Sensors and Monitoring Systems for Long-Term Performance Monitoring – Three Perspectives

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Abstract
We summarize three views concerning the perceived needs and recent progress in meeting the needs for sensors and monitoring systems for metals and radionuclides in the subsurface: (1) as described in the DOE Long Term Stewardship Science and Technology Roadmap; (2) as described in the observations and conclusions of the Long Term Monitoring Sensors and Analytical Methods Workshop; and (3) as being addressed by the Advanced Monitoring Systems Initiative (AMSI). Topics addressed will include vadose zone and groundwater tritium monitoring, strontium-90 monitoring, technetium-99 monitoring, a wireless moisture monitoring system, and Cr(VI) monitoring.

Three Perspectives
The need for advanced sensors and monitoring systems to address U. S. Department of Energy and other federal requirements in the area of long-term performance monitoring is well known. Several studies and actions that have assessed the sensors and monitoring needs and some that have begun to address them have been conducted or are under way. The perspectives of three of the more prominent studies and activities conducted under the auspices of the DOE Office of Environmental Management, Office of Science and Technology, will be described in separate sections below. They are the sensor and monitoring perspectives of the:

- Long-Term Stewardship Science and Technology (LTS S&T) Roadmap,
- Long-Term Monitoring Sensor and Analytical Methods Workshop, and
- Advanced Monitoring Systems Initiative (AMSI)

We will address them in order of increasing focus on fulfillment of specific, detailed site needs, rather than in their order of occurrence.

Sensors and Monitoring in the DOE Long-Term Stewardship S&T Roadmap
The Long-Term Stewardship Science and Technology (LTS S&T) Roadmap was developed under the sponsorship of the Office of Long-Term Stewardship. This was a rather broad, high level effort, involving a large interdisciplinary team consisting of subject matter experts from industry and academia, federal and state regulators, stakeholder groups, DOE national laboratories, DOE site contractors (end users), and other federal agencies. The Roadmap recommends research and development (R&D) pathways to provide a system of integrated capabilities needed for DOE to implement an effective LTS program. The R&D recommended in the Roadmap aims for significant performance improvements and cost savings within the next 2 to 10 years. A draft of the LTS S&T Roadmap was published in October 2002 (DOE 2002).

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DOE defines Long Term Stewardship as “the physical controls, institutions, information, and other mechanisms needed to ensure protection of people and the environment at sites where DOE has completed or plans to complete ‘cleanup’ (e. g., landfill closures, remedial actions, removal actions, and facility stabilization).” (DOE 2001a) According to its latest public estimate, DOE will be responsible for LTS at approximately 129 sites and residual radioactive materials and toxic metals at those sites will remain as potential threats to health and the environment for tens to thousands of years (DOE 2002).

The LTS Roadmap team considered Long-Term Stewardship as an integrated system that must perform four functions and must include seven key capabilities essential for fulfilling those four functions. The four functions and associated key capabilities are indicated in Table 1, below, where items involving Sensors, Sensor Systems, and Monitoring are shown in bold type for emphasis. The Roadmap team noted that all the key capabilities have some connection with at least two of the LTS functions and that some key capabilities, e. g., LTS Performance Verification and Monitoring, are important for all four LTS functions. Figure 1 shows the interdependence of the Key Capabilities, where those involving Sensors, Sensor Systems, and Monitoring (circled in red) clearly have a high degree of interdependence.

### Table 1. LTS Functions and Key Capabilities.

<table>
<thead>
<tr>
<th>LTS Functions</th>
<th>Key Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contain Contaminants</td>
<td>1. Site Conceptualization and Modeling Tools</td>
</tr>
<tr>
<td></td>
<td>2. Contamination Containment and Control Systems</td>
</tr>
<tr>
<td>Monitor the Site and the LTS System</td>
<td>3. Sensors and Sensor Systems for Site Monitoring</td>
</tr>
<tr>
<td>Communicate Within and Beyond the LTS System</td>
<td>4. Preservation and Communication of Site Information</td>
</tr>
<tr>
<td></td>
<td>5. Site-Community Relations</td>
</tr>
<tr>
<td>Manage the LTS System</td>
<td>6. LTS System Performance Verification and Monitoring</td>
</tr>
<tr>
<td></td>
<td>7. Effective and Survivable Land-Use Controls</td>
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</table>
The Roadmap team then identified and prioritized proposed capability enhancements according to their anticipated ability to provide one or both of the following benefits:

1. Without the enhancement, DOE closure sites may have difficulty meeting regulatory requirements.
2. The enhancement would substantially reduce risks to human health or the environment, reduce life-cycle stewardship costs, or decrease technical uncertainties.

