Imaging for Environmental Remediation (GRIER) (***EMSP***)
JCCEM Contaminant Transport and Modeling Studies (***SCFA & CMST-CP***)
Cone Penetrometer Sensor Development (***SCFA & CMST-CP***)
In Situ Tritium Monitor for Difficult Conditions (***SCFA***)
In Situ Sensors for Detecting Metals and Radionuclides in the Subsurface (***SCFA***)
Xenon Ionization Detector for CP (***INDP***)
Metal Ion Analysis Using Near-Infrared Dyes and the "Laboratory-on-a-Chip" (***EMSP***)
Specialized Separations Using 3M Membrane Technology (***INDP, SCFA & CMST-CP***, ***ESP-CP***)
Integrated Suite for Delineating Soil Contamination (***SCFA***)
Implementation of the MARSSIM Process at BGRR, NTS, and elsewhere (***DDFA***)
3-D Integrated Characterization and Archiving System (***DDFA & INDP***)
TRU Waste Characterization & Decontamination (***DDFA***)
Measurement of Radon, Thoron, Isotopic Uranium, and Thorium to determine Occupational and
Environmental Exposure at Fernald (***EMSP***)
Beryllium Surface and Air Monitor (***DDFA & CMST-CP***) for facility D&D
Real-Time Identification and Characterization of Asbestos and Concrete Materials with
Radioactive Contamination (***EMSP***)
Three-Dimensional Position-Sensitive Germanium Detectors (***EMSP***)
Metal Ion Analysis Using Near-Infrared Dyes and the "Laboratory-on-a-Chip" (***EMSP***)
In Situ Characterization of Actinides and Technetium via Fiberoptic Surface Enhanced Raman
Spectroscopy (SERS) (***EMSP***)
Miniature Chemical Sensor Combining Molecular Recognition and Evanescent-Wave
Cavity Ring-Down Spectroscopy (***EMSP***)

See also entries under **Nondestructive Methods**.

PROCESS AND PRODUCT MONITORING

Monitoring is the use of repeated measurements to detect and quantify changes across time. In many situations monitoring measurements do not need to meet the same stringent accuracy and precision requirements as some types of characterization and remediation verification measurements. As a trade-off, there can be great advantages to monitoring measurements performed on-site and even *in situ* (in place) in real time. These advantages include (a) immediate feedback for process control, (b) avoidance of sample handling with attendant risks and costs, and (c) avoidance of secondary wastes.

Processes that convert waste, nuclear materials, and contaminated materials into products that can be stored safely for the long term, and processes that restore site environments to a more pristine state are important elements of the DOE environmental management and cleanup mission. Needs for better process control have been identified by each focus area. An important aspect of process improvement is the application of better process control methods so that efficiency can be improved and products can be monitored in real time for compliance with specifications. Process control often involves monitoring similar chemical, radiological, and physical parameters, even for processes designed to achieve different goals such as decontamination, waste treatment, or materials stabilization. Development of improved process control methods to meet these similar control requirements is a major crosscutting activity.

HIGH-LEVEL TANK WASTE PROCESSING

High-level radioactive waste tank remediation is a major technical and programmatic challenge for DOE. The DOE currently stores about 340 million liters of waste containing more than 700 million Curies of radiation in 282 tanks at five major sites. These wastes are heterogeneous, both chemically and physically, between sites, between tanks on a given site, and even between phases of waste within a tank. To protect the public, workers, and the environment, this radioactive waste must be stored safely, retrieved from the tanks, and converted to a form appropriate for long-term disposal. The DOE has signed Federal Facility Agreements with State and Federal regulators that drive the scope and schedule for cleanup and closure of the tanks. The life-cycle cost for high-level waste (HLW) remediation has been estimated as $47B.

Tank waste processing involves three stages: waste retrieval, pretreatment, and stabilization. CMST-CP has collaborated with TFA to develop process monitors for all areas. Efforts include core development activities directed toward immediate needs, applied research activities relevant to needs requiring near-term deployments, and strategic research intended to solve problems requiring far-term solutions.

Specific challenges stemming from tank waste processing include the following:

! **Monitoring for waste retrieval.** Liquid wastes must be pumped from their present storage tanks to interim storage or staging tanks for pretreatment or stabilization. Solid waste in the tanks must be slurried so it can be transported as a solid/liquid suspension. Transport of liquid and slurries through transfer pipelines requires monitoring to avoid pipeline blockage, to regulate the solids content, and to detect possible tank leakage during transfer. Moreover, it is important to monitor physical and chemical properties of the waste stream both in the tank during slurry operations and during waste transport, as knowledge of physical and chemical composition is needed to control the proper blending of wastes fed to pretreatment and stabilization processes.

  Methods to monitor waste density and weight percent solids are at the core development stage. Monitoring of a solid-liquid separation process has already been demonstrated at the Oak Ridge Reservation (ORR). A system based on dual commercial density process monitors is being developed for in-tank deployment as early as FY 2002.

  At the applied research stage, plans are being made to support waste transport and mixing via deployment of both density solids monitors and monitors for flow velocity and viscosity at Hanford by 2005. The need for chemical composition monitors is also under evaluation as a site need. As new methods to slurry waste are developed, new process monitoring needs are expected to arise. (***TWP***)

! **Monitoring of tank waste pretreatment processes.** Pretreatment processing is critical to reducing the volume of high-level waste (HLW) and low-level waste (LLW) products in order to reduce disposal costs. Investments include clarifying liquid streams through solid-liquid separations, supernate processing to remove selected radionuclides, and sludge processing to remove excess chemical species that either increase the HLW volume or adversely impact the performance of the HLW immobilization process and final waste form. Methods are required to monitor chemical conditions to prevent gelation during sludge washing, to monitor the removal of radionuclides such as cesium, strontium, and technetium, and to verify that feedstock is within specifications for the stabilization processes.

The need to monitor radionuclides in liquid process streams is at the core level; function and design requirements have been formulated and conceptual designs created. Customized commercial process monitoring systems are expected to meet these needs on a short-term basis. Other pretreatment processes are less well defined; the development of control methods for them falls in the applied and strategic development regimes. (***TWP***; also related to ***MWP***, ***WNMC***)

! **Monitoring of tank waste stabilization processes.** One option for tank waste disposal is stabilization for safe storage. Current process control methods for HLW glass production require precise characterization and control of all materials added to the glass melter on a batch-by-batch basis. This feed-forward control scheme is effective but time-consuming; hence waste throughput rates are limited. Higher process efficiencies will be possible using improved on-line monitoring and feedback control mechanisms; development of these improvements is anticipated in conjunction with the fabrication of new and replacement melter systems. Technologies required include measurement methods for melt temperature and viscosity as well as on-line monitors for feedstock chemical composition.

Low level or low activity waste (LLW or LAW) fractions that remain will be stabilized in grout, saltstone, or other solid materials for disposal at site LLW repositories. One emerging challenge is the detection of separate phase layers of molten sulfur in process melters. Separate organic phases must also be detected to avoid adversely affecting the pretreatment processes.

Another need emerging in connection with tank waste treatment is that of monitoring any gases emitted during stabilization process and other thermal treatment processes. Additional technical needs are expected to arise as other stabilization system designs are produced for LLW and for the calcined waste at INEEL. These needs are not specific to tank waste, but are also found in the treatment and stabilization of mixed and TRU wastes and nuclear materials. (***TWP***; also ***MWP***)

MIXED AND MIXED TRU WASTE TREATMENT

The next set of specific challenges involves the treatment and disposal of mixed wastes generated by past DOE operations and current cleanup activities. Mixed wastes contain both radioactive and hazardous constituents, the latter consisting primarily of heavy metals such as mercury, cadmium, lead, arsenic, beryllium, and chromium as well as organic constituents such as solvents. TRU wastes contain transuranic elements. The Best Demonstrated Available Technology (BDAT) for the destruction of organically contaminated mixed waste is incineration. In response to concerns voiced by DOE end users, stakeholders, and regulators over potentially hazardous effluents, however, alternate treatment technologies such as chemical oxidation are being developed. Both incineration (thermal treatment) and non-thermal, non-flame alternatives require effluent and process monitoring. This re-prioritization requires the development of appropriate monitoring systems; this is a natural extension of prior off-gas continuous emissions monitor (CEM) technology development activities. Improved detection capability and data quality are required for comprehensive data analysis and modeling in order to work effectively with regulatory bodies in permitting new treatment processes.

One particular area of concern is the formation of hazardous air pollutants (HAPs), particularly poly-chlorinated dibenzodioxins (dioxins) and polychlorinated dibenzofurans (furans), during both thermal and non-thermal oxidation of chlorinated organic compounds. Current research is underway to further the understanding of the mechanisms and conditions which lead to the formation of these compounds, so that those conditions can be avoided. Measurement challenges exist both for these dioxin/furan formation studies and for subsequent monitoring of treatment processes intended to eliminate HAP formation.

Sorting TRU and TRU/MW for treatment, stabilization, or disposal requires process technologies with accurate characterization to minimize waste volumes and costs. Imbedded tags for waste containers may be required for public acceptance, maintenance of acceptable knowledge records, identification, tracing, or warning purposes. For safety, remote automated monitoring systems must continually track container environmental conditions. Advanced real-time data analysis, visualization, and reporting software with alert/warning features must be implemented. Accurate inventories and monitoring must provide verifiable data for national safeguard, security, and public and ecological stewardship.

! **Effluent monitors for alternatives to oxidation.** Real-time, accurate measurement technologies for waste treatment effluent monitoring are required to alleviate health and safety and regulatory concerns. The U.S. Environmental Protection Agency (EPA) regulates emissions of HAPs including the heavy metals, particulate matter, organics (including dioxins and furans formed during thermal treatment), and chlorine and hydrogen chloride gases. The EPA Maximum Achievable Control Technology (MACT) for Hazardous Waste Combustors Rule impacts the operation of DOE thermal treatment facilities. Comparable emissions monitoring technologies will need to be developed and verified in order for alternative mixed low-level and transuranic waste treatment technologies to be approvable under EPA regulation. (***MWP***)

! **Continuous emissions monitors.** Increasingly strict regulatory standards and increasing public concerns require operators of mixed waste treatment facilities to control air emissions to unprece-dented low levels and to provide ongoing assurance through monitoring that emissions controls are effective. In particular, continuous emissions monitoring and control will be required more extensively. To support stakeholder acceptance and regulatory compliance, monitors will need to be tested and verified thoroughly before installation and appropriate quality assurance plans will need to be implemented. (***MWP***, ***TWP***)

! **Monitors for improved and emerging control technologies.** Monitoring of control systems, such as High Efficiency Particulate Air (HEPA) filtration systems, must keep pace with advancing technologies and promote more efficient operation. This includes quality assurance plans that have calibration standards available. In addition, new instrumentation (such as cavity ring down spectroscopy systems) and components (such as lasers, spectrometers, and sampling systems) must be tracked and integrated into DOE site and facility measurement system operations. (***MWP*** and others)

! **Studies of Hazardous Air Pollutant (HAP) formation and destruction.** Mechanistic studies are required for better understanding of the mechanisms of HAP (particularly dioxin and furan) formation and destruction during processing using both thermal and non-thermal treatment technologies. These studies can significantly influence control strategies and effluent monitoring requirements under emerging regulation. Joint efforts by DOE, EPA, and industry and university researchers are required, as are pilot plant testing facilities. (***MWP***)

! **Remote automated monitoring systems for remote handled wastes.** In addition to NDA and NDE required for analysis and inventory control of remote handled wastes, discussed in the **NONDESTRUCTIVE METHODS** section, remote automated systems are needed to monitor waste integrity and environmental conditions. Data systems must provide reliable data for identification, historical information, inventories, and safeguards. (***MWP***, ***WNMC***, ***others***)

WASTE AND NUCLEAR MATERIAL STABILIZATION

Monitoring needs described previously for high-level tank waste stabilization apply also to mixed wastes, transuranic wastes, and nuclear materials. Once the organic constituents have been removed, the residues will contain radioactive constituents and possibly hazardous metals and other constituents as well. These residues must be prepared for long-term disposal. Moreover, DOE sites possess extremely valuable inventories of nuclear materials that should be preserved for future use. Stabilization processes apply to each of these, generating crosscutting process monitoring needs. Specific needs include the following.

