APPENDIX A

PROBLEM AND OPPORTUNITY AREAS

Identification of Needs And Technology Gaps

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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 groundwater. (***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 containment 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™ 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℠ Drilling (55)
StrataSampler™ (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 Explorer™ (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 unprecedented 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***, ***WNM*****C**, ***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.