In the first case, the enhancement fills an unmet need of site stewardship. In the second, the enhancement substantially increases the effectiveness and efficiency.

In the case of Key Capability 3, Sensors and Sensor Systems for Site Monitoring, the recommended capability enhancements were:

3.1 **Identify contaminant monitoring needs** for all media of potential transport or exposure and fill technology gaps
3.2 Establish site-specific parameters for on-site and off-site human exposure routes
3.3 **Improve** sensors and sensor systems for monitoring active and passive safety systems

In the case of Key Capability 6, LTS System Performance Verification and Monitoring, the recommended capability enhancements most pertinent to sensors and monitoring were:

6.1 **Provide** techniques and technologies to demonstrate, verify, and monitor long-term performance and management of contamination containment and control systems

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**Figure 1. Interdependence of LTS Key Capabilities.**
6.2 **Improve** tools to verify performance of contamination containment and control and monitoring subsystems

6.3 **Provide** tools to verify and monitor the overall (technical and non-technical) performance of the LTS system

6.5 **Improve** tools for collecting, analyzing, evaluating and disseminating performance data

Please note the repeated occurrence of “**Provide**” and “**Improve**” in the two preceding lists of recommended capability enhancements.

Based on the LTS S&T Roadmap discussion, it appears the two principal benefits to be realized through achievement and implementation of the recommended capability enhancements are:

- Reduce the risk of LTS system failure (through early identification of LTS component failures)
- Avoid unnecessary costs

It is a balancing act involving risk to human health and the environment versus cost. DOE can minimize one or the other; not both.

The LTS Roadmap team also identified targets that could be achieved in the near term (within the next two to ten years) for the recommended capability enhancements. The Near-Term Targets and the projected investment amount and duration for their achievement are indicated in Table 2, below. The type of challenge involved, i. e., Science (knowledge development) or Technology (tool development) is also characterized.

In the area of sensors and monitoring, the goals and objectives of the LTS S&T Roadmap are many and laudable but they lack definition, e. g., regarding specific analytes, surrogates, and indicators, and especially regarding measurement performance requirements such as limits of detection, reproducibility, and required dynamic range. Also, guidance concerning the relative priorities of the recommended development activities is not provided. To the best of our knowledge, no funding has been specifically allocated for pursuit of the goals and objectives of the LTS S&T Roadmap in the area of sensors and monitoring and no projects have been funded in that area as a result of the LTS S&T Roadmap activity.
Table 2. Near-Term Targets Related to LTS Sensors and Monitoring