- **Monitoring stabilization processes for radioactive wastes and nuclear materials.** This need is quite similar to that described previously for tank waste stabilization. For nuclear materials there is an enhanced need for process control to ensure the quality and consistency of the stabilized form so that desired valuable materials may be retrieved reliably when desired. (***MWP***; see previous ***TFA*** discussion)

- **Monitoring container integrity for nuclear materials and spent nuclear fuels.** Sensors and monitoring programs for NM and SNF canisters are needed; automated non-invasive systems are highly desirable. (***NMFA***; see related ***WTI*** needs)

- **Inventory control of nuclear materials.** In addition, challenges in inventory control will arise with nuclear materials stabilized for future use. Ideal monitoring methods will involve nondestructive assay (NDA), and is likely to involve robotic interfaces as well. (***WNMC***)

MONITORING OF SOIL AND GROUNDWATER REMEDIATION

Many soil and groundwater remediation processes are being and will be used at DOE sites. These range from simple removal of contaminated surface soil for off-site disposal to sophisticated techniques such as *in situ* destruction of DNAPLs and bioremediation. Opportunities for cost and schedule savings and risk reduction may be found through implementing advanced monitoring techniques in conjunction with many of these processes. These needs complement the improved characterization needs discussed previously; indeed, many technology needs expressed by the Site Technology Coordinating Groups (STCGs) are related to both characterization and monitoring.

Specific needs applicable to subsurface remediation processes include the following:

- **Real-time determination of radionuclide distributions in soils.** Real-time determinations can allow real-time remediation decisions, reducing the volume of soils treated or excavated and hence reducing costs and enhancing schedules. Techniques applicable to this challenge may often be similar to techniques useful in monitoring facility decontamination. (***SCR***; also ***FDD***)

- **Real-time delineation of DNAPL and other contaminant plumes.** Once the initial boundaries and nature of contaminant plume have been established, it may be possible to utilize less expensive and sometimes non-invasive sensors to determine changes in the plume. (***SCR***; also ***WTC***)

- **Real-time monitoring of *in situ* remediation techniques.** Some of the more innovative subsurface DNAPL treatment technologies involve *in situ* oxidation using heat (steam), chemical treatment, or enhanced natural biological processes. The progress of such treatments must be monitored to ensure that they are being applied to the desired target region and to verify their effectiveness. The challenge for both treatment and monitoring is due to the essential sparsity of locations actually accessed directly in the subsurface. (***SCR***)

MONITORING OF FACILITY DEACTIVATION AND DECOMMISSIONING

Once reliable real-time *in situ* sensors have been developed and accepted by regulatory agencies for use during facility D&D, many aspects of the distinction between characterization and remediation process monitoring will virtually disappear. Such sensors will enable real-time remediation process control and optimization of waste treatment systems as well as waste segregation while D&D activities are on-going, resulting in rapid, efficient volume reduction. They are critical for ensuring worker protection during D&D activities. Moreover, tremendous cost savings will result from replacing large numbers of samples sent out for costly off-site laboratory analyses by *in situ* analyses with little or no marginal costs once the sensors have been procured as well as no costs for sample shipping and secondary waste disposal.

The specific challenges involved here are virtually the same as those listed under **THE DEACTIVATION AND DECONTAMINATION FREE RELEASE GOAL** previously; these are not repeated here. Selected Near-Term Goals and Far-Term Goals follow.

Selected Near-Term Goals

Improve monitoring capability for tank waste and slurry density and solids content; benefits include avoidance of catastrophic process breakdown with attendant costs, exposure risks, and schedule slippages.

Improve capability to monitor tank waste liquid/solid separation processes; benefits include enhanced control of waste stabilization feedstock, resulting in more reliable schedule adherence and more consistent product.

Develop on-line monitors for feedstock chemical composition as well as melt temperature, viscosity, and related process control for tank wastes as well as mixed waste, mixed TRU waste, and nuclear materials stabilization; benefits include better process control resulting in a more reliable and consistent product.

Develop improved methods for HLW and LLW stabilization monitoring at the basic science level; ultimate benefits include better process control resulting in a more reliable and consistent product.

Continue and complete the development of off-gas continuous emissions monitors for various constituents including mercury and dioxins/furans capable of meeting EPA's MACT requirements; benefits include regulatory compliance and possibly cost savings related to resumption of Best Available Technology treatment of mixed wastes with organic constituents.

Identify and address issues raised in emissions monitoring for non-thermal treatment of mixed waste and mixed TRU waste alternative oxidation treatments and ensure that those issues are considered in the regulatory development process; benefits include regulatory compliance as well as cost and schedule savings resulting from early establishment of appropriate regulation.

Develop an improved basic understanding of generation and control mechanisms for dioxin and furan formation during thermal and non-thermal treatment facility off-gas systems; benefits include regulatory compliance and possible cost savings related to operational efficiencies.

Improve capabilities for real-time, *in situ* monitoring of subsurface remediation processes; benefits include cost avoidance, schedule acceleration, and improved information to input to long-term monitoring and long-term stewardship decision-making.

Develop and initiate use of real-time portable beryllium monitors for surface and airborne contamination at DOE facilities; benefits include cost avoidance, schedule acceleration, and improved worker safety and efficiency.

Develop and integrate *in situ*, real-time sensors for characterizing and monitoring distributions and concentrations of lead paint, low energy gamma-emitting radionuclides (thorium and plutonium), alloy constituency, polychlorinated biphenyls (PCBs), and general radioactive and hazardous materials in facilities slated for D&D; benefits include cost avoidance, schedule acceleration, and improved worker safety and efficiency (also a Characterization Goal).

Selected Far-Term Goals

Develop monitors for future tank waste slurrying methods and pretreatment processes yet to be determined; benefits include continued reliability and confidence in the tank waste retrieval and treatment process.

Guide promising *in situ* HLW and LLW stabilization monitoring technologies and strategies through engineering development and site demonstration to deployment at multiple DOE sites; benefits include achieving reliable final disposal for tank wastes in a cost-effective and technically sound manner acceptable to regulators and other stakeholders.

Develop acceptable methods for verifying waste tank closure risk analyses; benefits include more reliable technical support for long-term stewardship decisions and possible cost savings.

Develop and negotiate regulatory paradigms allowing the use of inexpensive even if possibly less accurate real-time, *in situ* measurements augmented by occasional confirmatory laboratory analyses during remediation processes; benefits include cost avoidance, schedule enhancement, and reduced exposure risk.

Develop effluent monitoring strategies and methods along with effluent control technologies that can facilitate continuously documented regulatory compliance; benefits include improved operational control and public acceptance of mixed waste treatment operations.

Develop techniques and strategies for monitoring the progress of bioremediation using natural or bioengineered microbes to track process functioning as well as contaminant concentration; benefits include advancing the acceptance of these advances on monitored natural attenuation viable options within the regulatory and stakeholder communities.

In general, develop waste remediation process monitoring, control, and automation to the level of reliability and acceptability expected of standard industrial production processes.

OST CMM R&D Successes

Metal Emissions Monitor for Mixed Waste Thermal Treatment (18) for ensuring that metals are removed from off-gases
Transient Infrared Spectroscopy (215) for off-gas monitoring
Compact High-Resolution Spectrometer (1564) for monitoring Hg and other metals in
off-gas emissions from treatment processes
Laser Spark Spectroscopy for Continuous Metal Emissions Monitoring (18)
Headspace Gas Sampling (2031)
Waste Inspection Tomography (259, 2123) for examination of containerized wastes during processing
Slurry Monitors (2935, 2936, 2970) for monitoring slurried tank waste properties during transport
Adaptive Sampling and Analysis Program (ASAP) (2946) for on-site updating of sampling plans
in response to results obtained on a day-by-day basis
Road Transportable Analytical Laboratory (292)
StataSampler™ (3106) for multilevel sampling
Innovative DNAPL Characterization Toolbox (237, 2237, 2238, 2949, 2950, etc.)
for monitoring DNAPL remediation
Cone Penetrometer (243, 307, 381, 873, 2364, 2399, etc.) for monitoring a variety of subsurface remediation processes
Integrated Suite for Delineating Soil Contamination (2157, 2361, 2362; also 626) for
directing and monitoring soil remediation via excavation
Rapid Liquid Samplers (1514) for obtaining groundwater samples with minimal delay, secondary waste, and cost
On-line Real-time Alpha measurements (312)
BetaScint (70) for real-time surveys of beta emitters in soil and facilities
Cold Wringer (3105) for on-site tritium analyses
Sol-Gel indicators (384) for uranium, mercury, and chlorinated organic constituents
Direct Ion Trap Mass Spectrometry (69) for on-site measurement of organic constituents
HaloSnif Fiber-Optic Spectrochemical Sensor (103) for detecting chlorinated VOCs
Electrical Resistance Tomography for Subsurface Imaging (17) for monitoring DNAPL remediation processes
Real-Time Monitor for Transuranics in Glass (2004) for monitoring the vitrification of valuable nuclear materials

Recent R&D Projects

Particulate Matter Continuous Emissions Monitors (***TMFA & CMST-CP***) for monitoring off-gas emissions from thermal and other treatment processes for mixed and mixed TRU waste
Dioxin/Furan Formation Studies (***TMFA & CMST-CP***) for determining and avoiding D/F formation during mixed waste oxidation
Development of AOTF Multi-element Metal CEM for Compliance Monitoring (***TMFA & CMST-CP***)
Compare Mercury Continuous Emissions Monitors (***TMFA & CMST-CP***) for monitoring off-gas emissions from thermal and other treatment processes
Development of Dioxin CEM (***INDP***)
Microwave Plasma Continuous Emissions Monitor (***TMFA***)
VOC Monitoring Using Laser Diodes (***INDP***)
Air Plasma Off-Gas Emission Monitors for Metals (***INDP***)
Isotopically Selective Monitors for Transuranic Elements (***INDP***)
LIBS as Process Monitor for Waste Thermal Treatment (***INDP***)
On-Line Multi-Spectral Imaging of Thermal Treatment Process (***INDP***)
Surface Acoustic Wave Mercury Vapor Sensor (***INDP***)
Dual Coriolis Pipeline and In-Tank Slurry Monitors (***TFA, INDP & CMST-CP***, ***ESP-CP***)
Acoustic Monitor for Slurries Measurements at Low Weight Fractions (***EMSP***)
Ultrasonic Diffraction Grating Spectroscopy and Reflection for Slurry Characterization (***EMSP***)
Waste Tank Chemistry Monitors (***INDP***)
MS Fingerprinting of Tank Waste Using Tunable, Ultrafast IR Lasers (***EMSP***)
Detection and Characterization of Chemicals Present in Tank Wastes (***EMSP***)
Detection of Gall Layer in High-Level Waste Melters (***INDP***)
Millimeter-Wave Measurements of High Activity and Low Activity Glass Melts (***EMSP***)
Actinide-Aluminate Speciation in Alkaline Radioactive Waste (***EMSP***)
The Effect of Temperature and Electrolytic Concentrations on Actinide Speciation (***EMSP***)
Non-Invasive Diagnostics for Measuring Physical Properties and Processes in High Level Wastes (***EMSP***)
Radioanalytical Chemistry for Automated Nuclear Waste Process Monitoring (***EMSP***)
Innovative DNAPL Characterization Toolbox (***SCFA & CMST-CP***) for monitoring DNAPL remediation
Geophysical Methods for DNAPLs (***SCFA & CMST-CP***) for monitoring DNAPL remediation
High Frequency Electromagnetic Impedance Measurements for Characterization, Monitoring and Verification Efforts (***EMSP***)
Complex Electrical Resistivity for Monitoring DNAPL Contamination (***EMSP***)
Automated Shallow Seismic Imaging (***EMSP***)
Integrated Suite for Delineation of Soil Contamination During Remediation (***SCFA & CMST-CP***)
Real-Time Downhole Tritium Monitors (***INDP***)
Bioremediation and Monitored Natural Attenuation (***SCFA***), with field verification
Metal Ion Analysis Using Near-Infrared Dyes and the "Laboratory-on-a-Chip" (***EMSP***)
Field Portable Microchip Analyzer for Airborne and Surface Toxic Metals ***(EMSP***)
Development of Novel, Simple Multianalyte Sensors for Remote Environmental Analysis (***EMSP***)
The Use of Radar Methods to Determine Moisture Content in the Vadose Zone (***EMSP***)
Radionuclide Sensors for Water Monitoring (***EMSP***)
On-Line Measurement of the Progress of Decontamination (***DDFA***)
Fast Response Isotopic Alpha Continuous Emissions Monitor (***DDFA***)
Mobile Integrated Piping Decontamination and Characterization System (***DDFA***)
Advanced Sensing and Control Techniques fo Facilitate Semi-Autonomous Decommissioning (***EMSP***)
Development of Monitoring and Diagnostic Methods for Robots Used in Remediation of Waste Sites (***EMSP***)
Waste Volume Reduction Using Surface Characterization and Decontamination by Laser Ablation (***EMSP***)
Beryllium Surface and Air Monitors (***DDFA & CMST-CP***) for monitoring progress and health conditions during Be removal
Fast-Response Isotopic Alpha Continuous Air Monitor (***INDP***))
Real-Time Identification and Characterization of Asbestos and Concrete Materials with Radioactive Contamination (***EMSP***)
Three-Dimensional Position-Sensitive Germanium Detectors (***EMSP***)
Verification of Plutonium Removal from Uranium (***NMFA***)
Implementation of Moisture Measurement Technology for Nuclear Materials Stabilization (***NMFA***)
Gamma Ray Imaging for Environmental Remediation (GRIER) (***EMSP***)
Miniature Chemical Sensor Combining Molecular Recognition and Evanescent-Wave Cavity Ring-Down Spectroscopy (***EMSP***)

See also entries under **Characterization** and **Nondestructive Methods**.

