# INTRODUCTION

## OVERVIEW

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

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

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

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

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

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

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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), and ***NMFA*** (Nuclear Materials Focus Area), along with ***ESP-CP*** (Efficient Separations Crosscutting Program), ***RBX-CP*** (Robotics Crosscutting Program), ***INDP*** (Industry and University Programs), ***EMSP*** (Environmental Management Science Program), and ***CMST-CP***.

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

**Identification of Goals**

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

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

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

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

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

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

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

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

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

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

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

**SUMMARY** recaps the presentations of the previous parts.

## A CMM R&D VISION FOR DOE-EM

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

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

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

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

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

### Science and Technology Development Visions; VIPs

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

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

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

## Waste, Source, and Nuclear Materials Characterization

**By 2012 DOE should**

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

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

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

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

**VIPs** include the following:

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

## Process and Product Monitoring

**By 2012 DOE should**

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

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

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

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

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

**VIPs** include the following:

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

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

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

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

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

## Long-Term Monitoring

**By 2012 DOE should**

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

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

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

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

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

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

**VIPs** include the following:

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

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

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

**Nondestructive Methods**

**By 2012 DOE should**

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

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

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

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

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

**VIPs** include the following:

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

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

## Improved Scientific Understandings

**By 2012 DOE should**

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

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

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

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

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

**VIPs** include the following:

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

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

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

## STRATEGIES

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

### The Role of the OST CMST-CP

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

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

### Site Needs-Based Science and Technology Development

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

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

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

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

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

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

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

**Other OST Strategies**

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

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

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

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

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

**Other Avenues**

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

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

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

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

**TechID 2238: Ribbon NAPL Sampler**