<table>
<thead>
<tr>
<th>Target</th>
<th>Type of Challenge and Projected Investment (Smillion)</th>
<th>Projected Investment Duration (months)</th>
</tr>
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<tbody>
<tr>
<td>Provide defensible methods for defining monitoring systems:</td>
<td>Principally a science challenge (knowledge development)</td>
<td>48</td>
</tr>
<tr>
<td>Define hazards, analytes, surrogates, indicators.</td>
<td>2</td>
<td></td>
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<tr>
<td>Define thresholds, action limits.</td>
<td></td>
<td></td>
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<tr>
<td>Provide new sensors and sensor systems:</td>
<td>Principally a Technology Challenge (tool development)</td>
<td>90</td>
</tr>
<tr>
<td>For wide range of geologic, hydrologic, biologic, chemical and thermal</td>
<td>22</td>
<td></td>
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<tr>
<td>analytes, surrogates and indicators</td>
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<td></td>
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<tr>
<td>High accuracy [auto-calibrating]; high sensitivity</td>
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<td></td>
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<tr>
<td>In situ; Non-invasive; volume integrating</td>
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<td></td>
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<td>High reliability; low maintenance; long life</td>
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<td>Miniature, easy emplacement, replacement</td>
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<tr>
<td>Remotely operable; wireless</td>
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<tr>
<td>Deploy standard options and design aids for tailoring (automatic)</td>
<td>Involves both Science and Technology Challenges</td>
<td>19</td>
</tr>
<tr>
<td>monitoring subsystems:</td>
<td>(knowledge and tool development)</td>
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<tr>
<td>To reduce amount of stationary sampling</td>
<td>1.4</td>
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<tr>
<td>To reduce capital and operating costs by 40% during first 10 years of</td>
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<tr>
<td>monitoring and more in later decades</td>
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<td></td>
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<tr>
<td>Optimize the monitoring system</td>
<td>Mainly Science Challenge</td>
<td>120</td>
</tr>
<tr>
<td>Use contaminant surrogates and/or performance indicators</td>
<td>Mainly Science Challenge</td>
<td>16</td>
</tr>
<tr>
<td>Provide tools to [auto-]verify the performance of the contaminant</td>
<td>Mainly Science Challenge</td>
<td>4.2</td>
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<tr>
<td>containment and monitoring systems</td>
<td></td>
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<tr>
<td>Provide action criteria for collecting, analyzing, and evaluating</td>
<td>Mainly Science Challenge</td>
<td>2.3</td>
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<tr>
<td>representative data on security and exposure systems (to reduce cost</td>
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<td></td>
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<tr>
<td>by 60%)</td>
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<tr>
<td>Provide tools to [auto-]verify the performance of the contaminant</td>
<td>Projected Total for Sensors and Monitoring Systems ≈$47 million</td>
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<td>containment and monitoring systems</td>
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Sensors and Monitoring in the Long-Term Monitoring Sensor and Analytical Methods Workshop.

The Characterization, Monitoring, and Sensor Technology Crosscutting Program and the Subsurface Contaminants Focus Area teamed to conduct the Long-Term Monitoring Sensor and Analytical Methods Workshop, in Orlando, Florida, in June 2001. The workshop focused strongly on DOE site needs as documented by Site Technology Coordination Groups that had been formally established by DOE. The workshop involved approximately 120 participants, and a formal report of workshop findings and recommendations was issued (DOE 2001b). Although the Orlando workshop report addressed sensors and analytical methods for organic and inorganic contaminants, including radionuclides, this presentation for the Metals and Radionuclides in the Subsurface workshop will focus on the metals and radionuclides portions only.

The Orlando workshop concluded that DOE had immediate needs for sensors and monitoring systems for metals and radionuclides in the following areas:

- Soil & Groundwater (principally for on-going compliance monitoring)
- Process Effluents to Air (Hg, Cd, Pb, As, Be, Cr)
- Waste (for safety assurance and treatment process monitoring and control)

It also concluded that DOE had longer-term metals and radionuclide monitoring needs for monitoring and controlling in situ and flow-through remediation processes and for monitoring the performance of waste isolation barriers and containments.

In the case of radionuclides, monitoring systems are needed for soil moisture content and flux, to support barrier performance monitoring and performance modeling. Sensors are needed for tritium (HTO) and mobile radionuclides (e. g., Tc-99, Sr-90, U, Pu, Am).

In the case of metals, the Orlando workshop concluded that real-time monitoring is not required to address DOE requirements and, second, that it is not clear that in situ monitoring has cost/benefit advantage over baseline methods (i. e., regular sample collection and off-site laboratory analysis).

With respect to available sensors/monitors for radionuclides, the workshop identified two emerging technologies, a field-deployable tritium analysis system and a Tc-99 monitoring system. One tritium system was being demonstrated the DOE Brookhaven National Laboratory and other tritium monitoring work was being pursued at the Nevada Test Site under the sponsorship of the Advanced Monitoring Systems Initiative. The Tc-99 monitor was based on rapid sampling and 3M scintillating disk technology.

Regarding available sensors/monitors for metals, the workshop identified a number of applicable techniques/methods:

- X-ray Fluorescence
- Laser Induced Breakdown Spectrometry
- Anodic Stripping Voltammetry
- Colorimetric and Fluorescence Methods
- Immunoassay Methods.