LONG-TERM MONITORING

The need for long-term stewardship at DOE sites was described in *Long-Term Institutional Management of U. S. Department of Energy Legacy Waste Sites* (National Academy of Science 2000):

> *It is now becoming clear that relatively few U.S. DOE waste sites will be cleaned up to the point where they can be released for unrestricted use. Long-term stewardship . . . will be required for over 100 waste sites. Physical containment barriers . . . and institutional controls intended to prevent exposure of people and the environment to the remaining site hazards will have to be maintained at some DOE sites for an indefinite period of time.*

Long-term monitoring needs begin, however, before site closure. Methods to monitor the performance of treatment and containment systems must be in place as soon as those systems are installed to ensure that the systems will not release contaminants into the surrounding environments. These challenges are particularly imposing at some DOE sites because of the presence of radionuclides with half-lives of thousands of years in addition to more common hazardous chemicals and heavy metals.

Long-term stewardship will require monitoring of water, soils, engineered units, and facilities, according to *From Cleanup to Stewardship* (U.S. DOE October 1999). The *Status Report on Paths to Closure* (U. S. DOE March 2000) states that long-term stewardship activities have already begun at 30 sites where cleanup has been completed as well as at portions of other, larger sites that are still in operation. That report points out that “EM’s challenge is to understand better its long-term stewardship obligations and associated costs more clearly, and to find ways to ensure that stewardship activities are safe, efficient, and sustainable.”

LONG-TERM MONITORING CHALLENGES

Long-term monitoring differs from process monitoring in several ways: there is often little or no ongoing activity at the facility; immediate feedback is not so important as with process monitoring; and monitoring frequencies are reduced since at most slow change is anticipated. Such monitoring, though at present relatively infrequent, represents a costly burden to DOE through its sheer magnitude. The CMM R&D challenge here is to develop technologies and strategies to verify the long-term performance and integrity of remediation and stewardship activities. Important goals are to reduce that burden through development of sensors capable of providing data of adequate quality less expensively than traditional sampling and laboratory analysis, and to allow for more parsimonious Data/Decision Quality Objectives (DQOs) to be established through improving the modeling process. Specific challenges include the following:

! **Monitoring of closed landfills.** Once a landfill has been closed and capped one must monitor for an extended period as determined by regulatory and stakeholder interaction. An interesting and attractive potential exists for monitoring landfill cover integrity through *in situ* monitors or remote sensing of suitable cover vegetation. In addition, studies similar to the fate and transport studies discussed previously could aid in reducing the analytical burden. (***SCR***, ***LTM***)

! **Monitoring of surface barriers.** A similar need may develop for facilities for which the treatment selected is entombment in place. Surface barriers will be placed over the facility remains in order to prevent water from leaching radioactive or hazardous constituents into surrounding soils or the groundwater. As with landfill caps, robust long-term monitoring will be needed to verify the continued integrity of the surface barriers. (***FDD***, ***WTC***, ***LTM***)

! **Subsurface barrier validation and tank farm monitoring.** Landfill linings and other subsurface barriers are in use. Monitoring of the integrity of such barriers and containment systems is required to detect and minimize the impact of releases to the vadose or saturated zones. The monitoring of these as well as grouted or entombed waste tanks can be facilitated through the use of innovative concepts and technologies; again, demonstrating and validating these to the satisfaction of regulators and other stakeholders is necessary. (***SCR***, ***WTC***, ***LTM***, ***others***)

- **Long-term monitoring of facilities slated for D&D.** Many DOE sites will require remote surveillance of facilities such as production areas, structures, utilities, equipment, drums, tanks, and effluent lines. Significant periods of time will elapse prior to D&D; thus, these facilities fall into the realm of Long-Term Stewardship. Currently, facilities awaiting D&D must be surveyed periodically for criteria including contamination levels, structural deterioration, water or animal intrusion, integrity of storage containers, atmospheric conditions, and radioactive and hazardous substance releases.

  In addition, some buildings and facilities will remain in their end states indefinitely and will require monitoring. In both circumstances, surveys conducted according to current practice are intrusive, time-consuming, and expensive, and expose personnel to radioactive contamination. Low-cost, low-maintenance remote surveillance systems capable of collecting data from a DOE site and transmitting the data to a central location are needed. Ideally, these systems will be modular in order to be easily applicable to emerging and changing site needs. Such systems should be capable of frequent monitoring of the facility and reduce the need for labor intensive and hazardous surveys, thereby providing significant cost savings. (***FDD***, ***LTM***)

- **Modeling and monitoring paradigms.** A key to stakeholder acceptance of innovative monitoring systems will be demonstrably reliable models of contaminant fate and transport anticipated in the event of releases. DOE should refine these models; more precise, less conservative estimates of input parameters will allow reducing the cleanup effort needed, so long as a strong technical basis for those estimates can be shown. Attention should also be paid to the judicious choice of indicator parameters suitable for parsimonious long-term monitoring and the interplay between such choices, sensor technology development, and the development and negotiation of appropriate DQOs for monitoring. Also to be addressed is the interaction of long-term stewardship requirements with choices made in addressing pressing priority needs today. (***SCR***, ***WTC***, ***LTM***)

- **Monitored natural attenuation.** In many situations the treatment of choice will be monitored natural attenuation, relying on natural or enhanced degradation of contaminants in the subsurface through biological, physical, or radiological processes. The challenges are to develop sensors capable of long-term, demonstrably reliable performance with minimal maintenance requirements along with monitoring paradigms relying primarily on such sensors which will meet with stakeholder and regulatory acceptance. (***SCR***, ***WTC***, ***LTM***)

- **Improved fundamental understanding of subsurface science.** This is discussed in the **IMPROVED SCIENTIFIC UNDERSTANDINGS** section of this **APPENDIX**. (***SCR***, ***WTC***, ***LTM***)

Selected Near-Term Goals

Develop better, carefully validated geophysical monitors and data integration methods for subsurface monitoring for DNAPLs; benefits include reduced monitoring costs and risk reduction through better early warning of impending problems.

Identify well-characterized test areas for modeling methods; benefits include better validation of sensor performance as well as fate and transport and decision models, resulting in potential cost savings and greater confidence in long-term stewardship decisions.

Adapt previously developed and commercially available sensors and monitoring systems for long-term, unattended, self-calibrating and testing operation with minimal maintenance and automated, remote data reporting; benefits include cost savings and risk avoidance.

Develop remote systems for monitoring large areas such as landfill covers and closed waste lagoons; benefits include cost savings and superior early warning of potential problems.

Develop and introduce automated systems with remote reporting for monitoring long-term operation of *ex situ* groundwater treatment processes; benefits include cost savings and risk reduction.

Selected Far-Term Goals

Develop automated systems with remote reporting for unattended long-term monitoring of closed structures, waste repositories, and stabilized waste tank farms; benefits include regulatory compliance, cost reduction, and improved early warning of potential problems.

Capitalize on current government and academic research on Micro-Electro-Mechanical Sensor (MEMS) and other innovative scientific development, and direct that development toward areas of importance to DOE-EM.

Develop techniques and strategies for monitoring the progress of bioremediation using natural or bioengineered microbes to track process functioning as well as contaminant concentration.

Continue to participate in collaborative efforts among DOE, EPA, and other stakeholder groups to enhance regulatory and public confidence in and acceptance of innovative monitoring strategies, equipment, and practices.

OST CMM R&D Successes

Electrical Resistance Tomography (140) for monitoring tank farms
Time Domain Reflectometry with Waveguides for Subsurface Barrier Verification (704)
SEAtrace™ Subsurface Barrier Validation System (308) for detecting releases from containment systems
Electrical Resistance Tomography (17, 2120) for subsurface monitoring
Remote Sensing Systems (208) for surveying and monitoring large areas
Long-Term, Post-Closure Radiation Monitor (288) for low-cost gamma monitoring subsurface monitoring systems
Long-Range Alpha Detector (596) for scanning soil surfaces for alpha radiation
Cone Penetrometer-based sensors (243, 307, 319, 381, 873, 2364, 2399, etc.) for detecting or monitoring subsurface contaminants
Alternative Landfill Covers and Monitoring Systems (10, 170, 2924)
Radiation Tracking System for Delineating Contamination in Soils (2361)
Crosshole Seismic Imaging (588) for hydrogeological modeling of the subsurface
Advanced Tensiometer (2122) for measuring hydrogeologic parameters of the subsurface
In Situ Permeable Flow Sensor (99) for determining hydrogeological parameters of the subsurface
Portable field detection of chlorinated VOCs (16, 103, 313)
Ground-Based Fluorescence Imaging (1999) for scanning buildings, soils, etc for uranium

Recent R&D Projects

Headspace Gas Sampling of RH-TRU Waste Containers (***TMFA***)
Transuranic Optimized Measurement System (***TMFA***)
Rapid Migration of Radionuclides Leaked from High-Level Waste Tanks (***EMSP***)
JCCEM Contaminant Transport Studies (***SCFA***)
Colloid-Facilitated Transport of Radionuclides Through the Vadose Zone (***EMSP***)
Dynamics of Vadose Zone Transport: A Field and Modeling Study Using the Vadose Zone Laboratory (***EMSP***)
Quantifying Vadose Zone Flow and Transport Uncertainties Using a Unified, Hierarchical Approach (***EMSP***)
Fate and Transport of Radionuclides Beneath the Hanford Tank Farms: Unraveling Coupled Geochemical and Hydrological Processes in the Vadose Zone (***EMSP***)
Migration and Entrapment of DNAPLs in Heterogeneous Systems: Impact of Waste and Porous Medium Composition (***EMSP***)
Physics of DNAPL Migrations and Remediation in the Presence of Hetergeneities (***EMSP***)
A Hydrogeologic Method for Characterizing Flow and Transport Processes Within the Vadose Zone (***EMSP***)
Geophysical Site Characterization (***SCFA & CMST-CP***) for comparing noninvasive DNAPL monitoring tools
Complex Electrical Resistivity for Monitoring DNAPL Contamination (***EMSP***)
Material Property Estimation for Direct Detection of DNAPL Using Integrated GPR (***EMSP***)
The Use of Radar Methods to Determine Moisture Content in the Vadose Zone (***EMSP***)
High Frequency Electromagnetic Impedence Measurements for Characterization, Monitoring, and Verification Efforts and for (***EMSP***)
Mapping DNAPL Transport and Contamination in Fractured Rock (***SCFA***)
VOC Monitoring Using Laser Diodes (***INDP***)
Novel Optical Detection Schemes for *In Situ* Mapping of CVOCs in the Vadose Zone (***EMSP***)
Metal Ion Analysis Using Near-Infrared Dyes and the "Laboratory-on-a-Chip" (***EMSP***)
Spectroelectrochemical Sensor for Technetium Applicable to the Vadose Zone (***EMSP***)
Radionuclide Sensors for Water Monitoring (***EMSP***)
Improved Methods for Long-Term Verification and Risk Assessment (***SCFA***)
Seismic Surface-Wave Tomography of Waste Sites (***EMSP***)
Development of Novel, Simple Multianalyte Sensors for Remote Environmental Analysis (***EMSP***)
Evaluation of Sensors for Long-Term Monitoring (***SCFA & CMST-CP***)
Tritium Monitoring in Difficult Conditions (***SCFA***)
Alternative Landfill Cover Demonstration (***SCFA & CMST-CP***) using automated *in situ* monitoring systems
Alternate Cover and Monitoring System for Landfills in Arid Environments (***SCFA***)
Development of Perfluorocarbon Tracer Technology for Verification of Cover Performance (***SCFA***)
Monitored Natural Attenuation Verification (***SCFA***)
Remote Surveillance of Facilities Awaiting D&D (***DDFA***)
Relative Humidity: A Practical Measurement of Material Moisture Content (***NMFA***)
Implementation of Moisture Measurement Technology for Nuclear Materials Stabilization (***NMFA***)

NONDESTRUCTIVE METHODS

Nondestructive assay (NDA) and nondestructive evaluation (NDE) techniques are characterized as being either passive, measuring radiation from spontaneous decay of nuclear material, or active, measuring radiation induced by an external energy source. Current baseline techniques generally involve sampling materials and analyzing the samples using destructive chemical procedures, involving considerable cost, time, worker exposure, and secondary waste generation. NDA and NDE avoid the need for sampling, reduce operator exposure, and are both faster and less expensive than chemical assay. NDA is often less accurate than chemical assay on a measurement-by-measurement comparison, although the overall accuracy of the latter can be adversely affected by difficulties associated with sampling heterogeneous materials. The development of NDA reflects a trend toward automation and workforce reduction that can be applied to all waste-owning facilities for material accounting, process control, criticality control, and perimeter monitoring.