Although these techniques are field-deployable, they are not really “sensor” methods, however.
The main conclusions/recommendations from the Orlando workshop were the following:

1. Moisture (flux, content, and soil moisture potential) is a high priority for monitoring (and performance modeling) waste isolation facilities.
2. Monitoring surrogate parameters that indicate the condition of a facility or site is a priority. Changes at sentinel locations can be used to trigger conventional monitoring.
3. Most technologies for measuring surrogate parameters are well developed compared to chemical contaminant sensors. We should begin immediately to apply these existing methods.
4. Beware point measurements; seek results that have lower uncertainty.

The workshop offered the following strategy recommendations for addressing long-term monitoring requirements:

1. Identify the highest priority problems (monitoring needs).
2. Consider the available solution strategies.
3. Identify the most promising technologies.
4. Establish the solution plan; integrate it into the system design and operations.
5. Focus resources on highest priority problems and most promising solutions. Do not try to solve all problems or provide every possible solution.
6. **IMPLEMENT, IMPROVE, AND REPEAT.** After all, we’re addressing a long-term activity. The most important thing is to start; the second is to keep improving.

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**Sensors and Monitoring Systems in the Advanced Monitoring Systems Initiative (AMSI).**

AMSI was founded in 2001 as a new approach to overcome the technical and institutional obstacles to **application** of advanced sensor and monitoring systems at DOE sites. AMSI is operated by the Nevada Site Office of the U.S. DOE and by Bechtel Nevada, with funding provided by Congress through the DOE EM Office of Science and Technology. It is a highly integrated development, demonstration, test and evaluation (DDT&E) enterprise that aggressively searches for, develops, tests, and integrates promising new sensors and monitoring system elements for end-user application. Its mission is to accelerate the development and application of advanced monitoring systems. The key AMSI objective is always **application**.

AMSI focuses its resources on high-impact solutions to end-user needs and is driven by end-user application requirements. When considering a new project, it looks for strong end-user support, including co-funding of the proposed work and organizational commitment to include the product in the end-user baseline. AMSI emphasizes partnership to accomplish its work, involving developers, end-users, and AMSI personnel. AMSI emphasizes late stage engineering, test, and evaluation in end-user application conditions. Finally, AMSI does not fund research projects.

AMSI emphasizes the importance of remote and automated, unattended operation. It also emphasizes internet communication in sensor and monitoring system operation, for data recording, display, and summarization, for information sharing, and for instrument control. Finally, AMSI tends to employ the spiral development model, i.e., build-a-little, test a little, repeat.
**AMSI Resources.** The principal AMSI resources are the Nevada Test Site (NTS) and its Hazardous Materials (HazMat) Spill Center, a one-of-a-kind facility permitted for releases of hazardous materials for training and testing under controlled conditions. The NTS is also home for the National Center for Combating Terrorism (NCCT), a newly created center for training first responders to terrorist acts. There is no other place in the U.S. where all combating terrorism activities can be addressed in an integrated manner. Other AMSI resources include the usual industry, university, and DOE national laboratory resources and the following Nevada resources: Bechtel Nevada, Special Technologies Laboratory, Remote Sensing Laboratory, Desert Research Institute, and Nevada Universities.

AMSI has a number of active sensor/monitor projects for radionuclides and metals in the subsurface. They are:

- Tritium in the vadose zone
- Tritium in groundwater
- Technetium-99 in groundwater
- Strontium-90 in groundwater
- Wireless sensor platform for landfill performance monitoring
- Universal sensor platform, currently providing support for monitoring Cr(VI) in groundwater.

The Purpose, Benefit(s), Customer, Developer, and key Technology Characteristics of each of these projects/monitors are provided in detail in the following sections.

**Monitoring Tritium in the Vadose Zone.**

The purpose of this system is to monitor for escape and/or migration of tritium from nuclear waste containments. The expected benefit is that early detection can stimulate early action to stop the escape/migration, thereby avoiding higher remediation and potential health costs. The customer for this system is the NTS. Other potential customers are the Savannah River Site, the Hanford site, and Brookhaven National Laboratory. The developer is Science and Engineering Associates, Inc., of Santa Fe, New Mexico. The system uses gas proportional counting to measure beta particles emitted when tritium in water vapor undergoes radiation decay. The limit of detection is less than 100,000 pCi/liter of water. A future version will likely provide a better (lower) limit of detection by condensing the water vapor and using a Proton Exchange Membrane to separate hydrogen and tritium from oxygen prior to counting.
Monitoring Tritium in Groundwater
The purpose of this system is to monitor for migration of tritium and contamination of groundwater. This is the number one need identified in the metals & rads sessions of the Long-Term Monitoring Sensor and Analytical Methods Workshop, Orlando, FL, June 2001. The expected benefit is that, at the Nevada Test Site, estimated savings of $65K/well/y are anticipated through avoidance of mobilization of personnel and equipment for sampling and analysis to fulfill documented regulatory requirements. The customer for this system is the NTS Groundwater Monitoring Program. Other potential customers include the Lawrence Berkeley National Laboratory and the Savannah River Site. Two developer organizations are involved in the tritium monitor work: Science and Engineering Associates (SEA), Inc., of Santa Fe, New Mexico, and the University Nevada, Reno (UNR). The customer needs daily measurement of tritium at 800 to 5000 feet below ground surface and at tritium levels of 1000 to 200,000 pCi/L of water. UNR reacts water with NaK to produce hydrogen and tritium gas, then uses a proportional counter to measure beta decay of the tritium, and finally captures hydrogen and tritium on a getter. The UNR system requires replenishment of the NaK every 50 to 100 days. The SEA monitor condenses water and HTO from their sparge sampling stream (using P10 as the sparging gas) and uses a Proton Exchange Membrane to separate hydrogen and tritium from oxygen prior to counting. The target LOD for the SEA system is less than 20,000 pCi/L of water, which is the same as the EPA Drinking Water Standard for tritium.
Monitoring Tc-99 in Groundwater

The purpose of this system is to provide in situ monitoring of Tc-99 to monitor plume migration and the performance of remediation activities. The expected benefit is a faster, cheaper method of monitoring plume migration and the effectiveness of Tc-99 remediation processes at the Hanford site (approximately one day turnaround time versus a 30 to 45 day turnaround for the baseline method). Also, no mobilization for sampling will be required. The customer is the Hanford Ground Water Monitoring Program. Other potential customers include the DOE Fernald and Paducah sites. The developer team includes Oleg Egorov, John Hartman, Jay Grate, et al, of the Pacific Northwest National Laboratory (PNNL). The system selectively and reversibly concentrates technetium (in the form of the pertechnetate ion) on anion exchange absorption beads and measures light from scintillator beads that emit light when struck by beta particles from the decay of Tc-99. The absorption and scintillator beads are in a mixed bed. The limit of detection for a 10-minute counting period is 7 Bq/L; the regulatory limit for Tc-99 in water is 33.3 Bq/L.
Monitoring Sr-90 in Groundwater

The purpose of this system is to provide in situ monitoring of Sr-90 in groundwater. The expected benefit is a faster, better, cheaper method of monitoring the effectiveness of Sr-90 remediation (barrier plus pump-and-treat plus phytoremediation) at the Hanford N-Reactor site. The Sr-90 monitor will provide approximate one day turnaround time versus 30 to 45 days for the baseline method (sample and laboratory analysis). Also, no mobilization will be required for sampling. The customer is the Hanford Groundwater Monitoring Program. The developer is Ron Brodzinski of PNNL. The system measures the Cherenkov light produced in water by high-energy beta particles from the decay of the Y-90 daughter of Sr-90. The sensitivity achieved by a laboratory prototype of this monitor is 14 pCi/liter. The drinking water standard is 8 pCi/liter, and the target sensitivity for the next generation model of this system is 1.4 pCi/liter. This is to be achieved by using a larger detection cell and longer measurement times.
The purpose of this system is to provide a wireless means of powering and “reading” sensors embedded in landfill covers, e.g., sensors for volumetric soil content and soil water potential. The expected benefit is a wireless means of monitoring barrier performance, providing early warning of degradation and early warning of the need for maintenance attention. The customer is the Idaho National Engineering and Environmental Laboratory (INEEL); other western DOE sites are potential customers. The developers are Dennis Kunerth and John Svoboda of INEEL. In this system, an induction coil both powers the sensors and collects the sensor output via a radio frequency signal generated by an embedded microprocessor. The prototype has been functional to 8 feet below ground surface in dry Idaho soil. An operating scenario for monitoring barriers is illustrated in Figure 7. Figure 8 shows photographs of a sensor package and Figure 9 shows photos of wireless sensor platform testing/demonstration at the Nevada Test Site.
Figure 7. An operating scenario for barrier monitoring using the wireless sensor platform and multiple sensor packages. Each sensor package can contain multiple sensors and can be individually interrogated. The power transfer and data logging unit is portable but it can be left in place.
Figure 8. Photograph of a typical sensor package in emplacement orientation. On the right, the red coil is the power receiver and data transmission antenna for the platform. The PC board attached to the antenna is the microprocessor and A to D converter. The partially assembled sensor package shown at the left of the figure includes, at the bottom, (1) a heat dissipation sensor (beige, just left of the lowest printed circuit board) for measuring soil water potential and (2) a TDR (time domain reflectometer) sensor (green) for measuring volumetric water content. A typical sensor package contains multiple sensors and it can be individually interrogated. The sensors are commercially available.
Monitoring Cr(VI) in Groundwater Using the Universal Sensor Platform