NDA methods were developed initially to meet the need for improved nuclear material safeguards. As safeguards agencies throughout the world needed more nuclear material measurements, it became clear that faster methods would be required that would not alter the state of the nuclear materials. Efforts to address these needs were supported by NRC, DOE, and IAEA, since rapid nondestructive measurement techniques are required by the safeguards inspectors who must verify the inventories of nuclear material held throughout the world.

NDA and NDE methods have several potential applications in the DOE environmental management and cleanup mission.

NDA AND NDE FOR MIXED AND MIXED TRU WASTES

Characterization of mixed waste is needed to meet DOE site requirements for waste treatment and storage operations, transportation, and disposal. The Resource Conservation and Recovery Act (RCRA) and the Atomic Energy Act require that DOE facilities characterize mixed wastes for hazardous and radioactive content and that treatment and disposal facilities require data on physical and chemical waste form properties.

The current baseline technology for identifying and quantifying RCRA contaminants is intrusive sampling coupled with destructive and/or nondestructive analysis. In this case the intrusive analysis provides the accepted value for the waste stream. Sampling variation introduces potential errors, so radioactive constituents are identified and quantified using a combination of NDA and acceptable knowledge. Recent developments of gamma-ray technologies (see the OST CMM Successes box) have reduced total measurement uncertainties to acceptable levels; all of the recently developed technologies have undergone audits by the Carlsbad Area Office technical audit team, receiving full approval for disposal of contact-handled waste at WIPP. While NDA does have uncertainties due to random and systematic errors, they have been reduced to manageable levels. Tomographic techniques have significantly reduced errors due to matrix interferences and nonuniform contamination distributions for both neutron and gamma-ray measurements. In addition, NDA reduces or avoids delays due to the unavailability of qualified analytical facilities.

Remote-handled wastes (i.e., wastes which cannot be physically handled by humans in proximity) present unique and complex challenges. Improved NDA/NDE technologies with decision support methodologies are required for the proper identification, segregation, handling, transportation, and storage of each DOE remote-handled TRU waste stream. This requires robotic handling and packaging, a suite of sensitive and precise non-intrusive characterization technologies, models, methods, standards for calibration and performance verifications, web-based data storage, analysis and reporting systems, and automated container tracking and monitoring. Technically the challenge is a tomographic (3-dimensional) visualization of all radionuclides within containers of widely varying matrices and sizes without intrusive sampling, performed remotely and with sufficient accuracy and precision in a high background signal environment.

Specific challenges in applying NDA and NDE techniques to characterize wastes include the following:

- **RCRA constituents.** Containerized wastes are interrogated by an external neutron source using an interaction called prompt capture. The neutrons are captured by the RCRA metals, producing an excited state which decays within 10-15 seconds with gamma radiation characteristic of that material. (***MWP***, ***WNMC***)

- **Polychlorinated biphenyls (PCBs).** Although most of the emphasis in NDA/NDE methods centers on RCRA metals and radionuclides, there is also interest in developing non-intrusive methods for characterizing other constituents such as PCBs in low-level wastes destined for treatment and disposal. (***MWP***, ***WNMC***)

- **Contact handled wastes.** Work has focused on developing solutions for material contained in 55 and 83 gallon drums, where advanced gamma-ray and neutron techniques have been shown to be very effective in reducing uncertainties for most waste streams; dense sludges may still prove to be a problem. Assay of waste boxes has also been addressed by issuing an Request For Proposal to design and develop a mobile system that can be deployed to different DOE sites. (***MWP***, ***WNMC***)

- **Remote handled wastes.** Work has focused on two solutions: gamma-ray spectroscopy combined with acceptable knowledge (GSAK) and multi-detector assay (MDAS). Direct measurements of materials containing plutonium and uranium are prevented by the presence of high intensity fission products such as cesium-137. As a result, analyses depend on measurements of the fission products and relationships between them, the fissile materials, and the operating history of the reactor (the AK portion). MDAS is still very much in the research stage. The technique uses an accelerator to produce an intense beam of low-energy neutrons which then produce gamma radiation from inelastic scattering and neutron capture and neutrons from induced fission. (***MWP***, ***WNMC***)

HIGH-LEVEL WASTE TANK INTEGRITY

The needs for high-level waste tank integrity characterization and monitoring have been mentioned previously. Hanford, Idaho, Oak Ridge, Savannah River, and West Valley share a common need to assess and confirm the integrity of their aging HLW storage tanks. At Hanford, single shell tanks (SSTs) that have little or no waste need to be selected for NDE of the tank wall and floor. The number and size of the cracks that led to the release of wastes from leaking SSTs need to be determined. Regulatory compliance requires life cycle integrity assessments, including NDE of six of Hanford's double shell tanks on a portion of the tank wall, bottom knuckle, and bottom.

Savannah River Site has high-level waste storage tanks and piping systems that have exceeded their original design life but are expected to be in use for another 30-40 years. New micro-scale inspection equipment is required to visually inspect the piping system and primary tank walls. An additional function would be to perform NDE of selected tank welds/base material, to characterize flaws reported by visual examinations and to provide periodic ultrasonic examinations for flaws and general or localized wall thinning.

At Oak Ridge Reservation the privatization schedule plans to transfer eight storage tanks to the private sector for waste remediation, before which time ORNL wants to inspect the condition of the tanks and quantify the volume of sludge under the supernatant. At Idaho National Engineering and Environmental Laboratory newly generated liquid waste is to be segregated in an unused spare tank; before use, it must be certified and permitted under RCRA.

Two 36-year old tanks used for HLW processing at the West Valley Demonstration Project still contain residual waste that must be maintained in a stable configuration pending development of the final closure method, a period that may exceed 10 years. Special equipment to monitor and maintain the tanks may need to be developed. Interim maintenance would include methods for prevention of tank corrosion, monitoring the tank integrity, and implementing structural stability measures.

The path forward identified by TFA, in collaboration with CMST-CP, is to focus on adapting existing instrumentation and methods. As solutions to the needs for tank integrity are identified and implemented, similar needs in other critical application areas can be evaluated to determine if the same or similar solutions can be applied. In this way TFA/CMST-CP NDE accomplishments can be leveraged to spin off solutions to other pressing needs. Along the way any gaps between existing methodology and DOE's collective NDE needs of identified and technology solutions developed.

Specific NDE challenges related to high-level waste tank integrity include the following:

- **NDE techniques for in-use HLW storage tanks.** Many aging DOE HLW storage tanks must remain in use for extended periods, even decades, as discussed above. Optimal NDE methods for evaluating the continued integrity of these tanks must be identified and/or developed. (***WTI***)

- **NDE methods for characterizing failure mechanisms.** NDE methods are needed for studying tanks that have corroded or developed cracks, so that the failure mechanisms can be understood. This understanding can then be used in improving tank maintenance, integrity assurance, and monitoring strategies. (***WTI***, also ***WNMC***)

NUCLEAR MATERIALS AND SPENT NUCLEAR FUELS

Specific measurement needs associated with spent nuclear fuels (SNF) have been identified by Hanford, INEEL, ORNL, and SRS. Common to most of these sites are NDA for fissile material, remote monitoring of dry-stored SNF, remote moisture monitors/sensors for SNF canisters, and NDE of SNF canisters and contents. Specific needs associated with SNF handling and storage include the following:

- **Re-certification of SNF documentation.** Prior to SNF transfer to a federal repository and following extended dry storage, data on canister contents may require independent certification and documentation. The use of NDA techniques would considerably reduce the need to open and inspect sealed SNF canisters. Without NDA additional personnel exposure and costs will be incurred and schedules will be delayed. (***WNMC***)

- **Physical condition and moisture content of dry-stored SNF.** Current DOE strategy is to package SNF into dry, sealed cans followed by storage in dry facilities for up to 30 years or more pending transfer to a federal geologic repository, where receipt limits require that the SNF and canisters be retrievable for up to 100 years. Assurance of SNF integrity during this period will require remote monitoring for such parameters as temperature, pressure, moisture, and perhaps microbiological species. Any canister opening would be costly and time-consuming and would expose workers to increased radiation levels.

  Moreover, internal pressure in SNF canisters is a critical parameter for SNF storage. Since most SNF are in wet storage, drying prior to encapsulation is important. In addition to residual moisture, however, some metals have chemically bound water attached, so internal pressure may build. Advanced NDE systems are required for monitoring SNF canister moisture content prior to shipping. (***WNMC***)

- **Automated inventory management.** In addition to remote sensing of conditions within waste and nuclear material containers, automated location and inventory control will become highly desirable as the stock of containerized, processed waste grows. (***WNMC***, ***LTM***, ***other***)

NON-INTRUSIVE TECHNIQUES FOR FACILITY D&D

R&D efforts are needed to identify new means of locating and quantifying difficult-to-measure contaminants in support of facility D&D characterization and remediation verification. While much NDA/NDE work is oriented toward containerized wastes, there is also a need to locate, identify, and quantify contaminants of interest (such as tritium, ^{99}Tc, ^{239}Pu and other actinides, Be, Hg, asbestos, and PCBs) embedded inside concrete, stainless steel, and equipment. Specific challenges include the following:

- ! **Methods to assess the volumetric distribution of contaminants within materials, especially concrete.** The development of minimally- and non-intrusive real-time *in situ* sensing technologies to characterize the concentration of contaminants as a function of depth in concrete would eliminate difficulties associated with core sample collection and subsequent analyses. Minimally invasive schemes like laser ablation mass spectroscopy and non-intrusive techniques like neutron activation and X-ray analysis appear to be attractive candidates for research. (***FDD***)

- ! **Sensors to measure contaminants on the surface and within micro-cracks of metals.** More sensitive detectors and simple-to-use techniques such as chemical indicators are needed to quickly certify levels of nuclides and other hazardous materials on structural surfaces and equipment. This will help ensure safety in the workplace and may also reduce costs by, for example, allowing non-hazardous waste to be disposed in landfills. Analysis of residual low-energy beta emitters like tritium and ^{99}Tc is particularly challenging when these isotopes are inside equipment or mixed in heterogeneous waste matrices because the beta particles cannot penetrate most materials. (***FDD***)

Selected Near-Term Goals

Continue development of NDA technologies for the assay of RCRA metals; benefits include cost reduction, schedule enhancement, reducing worker exposure to radiation and toxic materials, and eliminating secondary waste.

Continue development of NDE and NDA methods for contact-handled drum wastes to handle more complex mixes of analytes such as may be found in dense sludges; benefits include cost reduction, schedule enhancement, reduced worker exposure, and minimization of secondary waste.

Develop technologies for reliable and accurate non-intrusive tomographic NDA and NDE of boxed wastes; benefits are similar to those above.

Develop multi-detector NDA technologies to provide improved characterization of remote-handled wastes; benefits are similar to those above.

Enhance capabilities for NDE of high-level waste tank wall, bottom knuckle, bottom, and piping integrity; benefits include avoidance of potential releases with attendant costs for remediation of subsurface contamination.

Develop NDA techniques for verification of previously inventoried or assayed containerized SNF; benefits include reduction in cost and risk of re-certification prior to transferring SNF to a federal repository.

Develop remote technologies for monitoring containerized SNF in dry interim storage and in federal repositories for extended periods, for parameters such as temperature, pressure, moisture content, and, perhaps, microbial species; benefits include cost savings and avoidance of exposure to increased radiation levels.

Develop sensors for determining both residual moisture and chemically bound water in SNF prior to encapsulation; benefits include enhance safety of containerized materials resultingin potential cost, delay, and exposure avoidance.

Selected Far-Term Goals

Continue development of NDE methods and technologies for monitoring the integrity and safety of aging high-level waste storage tanks; benefits include avoidance of potential releases with attendant additional remediation costs and potential subsurface contamination.