The purpose of this system is to provide in situ, real-time monitoring of Cr(VI) in groundwater. The expected benefit is much better temporal monitoring coverage without much greater cost. The customer is the Hanford Groundwater Monitoring Project. That project wants to accurately monitor Cr(VI) in the pore water of Columbia River sediments and gravel beds (salmon spawning area), which are fed by contaminated groundwater from the DOE Hanford site. Hourly automated measurements are desired. The purpose is to ensure that the Hanford groundwater remediation activities are producing the desired result for protection of aquatic species (salmon) in the Columbia River. The developer is Scott Burge of Burge Environmental, Tempe, Arizona. The Burge Cr(VI) monitor uses a colorimetric reaction with diphenylcarbazide and the Burge “universal” sampling, analysis, and calibration system. The system has a 1 ppb limit of detection for Cr(VI). The regulatory standard is 11 ppb. The Burge system, notably, is capable of performing automated in-field calibration and it has a reagent reservoir sufficient for 100 analyses (100 hours). Other important components of the Burge system, including solar power and battery storage, sample pumps, air compressor, green LED photoabsorption cell, laptop computer, and RF modem for remote control and data communication, can be seen in Figure 10. Finally, it should be noted that chloroform and trichloroethylene monitors based on the Universal Sensor Platform are also available from Burge Environmental, http://www.burgenv.com/index.html.
Figure 10. Universal Sensor Platform by Burge Environmental Company. The system is housed in a field-deployable 2’ x 2’ x 4’ job site box with solar panels.

Key AMSI Achievements and AMSI Contacts
In summary, the key achievements of AMSI have been: (1) involving the end-users in the technology development-to-application endeavors described here and (2) getting end-user commitment to include the product in their application baseline.

If you have a sensing or monitoring problem that you want AMSI to help you solve or, if you want AMSI to help you adapt your sensor or monitoring system for solution of an important, identified DOE monitoring problem, please contact John B. Jones, USDOE NSO, (702) 295-0532, jonesjb@nv.doe.gov or Charles Lohrstorfer, Bechtel Nevada, (702) 295-5688, lohrstcfi@nv.doe.gov.
Summary
The LTS S&T Roadmap, the Orlando workshop on Long-Term Monitoring Sensor and Analytical Methods, and the Advanced Monitoring Systems Initiative (AMSI) provide valuable, different, and increasingly focused perspectives concerning the needs and progress in sensors and monitoring systems for DOE Long-Term monitoring applications. Some additional perspectives regarding sensors and monitoring systems (including for organic compound contamination) are available from other federal and state sponsored works (EPA 2003, ITRC 2003, DOE 2003, NAP 2003). AMSI, in particular, seems to be making real progress in bringing the state-of-the-art from industry, universities, and laboratories to application and baseline practice in DOE monitoring work for radionuclides and metals in the subsurface. The keys to this success seem to be: (1) involving the end-users in the technology development-to-application endeavors and (2) getting end-user commitment to include the product in their application baseline before investing in further technology demonstration or development.
References