OST CMM R&D Successes

NDA Capability Evaluation (2176) of Waste Inspection Tomography, Segmented Gamma Scanner, High Efficiency Neutron Counter, IQ3 Gamma System, and Tomographic Gamma Scanner
Waste Inspection Tomography (WIT) (259 and 2123) for NDE and NDA of containerized wastes
Active & Passive Computed Tomography (A&PCT) (2123) for NDE and NDA of containerized wastes
Combined Thermal/Epithermal Neutron Analysis (CTEN) (1568) for NDA of containerized wastes
Pulsed Gamma Neutron Activation Analysis (2226) for non-intrusive characterization of RCRA metals in sludge and debris waste containers
3-D Visual and Gamma Imaging System (2402)
Many spectrographic methods are inherently related to NDA/NDE, including 18, 70, 78, 133, 215, 289, 382, 430, 434, 873, 1560, 1999, 2001, 2004, 2015, 2157
Associated Particle Imaging (413)
Robotic Tank Inspection End Effector (278)
Near-Infrared Spectroscopy for In-Tank Characterization (86)
X-Ray Fluorescence Spectroscopy (622)
BetaScint (70) for portable high-energy beta emitter detection
Portable X-Ray, K-Edge Heavy Metal Detector (134)
Transient Infrared Spectroscopy (215) for assaying molten waste streams

Recent R&D Projects

Induced Gamma Radiation Using Prompt Neutron Capture (***TMFA***) for NDA/NDE of containerized wastes
Mobile Gamma-Ray and Neutron Tomography of Contact-Handled Waste Boxes (***TMFA***)
NDA of Boxes Containing TRU Waste (***TMFA***)
Multiple Detector Analysis System(MDAS) Development (***TMFA***) extending CTEN and other methods
Gamma Spectrometry Combined with Acceptable Knowledge (GSAK) (***TMFA***)
PGNAA System for Assay of RCRA Metals (***INDP***)
Field Portable Microchip Analyzer for Airborne and Surface Toxic Metals (***EMSP***)
Microsensors for *In Situ* Chemical, Physical, and Radiological Characterization of Mixed Waste (***EMSP***)
Headspace Gas Sampling of RH-TRU Waste Containers (***TMFA***)
Development of Advanced Electrochemical Emission Spectroscopy for Monitoring Corrosion in Simulated DOE Liquid Waste (***EMSP***)
Collaborative Multi-Site Evaluation of Tank Integrity Evaluation Methods (***TFA & CMST-CP***) for identifying superior current practices in use across the DOE complex
Mass Spectrometric Fingerprinting of Tank Waste Using Tunable, Ultrafast Infrared Lasers (***EMSP***)
Radiochemical Analysis by High Sensitivity Dual-Optic Micro X-ray Fluorescence (***EMSP***)
Millimeter-Wave Measurements of High Level and Low Activity Glass Melts (***EMSP***)
Non-Invasive Diagnostics for Measuring Physical Properties and Processes in HLW (***EMSP***)
Alternative Landfill Cover Demonstration (***SCFA & CMST-CP***) using automated *in situ* monitoring systems
Development and Implementation of Geophysical Techniques for DNAPL Monitoring (***SCFA***)
Development of Novel, Simple Multianalyte Sensors for Remote Environmental Analysis (***EMSP***)
Three-Dimensional Position-Sensitive Germanium Detectors (***EMSP***)

See also other sections.

IMPROVED SCIENTIFIC UNDERSTANDINGS

Advances are needed in areas that are not strictly technology development, but are related to the collection and processing of information obtained during characterization and monitoring and the incorporation of that information into predictive models. The collective goal of these advances is to ensure that the right measurements are made at the right places and times, are collected and processed effectively, and can be shown to reliably and validly support the decision-making for which they were intended. Moreover, the whole area of sensor development is rapidly expanding with exciting initiatives in micro-, nano-, and bio-technologies; DOE-EM should take steps to ensure that it maintains awareness of and access to this development.

SUBSURFACE SCIENCE

Most prominent among these areas is understanding subsurface geology and hydrology as they relate to contaminant fate and transport; the Hanford Site calls this "Groundwater/Vadose Zone Phenomenology" in its Science and Technology Strategic Assessment. Improved understanding of these areas is critical to enhancing the reliability of models on which site closure and long-term stewardship decisions must be made. One benefit should be more ready regulatory and stakeholder acceptance of these decisions.

! **Identifying subsurface characteristics of importance and methods to evaluate them.** Subsurface characteristics determine contaminant fate and transport. Present understanding of subsurface processes, however, is not advanced enough to support the optimal selection of characteristics to be used in predictive fate and transport models. Moreover, challenges remain in measuring those characteristics over large areas or volumes using either direct or indirect techniques. The resulting uncertainties are particularly severe at large DOE sites with deep, complex, and heterogeneous geologic and hydrogeologic settings. (***SCR***, ***WTC***, ***LTM***)

! **Basic science of fate and transport.** Accurate conceptualization and modeling are essential for understanding the long-term fate of contaminants in the subsurface, but the chemical, biological, and physical processes that determine the long-term behavior of contaminants are poorly understood. Progress is needed toward developing more realistic and reliable predictive models that incorporate a broad range of processes that may affect contaminant fate and transport; complexities include colloid formation, biological activity, and transport paths in fractured rock. Some transport predictions made in the past have been seriously in error. (***SCR***, ***LTM***, ***others***)

A related area involves the choice of monitoring indicator parameters, frequencies, and decision rules; this is discussed under <u>Modeling and monitoring paradigms</u> in the **Long-Term Monitoring** section.

EMERGING AND EVOLVING TECHNOLOGIES

Exciting new technologies being developed in the nation's academic, industrial, and government laboratories promise to revolutionize field analysis. These technologies include Micro-Electro-Mechanical Sensors (MEMS), affinity-based sensing using surface plasmon response, fiber-optic array sensors, and micro-cantilever-based sensors. Currently available technologies will continue to evolve by being miniaturized, ruggedized, automated, and made self-calibrating, self-testing, even self-repairing, and less dependent on consumables. These may include miniaturized nuclear magnetic resonance instruments, miniaturized rapid chromatographic separation systems, quantitative laser vaporization techniques, etc. Likewise, the development of novel remediation technologies such as subsurface bioremediation will require corresponding advances in monitoring technologies and strategies. Specific challenges for DOE-EM are the following:

! **Steering and keeping up with sensor technology development.** DOE-EM must continue to publicize its needs as opportunities (potential markets) for advanced technology development to researchers in appropriate forums and to keep abreast of the progress of technology development. This virtually mandates DOE-EM participation in workshops, working groups, conferences, technology expositions, etc. (***All CAAs***)

- ! **Biosensors.** There has been tremendous growth in development and commercialization of a broad range of biosensor devices and applications. Modern devices can range from fiber-optic and micro-cantilever-linked immunoassays to sub-cellular and cellular micro-electronic devices. Analytes measurable by biosensors include a vast array of organic chemicals, biochemicals, inorganics, metals, and even ionizing radiation. Research to integrate microelectronics and nanotechnology with elements of gene array technology and cellular engineering may lead to new sensor technology. This technology could create a greater ability for continuous and remote monitoring in chemically and physically complex environmental and structural systems than will otherwise be available in the near future. (***All CAAs***)

- ! **Developing monitoring strategies for novel remediation technologies.** DOE-EM must encourage the development of appropriate monitoring strategies as part of the development of novel remediation techniques. Such monitoring strategies are essential to the deployment of any new technology; in particular, they are crucial to the regulator and stakeholder acceptance of the innovative technology. (***FDD***, ***SCR***, ***WTC***, ***LTM***, ***others***)

DATA COLLECTION AND INTERPRETATION

A related challenge in improving basic understandings has to do with monitoring data collection, transmission, storage, and interpretation, particularly for remote long-term monitoring.

- ! **Data systems.** Long-term monitoring will require development of appropriate data collection, recording, and interpretation systems. Such systems should be self-validating, should be capable of automated reporting for extended periods of time, should provide guarantees of data authenticity and reliability analogous to chain-of-custody and QA/QC reports for conventional laboratory data, and should provide for secure and redundant data storage and retrieval over extended time periods (from several years to decades). Systems will be required to automatically screen data to provide early warnings of atypical events and of sensor failures. (***LTM***, ***SCR***, ***FDD***, ***others***)

- ! **Remote sensing of contaminants.** Remote sensing systems can provide both economic and safety benefits by distancing the worker from hazardous work areas. Smaller versions of existing gamma cameras with higher sensitivity and resolution would be desirable for remote mapping of activity levels; these advances may be achievable through further research on detector materials and geometries. Fiber-optic sensing for remote detection of some chemical species is feasible. Further research could lead to its use in sensing chemical contaminants relevant to D&D. Fiber-optic radiation sensors are a more recent development; opportunities exist for both improved performance and novel features such as optical interrogation.

  Once current generation technological advances such as miniaturization have been realized, science and technology development for the integration of robotic devices and characterization tools will greatly enhance the safe and accurate determination of contaminants in areas that are difficult or impossible to access, such as embedded small-bore pipes and ducts. Further upgrades in robotic actuators, universal operational software to provide criteria-based decision making, and even virtual reality-based software may offer significant advantages for characterization issues during D&D operations. (***FDD***, ***others***)

Selected Near-Term Goals

Develop better basic understandings of subsurface structures and their relationship with contaminant fate and transport; benefits include more reliable modeling and prediction, resulting in risk reduction and greater confidence in modeling results used in planning long-term monitoring and long-term stewardship activities.

Develop better basic understandings of contaminant fate and transport processes and their relationships with geology, hydrogeology, and geochemistry; benefits include more reliable modeling and prediction, resulting in risk reduction and greater confidence in modeling results used in planning long-term monitoring and long-term stewardship activities.

Develop remote data acquisition and reporting models, possibly internet-based, that can provide data reliability and integrity assurance comparable with standard practice protocols; benefits include enhancing regulatory acceptance of monitoring strategies based on remote, *in situ*, rarely attended sensors.

Selected Far-Term Goals

Develop better fundamental understanding of subsurface processes and characteristics critical for determining contaminant fate and transport; benefits include improved capability for reliable modeling in support of long-term stewardship.

Improve capability to evaluate those critical subsurface processes, particularly at large DOE sites with heterogeneous geological and hydrogeological conditions; benefits include improved confidence in closure and long-term stewardship decisions relying on monitored natural attenuation.

Develop automated, self-testing, self-reporting, self-calibrating versions of all sensors to be used in long-term monitoring; benefits include compliance with regulatory and stakeholder criteria as well as cost reduction.

Develop secure, redundant, automated data collection, storage, retrieval, evaluation, and reporting systems for long-term monitoring data; benefits include compliance with regulatory and stakeholder criteria as well as cost reduction.

OST CMM R&D Successes

Expedited Site Characterization (77)
Adaptive Sampling and Analysis Programs (2946)
Geophysical Data Fusion (290) for holistic interpretation of geophysical data
Hydrogeologic Data Fusion (2944) for holistic interpretation of hydrogeologic data
PLUME - Groundwater Modeling (733) software for subsurface data visualization
RSS Software (2362) for centralized data collection and interpretation using telemetry
Long-Term Post-Closure Radiation Monitoring System (288)
Remote Sensing Systems (208) for acquisition of data from airborne platforms
Three Dimensional Integrated Characterization and Archiving System (3D ICAS) (97)

Recent R&D Projects

Dioxin Formation and Prevention Studies (***TMFA***)
Rapid Migration of Radionuclides Leaked from HLW Tanks: A Study of Salinity Gradients, Wetted Path Geometry, and Water Vapor Transport (***EMSP***)
Colloid-Facilitated Transport of Radionuclides Through the Vadose Zone (***EMSP***)
JCCEM Contaminant Transport Studies (***SCFA & CMST-CP***) for validating and improving contaminant transport models using data from the well-characterized Russian Tomsk and Mayak sites
Hanford Vadose Zone Characterization of Flow and Transport Processes and Groundwater/ Vadose Zone Integration Project (***SCFA***, ***EMSP***)
Physics of DNAPL Migrations and Remediation in the Presence of Heterogeneities (***EMSP***)
The Dynamics of Vadose Zone Transport: A Field and Modeling Study Using the Vadose Zone Observatory (***EMSP***)
Quantifying Vadose Zone Flow and Transport Uncertainties Using a Unified, Hierarchical Approach (***EMSP***)
A Hydrologic-Geophysical Method for Characterizing Flow and Transport Processes Within the Vadose Zone (***EMSP***)
Fate and Transport of Radionuclides Beneath the Hanford Tank Farms: Unraveling Coupled Geochemical and Hydrological Processes in the Vadose Zone (***EMSP***)
Spectroscopic and Microscopic Characterization of Contaminant Uptake and Retention by Carbonates in Soils and Vadose Zone Sediments (***EMSP***)
Mapping DNAPL Transport and Contamination in Fractured Rock (***SCFA***)
Migration and Entrapment of DNAPLs in Heterogeneous Systems: Impact of Waste and Porous Medium Composition (***EMSP***)
Novel Optical Detection Schemes for *In Situ* Mapping of CVOCs in the Vadose Zone (***EMSP***)
Material Property Estimation for Direct DNAPL Detection Using Integrated GPR (***EMSP***)
Microsensors for *In Situ* Chemical, Physical, and Radiological Characterization of Mixed Waste (***EMSP***)
Correlation of Chemisorption and Electronic Effects for Metal/Oxide Interfaces: Transducing Principles for Temperature-Programmed Gas Microsensors (***EMSP***)
3D Integrated Characterization and Archiving System (***INDP***)
Miniature Chemical Sensor Combining Molecular Recognition with Evanescent-Wave Cavity Ring-Down Spectroscopy (***EMSP***)
Optical and Microcantilever-Based Sensors for Real-Time *In Situ* Characterization of High-Level Waste (***EMSP***)
In Situ Characterization of Actinides and Technetium via Fiberoptic Surface Enhanced Raman Spectroscopy (SERS) (***EMSP***)

See also other sections.

APPENDIX B

SELECTED
VISIBLE AND IMPORTANT PROBLEMS

TABLE OF CONTENTS

SELECTED VISIBLE AND IMPORTANT PROBLEMS

In this Appendix we revisit the **Visible and Important Problems** (**VIPs**) featured previously in this ***ROAD MAP***. These are only a small portion of the universe of CMM science and technology development challenges to be faced by DOE-EM. They were selected because they are topics of considerable recent and current concern. The goal of **APPENDIX B** is to describe specific aspects of the selected **VIPs** in detail and to outline solution strategies. The **VIPs** are, on the whole, multi-part challenges that may require several different responses. The approaches presented here may be thought of as brief technical responses to some of the highest priority CMM-related challenges facing DOE-EM at this time.

Most of these selected **VIPs** are currently being addressed by OST with CMST-CP involvement; technical solution paths are reasonably clear, and appropriate technology development is already underway. For these the solution path already selected is presented here. In other cases, although the need may be equally important, the solution path is not so clear at the present time; a solution strategy is proposed for those cases. The solution paths and strategies presented are based on OST's past successes in CMM R&D.

VIP EMISSIONS MONITORING FOR HIGH-LEVEL WASTE PROCESSING

There are many monitoring challenges associated with HLW processing. This one is notable because it is related not only to HLW processing but also to mixed and mixed-TRU waste and nuclear materials stabilization concerns.

Effluent monitoring for NO_x and other constituents during HLW processing

Direct vitrification is one possible treatment of choice for the remaining sodium-bearing liquid wastes (SBW) at INEEL. If this approach is selected, it is anticipated that a vitrification facility will be built that will include an off-gas treatment train as a major system. Regulatory permitting of the off-gas treatment system will require monitoring effluent gases for NO_x (NO, NO_2) and possibly also for CO, NH_3, CO, and/or H_2., depending on the off-gas treatment strategy selected.

Four NO_x removal processes have been considered for the design of a pilot melter facility at INEEL. Two of these processes use NH_3 for the reduction of NO_x; the third involves steam reforming that may produce CO, H_2, and unchanged NO_x as products; and the fourth, a reburner process, may produce CO and unchanged NO_x. If NH_3 processes are used for NO_x level reduction, upstream and downstream NH_3 monitoring will be required for both process control and effluent monitoring. If other processes are selected, off-gas monitors will be needed to determine the efficiency of NO_x removal. Downstream monitoring for CO and H_2 may also be required for the steam reforming and reburner processes.

In addition to the melter facility, other thermal waste process facilities at INEEL and elsewhere will require effluent monitoring for a variety of hazardous constituents including radionuclides, toxic heavy metals, hydrocarbons, halogenated organics, and priority pollutants. Operation of off-gas control systems will be regulated by state agencies and by U.S. EPA in accordance with the Maximum Achievable Control Technology (MACT) rule for incinerators, the Clean Air Act (CAA), the Resource Conservation and Recovery Act (RCRA), and related laws and regluations. On-line monitoring of Hg, CO, NO_X, total hydrocarbons, and other species will facilitate compliant operation and will provide independent verification of process off-gas sample analyses.

Technology development within DOE and beyond

The need to monitor gaseous and particulate emissions extends well beyond DOE concerns to off-gases from thermal processes such as incineration and power generation as well as emissions from petroleum and metal refineries and chemical processing plants. A good deal of technology development has already taken place in response to this wider need, and commercial instrumentation is available for a number of applications. To expedite the acceptance and use of such instrumentation, U.S. EPA sponsors the Environmental Technology Verification program. This EPA program has already verified the operation of four technologies to monitor HF, NO, NH_3, and other compounds under simulated test conditions. A Phase I test of six commercial mercury monitors has been completed at a pilot scale combustion facility. The most successful mercury monitors will undergo Phase II testing at a commercial test facility.

Supplementing the U.S. EPA program, TMFA has been testing Continuous Emissions Monitoring (CEM) technologies as well. Given the advanced state of development and verification of commercial CEM technologies, an appropriate approach to meeting the INEEL CEM needs is the adaptation of these technologies to site-specific functions, requirements, and conditions. Most relevant in the HLW tank sphere of concern is monitoring volatile off-gases produced by the introduction of HLW and LLW into a melter. Since such measurements are needed to design and qualify melter operations, adaptations of commercial instruments for use with off-gas systems should be given the highest priority.

Meeting the site needs

The first step is for the site, utilizing technical expertise and assistance from the appropriate Core Technology group, and working in concert with regulators and interested stakeholders, to develop function and design (F&D) requirements to specify specific gases and concentrations to be monitored as well as data and engineering requirements. Following documentation of F&D requirements, the site, again assisted by DOE-EM OST as appropriate, will select a commercial monitoring system and identify a technology provider to assist it in the installation and demonstration of the monitoring technology in the planned pilot vitrification facility. To address the need to provide CEM technology for regulatory compliance of thermal processes, OST has taken the lead in the development and deployment of both new and commercial technologies.

VIP

ALTERNATIVE HIGH-LEVEL WASTE TANK DISPOSITION

New disposition approaches will present characterization and monitoring challenges.

Alternatives to HLW removal and processing

Removing, pre-processing, stabilizing, and shipping high-level tank wastes to long-term storage repositories present both substantial cost and technical risk. Accordingly, at this time DOE-EM is evaluating alternative scenarios for HLW tank disposition, including addressing the inherent risks associated with waste residuals that may remain following the completion of retrieval operations. Aspects of these closure scenarios include the following.

! Inventory remaining in the tanks must be assayed regarding the volume and composition of the wastes.
! Inventory remaining in the tanks must be stabilized to minimize the likelihood of leakage.
! Tank integrity must be assured before closure and subsequently monitored.
! Subsurface barriers may be required to guard against groundwater contamination in the event of tank leakage.
! Sensitive leak detection systems must be emplaced to ensure rapid detection of any leaks; contingency plans must be formulated for dealing with any leaks that might occur.

Such closure scenarios include post-closure monitoring to validate the assumptions and performance of the closure approach. Following retrieval operations, any residual waste that may be present is not expected to be uniformly distributed, nor of uniform composition, nor readily accessible with available risers. Information about residual waste is key to concluding retrieval operations as well as developing closure agreements and proceeding with closure operations. Timely sampling and analysis to support the on-going work of crews engaged in these operations is critical. Feedback of sample information in hours is essential to maintaining the productivity of the deployed crew.

Resulting characterization challenges

These challenges are similar to those faced previously, but demand greater refinement in this closure scenario.

- Careful estimation of residual waste volumes is needed. The Topographical Mapping System (TechID 130), developed by OST and previously deployed, has potential for this application, although further development appears to be needed. There is also interest in investigating alternative volume estimation methods.
- Characterization of the tank residual radionuclide inventory is needed as well. This presents significant technical challenges due to tank waste heterogeneity, difficulties in sampling, and self-absorption. Traditional sampling (where feasible) and radio-chemical analyses are available but costly due to the hostile environment inside the tanks, the risk of exposure, and the need for disposal of secondary waste; even this approach has its uncertainties due to the heterogeneity. Alternatives could involve robotically deployed radiation sensors. A related challenge is to establish the degree of characterization needed to support *in situ* closure scenarios. For example, it may be less important to provide a complete assay of tank contents than to provide a scientifically defensible short list of indicator parameters for subsequent leak detection and monitoring.
- Characterization of structural integrity will also be required. The structures involved include both the tanks themselves and subsurface barriers that would be installed to intercept any leaks that might develop.

Resulting monitoring challenges

Similarly, the nature of the objects being monitored will place stringent demands on monitoring systems.

- Improvements on current methods for monitoring tank integrity will be needed for both single-shell and double-shell tanks. Currently only a very small proportion of the tank wall is monitored at any given time, as making these measurements is cumbersome and time-consuming. One must anticipate increased monitoring requirements as a prerequisite to *in situ* closure. TFA and CMST-CP have been investigating tank integrity issues during recent years; these investigations will assume greater importance in this scenario.
- *In situ* sensor systems will be needed to provide early-warning detection capability for possible releases. These systems would be similar to those deployed in more typical subsurface monitoring scenarios, but would possibly need to be even more sensitive. In this setting one may be able to exploit known properties of the wastes in choosing indicator species or parameters One interesting possibility would be to artificially incorporate highly mobile indicators into the grout or other materials used to stabilize the wastes.

Strategies

Many of these challenges may be addressed by modifying technologies and strategies previously developed for this and other settings. The Topographical Mapping System (TechID 130) has already been mentioned as a tool for estimating the total volume of residual wastes. Providing an assay of the radio-nuclide content of residual wastes is more challenging because of the heterogeneity of the wastes and their self-absorption, particularly of alpha particle emissions. One possibility is to modify the Pipe Explorer™ (TechID 74) by inserting the everted membrane, with beta and gamma sensors and alpha scintillators, into slotted tubes that can then be used to probe the sludges and provide a three-dimensional sampling of emissions. For monitoring outside the tanks CMST-CP and others have been developing a variety of cone-penetrometer-deployed sensors for radiation and other indicator parameters that may readily be employed in this setting. For subsurface barriers, the SEAtrace™ technology (TechIDs 308, 2204) of introducing a non-naturally occurring gas to act as a sentinel may be attractive, although this would involve recurring expendables; the idea of emplacing mobile indicator species on the tank side of the barrier or even embedding them in the grouts in the tanks may also be attractive.

For other challenges the path forward is not yet so clear. In particular, the TFA and CMST-CP studies of tank integrity verification and monitoring have begun to identify approaches, with some promising results. These studies should be continued whether or not the alternative disposition strategies are adopted.

VIP

MONITORING MIXED WASTE TREATMENT PROCESSES AND EFFLUENTS

This **VIP** and its solutions involve multiple agencies, developers, and technology users.

Continuous Emission Monitors

Current baseline compliance strategies attempt to control emissions by setting operating parameter limits (OPLs) based on comprehensive trial runs. This methodology alone cannot, however, ensure facility emission compliance during routine operation.

The most direct and perhaps only way to ensure that Mixed Waste treatment facilities are operating properly is to implement continuous emission monitors (CEMs). If acceptable CEMs are used, not only are the regulators and stakeholders more confident that actual emissions are below allowable levels, but also the extent of waste feed characterization and expensive off-line performance testing can be reduced. DOE has undertaken a program of developing and testing CEMs for a range of pollutants including mercury, multiple metals, dioxins and furans (D/F), and particulate matter (PM). CEMs offer the potential to provide a continuous, near real-time record of emissions for a variety of potential pollutants, as well as optimized real-time process control.

Treatment systems are needed for DOE LLW and HLW, mixed waste (MW) and mixed transuranic (MTRU) waste. Thermal treatment systems such as melters, incinerators, and plasma systems have traditionally been used. In the future, other processes are expected to be implemented, including steam reforming, thermal desorption, and chemical oxidation. These will also operate under regulatory permits, which are becoming increasingly stringent. Developing CEMs for alternative treatment technologies is, therefore, a natural extension of current CEM development.

U.S. EPA promulgated its Maximum Achievable Control Technology (MACT) for Hazardous Waste Combustors rule in September 1999. The MACT Rule establishes regulatory requirements for the operation of incinerators and certain kilns. It does not explicitly cover other treatment processes, but permit writers are expected to model many permit provisions after the MACT Rule, particularly those regarding emissions. Moreover, worker safety, public health, and environmental responsibility demand that DOE treatment facilities not emit hazardous pollutants.

Particulate matter

Two primary challenges for PM CEM development are (1) instrument calibration and (2) facilities using high efficiency particulate air (HEPA) filters. EPA has proposed that calibration correlation coefficients should be at least 0.95. Achieving this requires that the CEM be challenged over its entire response range; challenging the high range requires a PM concentration greater than the MACT emission limit. Even though EPA has indicated that this may be allowable during brief calibration periods, this is not an option for DOE facilities if radionuclides are present. TMFA, CMST-CP, Florida International University and Oak Ridge TSCA incinerator investigators recently completed a comparative evaluation of commercial PM CEMs. The better CEMs are expected to satisfy the correlation requirement.

In facilities using HEPA filters in the effluent stream, PM levels downstream of the HEPA filter are orders of magnitude lower than the MACT Rule emission limit (34 mg/dscm). These downstream levels are below the level of detection (LOD) for the current generation of PM CEMs and may be below the LOD for EPA Reference Method 5i, against which PM CEM performance must be judged. An EPA/DOE National Technical Workgroup (NTW) has been established to address this problem. One technical challenge involves developing a protocol for calibrating the instrument at this low level, which may also require modifying Method 5i for PM levels below 1 mg/dscm. A second technical challenge is to establish a protocol for CEM use for compliance monitoring at MW treatment facilities. It is likely that CEM measurements will be nondetects during normal HEPA filter operation. However, if the HEPA filter were to fail, then the instrument must be able to detect that failure. The NTW study is designed to determine what type and degree of HEPA filter failures can be detected by a PM CEM. EPA and state permit writers are involved in this study, as are DOE-EM personnel including CMST-CP; the major work is taking place at the Mississippi State University's Diagnostic and Instrumentation Analysis Laboratory (DIAL) under DOE-EM support.

Mercury

Mercury is present in many DOE waste streams, although exact quantities and forms are rarely known. Most treatment facilities do not presently have control technology for mercury emissions; hence facility designs and permits assume that all mercury present in the feed is emitted to the atmosphere. The new MACT Rule emission limit for mercury (130 µg/dscm) is two to three times lower than current allowable limits. At the MACT off-gas concentration, and assuming no removal in the treatment process, the maximum waste feed mercury concentration would need to be less than about 10 ppm. Sampling and analyzing waste feed for mercury to that level is very costly and would greatly increase the potential for worker exposure to radionuclides. Reliable CEM technologies are available; DOE could easily offset their cost with savings in waste characterization.

Previous testing of mercury CEMs by DOE and EPA found that systems needed to be made more rugged to withstand the very harsh conditions potentially found in some treatment facility off-gas streams: high PM, moisture, and sulfur dioxide all have caused severe maintenance problems. Additionally, detectability and accuracy need to improve somewhat. TMFA is conducting a long-term evaluation of several mercury CEMs at TSCA. Florida International University (FIU) and DIAL will assist in the test and data analysis. These efforts are being coordinated with the EPA Environmental Technology Verification Program, which conducted a Phase I test of five commercial mercury CEMs in January 2001 at a pilot-scale facility and is now proceeding with Phase II testing at full-scale facilities. Novel mercury monitoring methodologies such as cavity ring down spectroscopy, a high-resolution compact field spectrometer, and a surface acoustic wave sensor are also being developed; these are related to technologies previously developed by DOE-EM OST for use in other settings.

Multiple metals

The MACT Rule multiple metals (MM) include mercury, cadmium, lead, arsenic, beryllium, and chromium. With the exception of mercury, DOE facilities readily meet the MM emission limits; these metals are present mostly in the particulate phase and DOE facilities have extensive PM control for radionuclides. The incentive to deploy MM CEMs comes from stakeholder interests in assuring that hazardous metal emissions are monitored and communicated on a continuous basis, as well as from a desire to minimize waste feed analysis costs. Previous testing found that most of the instruments had difficulty detecting mercury and arsenic with adequate precision and accuracy. Detectability and interferences remain as technical challenges for application at most waste treatment facilities.

Dioxins and furans

Dioxins and furans (D/F) present a unique challenge in that their principal source is formation in the combustion system or the air pollution control system. The mechanisms for this formation are not yet totally understood despite considerable research. Complicating the problem further, the regulatory levels of D/F are extremely low. Individual congeners must be measured down to about 0.005 ng/dscm, or about 5 parts per quadrillion; no "real-time" monitor can achieve these LODs. The current method for measuring D/F involves sampling for two to six hours followed by off-site analysis, which takes four to six weeks. Therefore, studying how D/F formation responds to process conditions is an extremely laborious and costly procedure. To address this problem, a coordinated EPA/INDP program is developing a D/F CEM with high selectivity and sensitivity for individual congeners to aid in the study of the formation and destruction mechanisms for DOE treatment systems. The technical challenge is to understand D/F formation and destruction sufficiently well that a simple, less expensive monitoring technique, perhaps involving detecting precursors or indicators of the relevant D/F congeners, may be developed. The ability to have data within minutes rather than weeks will allow researchers to generate data much efficiently over a much wider set of experimental conditions.

VIP LONG-TERM MONITORING OF REMEDIAL MEASURES

All major DOE sites require long-term monitoring of passive remedial measures, which include natural processes, containment, reactive barriers, and stabilization operations.

The SCFA three-pronged approach

The SCFA has identified a three-pronged approach to meeting these needs. One approach will address groundwater monitoring needs by developing *in situ* sensors capable of meeting compliance requirements for VOCs, followed by heavy metals and radionuclides. This will be supplemented by employing advanced geophysical tools for monitoring contaminant transport fluxes in the vadose zone, combined with geostatistical sampling techniques to provide ground truth results. Finally, in larger areas, particularly those difficult to access, aerial monitoring platforms will be developed to measure key indicators of contaminant breaching.

Containment and stabilization

In view of the importance of containment as the preferred remedy at DOE sites, the DOE-EM OST has sponsored several technology development projects for verification and monitoring of the caps and covers used with buried waste. These include remote sensing systems development, subsurface barrier validation using the SEAtrace™ monitoring system, a monitor for demonstrating the effectiveness of barrier installation and long-term performance using electrical resistance tomography, and the advanced tensiometer.

In 1996 the OST CMST-CP, working with SCFA, identified areas of needed technology development based on assessment of Technology Development Needs Statements, Site Technology Deployment Plans, and site cleanup schedules and plans. One need identified through this process was for monitoring the emplacement and effectiveness of subsurface barriers. A Program Research and Development Announcement (PRDA) solicitation was commissioned by the National Energy Technology Laboratory (NETL, at that time the Federal Energy Technology Center, FETC). The "Subsurface Barrier Validation with the SEAtrace™ Monitoring System" project was selected competitively for development by industry; the resulting technology is a gaseous tracer-based verification system for use with subsurface containment barrier structures.

Another technology need identified was for improved, preferably real-time, field characterization and monitoring techniques for the remediation of contaminated soils. To address this need, OST leveraged support from the Accelerated Site Technology Deployment (ASTD) program and managed the technical progress of the project, "Radiation Tracking System for Delineating Contamination in Soils." This ASTD project involved the integration and implementation of four existing technologies developed with EMSP and other OST support: (1) mobile radiation tracking system, (2) portable high-purity germanium sensors for *in situ* gamma spectrometry, (3) the Warthog system for 3D, real-time excavation screening support, and (4) software packages of provide data analysis for decision support.

Monitored natural attenuation

DOE-EM will continue to need to develop long-term monitoring solutions for other requirements. The future focus will be on monitoring of post-closure sites and natural and *in situ* remediation processes (such as monitored natural attenuation, bioremediation, and reactive barriers) for meeting regulatory and stakeholder requirements. Monitoring of these processes will also determine their efficacy and help determine measures for their enhancement.

Regulatory acceptance and EMSP research

A requirement for regulatory buy-in for natural attenuation and/or bioremediation for organic contaminants in the subsurface is an ability to demonstrate that actual decontamination is occurring, rather than mere diffusion of the contaminant into a larger volume. Several EMSP projects are exploring potential techniques; the most likely path forward will be to assess the most successful of these projects. One project, for example, involves using ratios of carbon isotopes to determine whether or not biodegradation is occurring; other isotopic ratios have been used to study the exchange between different aquifer layers. Another EMSP project explores the use of precise isotopic ratio measurements of chlorine and carbon to determine the mechanism and extent of in situ bioremediation of chlorinated organic solvents. Several other projects involve genetic engineering approaches to developing microorganisms for bioremediation of chlorinated organics in mixed wastes with high radiation levels as well as of a variety of other contaminants found at DOE sites.

The future challenge for DOE-EM will be to guide these basic and applied research results from EMSP through development to regulatory and stakeholder acceptance and ultimate field implementation.

REAL-TIME MONITORING AND CHARACTERIZATION OF SOILS AND GROUNDWATER

This **VIP** involves building on the long history of OST and CMST-CP sensor technology and integration successes within DOE-EM.

Early advances

Through OST, DOE-EM has followed a progressive approach toward addressing characterization, monitoring, and modeling of groundwater and soil contamination. In the early years the focus was on developing field analytical instruments for meeting site screening characterization needs. The analytical instruments developed have been used for surface soil characterization for VOCs, heavy metals, and radionuclides as well as in conducting well-head analyses of water samples.

Expedited Site Characterization

Later technology development combined these field analytical tools with deployment platforms such as the cone penetrometer and GeoProbe™ to enable subsurface characterization for these contaminants of concern. These field analysis capabilities were coupled with the development of decision support tools such as data fusion and statistically-based sampling techniques, culminating in a streamlined site characterization approach known as Expedited Site Characterization (ESC).

Researchers at Argonne had identified a methodology and procedure for remedial site characterization at Department of Interior and Department of Agriculture sites. A private sector organization had also developed and was practicing a similar approach. OST, through CMST-CP, began funding further developments for DOE sites in February 1993. The ESC process emphasizes the use of a variety of minimally intrusive technologies to optimize sampling locations and thereby minimize monitoring well installation. On-site decisions about subsequent sampling locations are made daily; this is made possible by the use of on-site analytical capabilities. This approach cuts the time necessary for full site characterization from many months or even years to a few weeks.

A parallel OST/CMST-CP project at Ames Laboratory that began in FY94 focused on the use of the ESC methodology as a driver for accelerated transfer of site characterization technologies. This work characterized contaminated sites using state-of-the-practice and new technologies simultaneously to enable quantitative evaluations of the merits of the new technologies. The work of this project is summarized in the OST ITSR *Expedited Site Characterization* (TechID 77). The ESC approach was accepted as an ASTM standard practice (D6235-98a, *Standard Practice for Expedited Site Characterization of Vadose Zone and*

Ground Water Contamination at Hazardous Waste Contaminated Sites) to provide guidance on site characterization. These techniques to characterize the perched aquifer at Pantex and the SRS D-Area Oil Seepage Basin during FY 1995, the Central Nevada Test Area and a Formally Utilized Sites Remedial Action Program location in Ohio during FY 1997, and numerous other Federal and non-Federal sites.

Electrical Resistance Tomography and Electrical Impedance Tomography

Another set of technologies aimed at improving real-time subsurface monitoring and characterization involves Electrical Resistance Tomography (ERT) and Electrical Impedance Tomography (EIT). OST has sponsored projects involving ERT for subsurface imaging, tank leak detection, and monitoring. ERT has been used as a monitor for demonstrating the effectiveness of barrier installation, subsurface remediation of DNAPLs, and long-term performance of remediation measures including monitored natural attenuation. One of the most challenging and important remaining subsurface characterization needs is to develop reliable methods for locating DNAPLs in the subsurface; EIT has been and is being explored for this purpose. Basic science research supported by EMSP continues to explore fundamental aspects of a variety of electromagnetic methods potentially useful for subsurface imaging.

The new generation of soil and groundwater sensors

DOE sites have continued to express a high priority need for improved field characterization methods; this need has evolved from field screening and characterization applications to final assessment applications. For example, several sites have expressed the need for real-time characterization of soil for radionuclide and heavy metal contamination during excavation to judge when it is appropriate to stop excavating. Such real-time characterization is needed also to perform waste sorting and separation based on contamination by radionuclides and/or heavy metals; effective separation would reduce the volume of contaminated soils to be dealt with and hence the cost of remediation.

DOE-EM should place a priority on the development of improved real-time subsurface characterization and monitoring techniques by FY 2006. The focus during the next few years should involve engineering design, development, and integration of field analytical tools to work with various platforms to provide needed solutions for technology performance gaps identified in **APPENDIX A**. These gaps include real-time subsurface characterization in deep, hard-to-access areas beyond the reach of existing platforms. Also, integration of real-time characterization tools with excavation platforms and conveyor belt operations should be pursued to enable real-time differentiation of soil based on contamination by VOCs, heavy metals, and radionuclides.

Again, an attractive strategy will be to follow the progress of several EMSP projects. Promising sensing techniques under EMSP development include Laser-Induced Breakdown Spectroscopy (LIBS) and electrochemical techniques for subsurface characterization of heavy metals and radionuclides; Micro-Electro-Mechanical Sensors (MEMs) with applicability for all contaminants of concern; and other new schemes for detecting radionuclides and heavy metals; see the "Recent R&D Projects" panels in **APPENDIX A**.

VIP

IN SITU DETECTION OF SURFACE CONTAMINATION TO FREE-RELEASE GOALS

This **VIP** involves a collaboration of several OST programs (DDFA , INDP, and CMST-CP), sharing expertise and resources to solve a prominent challenge facing DOE-EM.

Deactivation and Decommissioning safety challenges

The varied nature of facilities undergoing deactivation and decommissioning (D&D) presents a wide range of contaminant types and site-specific characterization challenges, each typically requiring a detector tailored specifically to the contaminant being measured and its matrix. One such challenge involves the characterization of property and equipment contaminated with beryllium (Be).

During DOE characterization and D&D efforts at the Rocky Flats Environmental Technology Site (RFETS) and elsewhere, workers may come into contact with property and equipment contaminated with Be. RFETS is concerned about the safety of workers from potential exposures to airborne Be re-suspended from surfaces and the potential liability associated with property release. Epidemiologists associated with the Beryllium Health Effects Study have expressed the opinion that with respect to berylliosis no safe exposure level exists for airborne Be. They have also indicated that dermal exposure to Be may result in sensitization, especially if the skin is cut or abraded. A primary site concern is the prevention of Chronic Beryllium Disease (CBD).

A portable surface and air beryllium monitor

DOE would benefit greatly from the implementation of a nearly instantaneous and continuous real-time monitor to measure both surface and airborne Be contamination. This monitor could be utilized to improve worker safety by providing an alarm for airborne Be. As a surface contamination monitor, it will allow for more effective free release of property. It will also aid in the identification of Be-contaminated work areas prior to potential worker exposure. By providing reliable real-time worker safeguards, real-time Be monitoring will increase worker efficiency and accelerate site closure.

Numerous other DOE sites may be able to benefit from real-time surface and/or air Be monitors, since these sites must establish their own Be exposure levels in response to the Chronic Beryllium Disease Prevention Program, promulgated as Title 10, Code of Federal Regulations, Part 850 December 8, 1999 (10 CFR 850).

The development of a real-time monitor for airborne and surface Be contamination has been identified as an OST priority. The monitor will be required to measure all types of Be inhalation hazards, including salts, oxides, and metal, in both air and surface surveys. It must possess sufficient sensitivity, accuracy, and precision to verify meeting or exceeding site action limits and other limits. It will need a lower detection limit of 0.1 micrograms Be per cubic meter for airborne measurements and 0.2 micrograms Be per hundred square centimeters for surface measurements.

The Be monitor is being developed by a commercial firm, Science & Engineering Associates (SEA). To initiate the development and funding process INDP issued a Request For Proposals (RFP) through NETL. CMST-CP personnel canvassed the DOE complex, including of course RFETS, to determine technical specifications. A Technical Evaluation Committee was formed to evaluate the proposals received, consisting of members from INDP and CMST-CP along with advisors from RFETS, Los Alamos National Laboratory (LANL), and Lovelace Respiratory Research Institute (LRRI). SEA is currently funded to develop the real-time beryllium monitor based on their winning R&D proposal. SEA drafted and presented an Engineering Design shortly after funding was awarded; review and revision comments provided by RFETS end-user (D&D and Environmental Safety and Health), INDP, and CMST-CP personnel. Delivery and on-site evaluation of the prototype instrument is slated for early 2002.

Experience and teamwork

SEA's solution is based on its extensive experience with LIBS instrumentation. An important part of SEA's instrument design is proper consideration of aerosol behavior and properties, including size distribution. SEA will team with Lovelace Respiratory Research Institute (formerly the Inhalation Toxicology Research Institute) to provide the world class aerosol science capabilities needed to ensure that the end result is a robust instrument ready to meet the required performance certifications.

Demonstration and delivery

A critical development step is an on-site demonstration including federal and state regulators at a RFETS D&D facility. Because of the critical importance of regulatory acceptance to the ultimate deployment of innovative technologies, every effort is being undertaken to involve regulatory bodies early in the development process, to help them acquire confidence in the instrument.

As of May 2002, two prototype airborne and surface beryllium monitors have been fabricated, tested with samples from the Lovelace Respiratory Research Institute and Rocky Flats following NIOSH guidelines, and are being demonstrated and deployed at Rocky Flats and Paducah. Additional monitors will be fabricated according to market demand.

VIP

UNDERSTANDING NATURAL PROCESSES AFFECTING CONTAMINANT FATE AND TRANSPORT

Filling this gap in basic scientific understanding is a high priority **VIP** for DOE-EM.

Reliable predictions needed to support closure and long-term stewardship

SCFA's highest priority Work Package has been "Vadose and Saturated Zone Characterization, Monitoring, Modeling, and Analysis." Related need areas identified by SCFA include improved understandings of permeability patterns, contaminant inventories, and distribution and movement in the vadose zone. Also needed are tools to better predict groundwater flow and transport.

Needs for improved subsurface characterization techniques were also cited in *Research Needs in Subsurface Science* (National Research Council, March 2000), which noted that "there is inadequate understanding of the details of the characteristics that must be understood in order to make reliable predictions of fate and transport. In addition, there are no adequate technologies for determining subsurface characteristics over large volumes with either direct or indirect techniques." It was also pointed out that "little progress has been made on developing predictive models that incorporate the entire range of processes that may affect contaminant transport." Every major DOE site has identified needs for defining the location and spatial distribution of contaminants, for estimating quantitatively the extent of contamination, and for developing or identifying methods to monitor the movement of subsurface contaminants.

Previous studies

Previous DOE-EM CMM projects in this area have included studies of flow and transport in fractured rock, groundwater modeling, and data fusion techniques for combining and interpreting information from diverse geophysical techniques. EMSP has also sponsored numerous studies in this area including assessments of factors that contribute to the transport of specific contaminants in the subsurface and the development of a variety of geophysical techniques for improved subsurface characterization. EMSP studies of transport mechanisms and soil fixation methods are related to high-priority needs cited at Hanford, Oak Ridge, and other DOE sites.

Geophysical characterization tools

DOE-EM should continue to develop geophysical characterization tools to better delineate subsurface characteristics. Many such techniques are being developed by the EMSP, including very early time-domain electromagnetic (VETEM), seismic, electromagnetic, and radar techniques, and combinations of these to provide high resolution subsurface mapping. Advances in these geophysical tools will lead into further development and demonstration phases to address DOE site needs for delineation of burial grounds and identification of buried wastes.

Contaminant fate and transport

With respect to other characteristics affecting flow and transport properties, DOE-EM Core Technology groups can aid in identifying site-specific needs for the following.

- Improving capabilities for characterizing the physical, chemical, and biological properties of the subsurface, particularly for deep and complex geologic settings

- Characterizing physical, chemical, and biological heterogeneity and providing improved models to enable more reliable predictions of migration

- Identifying and developing methods to integrate data collected at different spatial and temporal scales to improve estimates of contaminant and subsurface properties

- Incorporating complexities such as colloid formation, biological activity, and transport paths in fractured rock into transport models

- Conducting new experimental and modeling studies to account for the interacting chemical, physical, and biological processes that determine contaminant fate and transport

DOE-EM OST programs have supported projects involving geophysical characterization tools since their beginning; some of the earlier work was similar to basic science research efforts now being conducted by EMSP. It is anticipated, therefore, that future contributions in this area will involve working with EMSP and other programs to identify areas in which more basic research is needed and with the sites and other DOE-EM organizations to identify the EMSP projects that appear to be most suitable for extended demonstrations or deployment.

IMPROVED METHODS AND STRATEGIES FOR MANAGING AND INTERPRETING DATA

Evolution in characterization and monitoring technology will require parallel advances in data acquisition, storage, and interpretation as well as in regulatory strategies.

New technologies yield new types of data

Previous DOE-EM CMM R&D projects have produced significant advances in the efficient and effective use of real-time data in characterization (e.g., ESC and Hydrogeological Data Fusion) and remediation (e.g., Adaptive Sampling and Analysis Programs, PLUME - Groundwater Modeling Software, and RSS Software for Soil Excavation Control for Delineating Contamination in Soils). These projects provided ways of handling data generated on site and available within at most a few hours of sampling from a variety of types of measurements, and combining such data in producing reliable, accurate, and defensible characterization or remediation decisions.

There are three conceptual components to such systems.

- Data collection systems (hardware and software)

- Decision algorithms and concepts which enable better understanding and use of such data (data fusion and related decision support tools)

- Establishing and documenting processes to ensure regulatory and stakeholder acceptability of data obtained and decisions made

Data collection systems

Past advances in data collection systems include transmitting data from mobile radiation sensors along with global positioning system (GPS) location data by radio link to a central on-site facility. This process enabled real-time mapping of radiation levels at Fernald in support of soil excavation and remediation decisions.

The RSS Software mentioned above provides the real-time mapping and decision support for using this data.

Decision models and regulatory acceptance

Past advances in decision algorithms and concepts include the use of Bayesian geostatistical analysis to combine “soft” prior information (historical records, computer modeling results, institutional memory, etc.) about the likelihood of contamination at various locations on a site with “hard” sampling data to provide updated estimates of contamination likelihood or contaminant concentration contours. Adaptive Sampling and Analysis Programs (ASAPs) is a peer-reviewed procedure for such analyses. Peer review has also aided in the regulatory and stakeholder acceptance of the use of innovative data and decision methods, as with ASAPs and ESC; the latter, for example, is the topic of ASTM Standard D6235-98a.

Future development: hardware

Future challenges in this area will be to make similar advances with regard to long-term monitoring. Commercial entities are already working on developing and marketing monitoring networks which will be able to gather real-time data from in situ sensors, and this is a topic of considerable interest in the research communities (national laboratory and academia) as well. DOE-EM should promote and participate in appropriate forums for exchanging information about the state of the technology, on one hand, and DOE, regulator, and stakeholder requirements, on the other. Particular requirements for DOE long-term monitoring applications will include technologies to implement data quality issues such as sensor self-calibration and self-testing, data transmission and recording integrity comparable to current chain-of-custody protocols, etc., and development of automated data screening algorithms.

Future development: decision strategies

Parallel development of design and decision paradigms is needed. Such development must involve regulatory agencies, interested regulated parties, and ultimately other stakeholder groups. One path forward is to continue presenting proposed innovative methodologies for peer review and acceptance in professional publications as well as such forums as ASTM. Another is continued DOE-EM participation in inter-agency task groups such as the Interstate Technology Regulatory Council (ITRC), an association primarily of state regulators interested in easing the path toward adoption of innovative environmental technologies, and the Long-Term Groundwater Monitoring Task Committee of the American Society of Civil Engineers’ Environmental & Water Resources Institute, consisting of professionals from DOE, DoD, U.S. EPA, U.S. Geological Survey, academia, and the private sector, and tasked with preparing a monograph *Long-Term Monitoring Design for Contaminated Groundwater Sites*. Such participation not only brings DOE expertise to the evolution of regulatory thinking on these issues but also ensures that DOE concerns will be represented in that evolution. In addition, DOE-EM should collaborate with other government agencies in sponsoring workshops on optimal monitoring and modeling designs, technologies, and software with invited participants from all sectors.

SUMMARY OF SOLUTION PATHS AND STRATEGIES

From the **VIPs** presented here we can abstract several general strategies and paths which DOE-EM can use for future R&D. These are outlined below, with reference to the **VIPs** which followed or are following each one.

- **Tryouts by invitation.** Organize comparative testing of invited commercially available technologies; identify those most likely to meet DOE requirements; fund further development by the vendor as needed to meet those requirements. **VIPs** following this path include the Mercury and Particulate Matter Continuous Emissions Monitors for Waste Treatment Effluent Monitoring. Development of the Mercury CEM is a joint effort with the U.S. EPA Environmental Technology Verification Program.

- **Procurement through a DOE lab.** Prepare functional and design requirements appropriate for the intended site deployments; work with a DOE laboratory to identify a technology provider who can meet those requirements, possibly with some funded development work. This path overlaps somewhat with the previous one; **VIPs** following it include Continuous Emissions Monitors for treatment process effluents.

- **RFPs to industry.** Develop functional requirements corresponding to site needs; publish these in Requests For Proposals (RFPs); review responses from industry and other respondents; contract technology development and provide oversight and review as needed. **VIPs** following this path include the Surface and Air Beryllium Monitor and the SEAtrace™ Barrier Validation System.

- **Leapfrog from past successes.** Identify successful technology solutions for related problems; fund adaptation, modification, and/or integration as needed for the current DOE requirement. **VIPs** following this path include modifying Neutron Etch Recorders for detecting and measuring radioactive contamination under tank floors and modifying the Pipe Explorer™ for characterizing sludges and difficult to access portions of tanks and other spaces.

- **Publicize unsolved problems.** Present DOE requirements for previously unaddressed problems to research communities including EMSP and DOE labs. **VIPs** following this path include next-generation robust, in situ, autonomous, self-calibrating and self-maintaining sensors for long-term monitoring; data collection methods and protocols for such sensors; and in situ tank waste characterization technologies capable of providing data satisfying regulatory certification requirements.

- **Fine-tune and expand available tools.** Fund integration and/or incremental evolution of successful technologies. **VIPs** following this path include soil excavation control technologies for precise, timely on-site delineation of contaminated regions during remediation; Expedited Site Characterization; Electrical Resistance Tomography; and Electrical Impedance Tomography.

- **Collaborate with researchers and stakeholders.** Organize and conduct workshops and participate in multi-agency and similar task groups on emerging technologies, DOE requirements, and emerging regulation. **VIPs** following this path include long-range planning for sensor technology development; development and evolution of regulatory paradigms and reference method performance specifications; evolution of methods, standards, and regulations for data reporting, recording, and interpretation; and parallel development of technology and regulatory standards for PM emissions for processes using High Efficiency Particulate Air (HEPA) filters.