SENSORS INITIATIVE FOR IDENTIFICATION OF LONG-TERM STEWARDSHIP RESEARCH OPPORTUNITIES

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ABSTRACT

The Department of Energy (DOE) Environmental Management Science Program (EMSP) funds numerous projects related to sensor development for long-term stewardship (LTS) applications. The focus of these projects is transformational research to improve current environmental monitoring methods or provide solutions to problems that are currently intractable. Low cost, robust sensors that can be left in place are being sought for remote monitoring of contaminants, verification of cleanup remedies, or other indicators of potential stewardship failures in a variety of media.

The EMSP has launched a Sensor Initiative to define a research agenda for sensor development. A working group comprised of representatives from the DOE sites, national laboratories, the Characterization, Monitoring, and Sensor Technology Crosscutting Program (CMST-CP), the Subsurface Contaminants Focus Area (SCFA), the LTS Program, and the EMSP has been formed to facilitate this effort. The objectives of this working group are as follows:

- promote an understanding of LTS operational needs and site conditions throughout the scientific community
- define the functional requirements for sensors for long-term stewardship applications
- better understand the current sensor capabilities, emerging technologies, and promising research
- provide feedback and target the basic science towards pressing environmental problems
- integrate relevant Environmental Management Science Program (EMSP) research into site operations.

This paper provides a preliminary evaluation of critical sensor needs and site conditions for LTS monitoring and validation applications, summarizes current monitoring processes, discusses categories of sensors, provides general design and performance considerations for the sensors, and outlines applications for current EMSP sensor research. This information provides the basis for the research, development, and deployment of new sensor technologies to meet site long-term monitoring needs.

INTRODUCTION

Depending on the nature of the contaminant and the medium in which it occurs, environmental remediation sufficient to permit unrestricted land use may not be possible at a number of DOE sites. In some cases, no complete remediation strategy currently exists. Even when remediation strategies exist, the costs to employ them may be prohibitive (1).

Sensors are needed to monitor the performance of remedial actions and engineered solutions, including the potential release and migration of contaminants. As such, low cost, robust sensors that can be left in place are being sought for remote monitoring of contaminants or other indicators of potential stewardship failures in a variety of media, including water, soils, atmosphere, biota, engineered units, and facilities. In situ, remote monitoring technologies allow data to be collected as needed at a substantial cost savings, compared to periodic field sampling with subsequent laboratory analysis.

Many post-closure plans center around DOE's reliance on engineered barriers and institutional controls, which are inherently failure-prone. A recent report on LTS by the National Research Council has found that "site stewardship that includes the monitoring and encouragement of emerging new technologies and scientific breakthroughs for their relevance to further reducing the risks associated with residual contamination would, over the long run, decrease the potential consequences of stewardship failures" (2). Reliable monitoring systems will be critical to protecting human health and the environment and assuring a high level of confidence in engineered solutions (3). In pursuit of final disposal and site stewardship options, improved sensors will increase confidence and provide an earlier, more sensitive warning system when failures occur. Sensors with the capabilities to automatically detect and monitor hazardous materials in the environment are being sought to verify that a remedy remains protective of human health and the environment, maintain compliance with applicable regulations, and validate to stakeholders that a remedy is successful.

CRITICAL SENSOR NEEDS

Research and technology development funded by the DOE Office of Environmental Management is based on science and technology needs compiled by the Site Technology Coordination Groups (STCGs) at the various DOE sites throughout the DOE complex. The STCGs are in the process of updating their documented needs pertaining to LTS. Critical needs for long-term monitoring and stewardship identified by the Sensor Initiative working group will eventually need to be incorporated into the STCG needs at the various sites, enabling EMSP and DOE national laboratory researchers to target their research towards specific site problems.

The role of the working group is to facilitate matching site needs with research and serve as a multi-site advocate for promising emerging technologies. Each member is responsible to review and validate the information produced by the working group and serve as a point of contact to subject matter experts within their organization.

Multiple sites have identified contaminants that exist in various media at their respective site. Contaminated media encompass:

- *Water*—Contaminated surface water, surface water sediments and groundwater plumes that cannot or have not been remediated to levels appropriate for unrestricted use (including monitored natural attenuation and bioremediation)
- *Soils*—Surface and subsurface (vadose zone) soils where residual contamination exists or where wastes are contained under or within engineered units
- *Atmosphere*—Meterological and ambient air conditions
- *Biota*— Biological and vegetation
- *Engineered units*—Land-based waste disposal units with engineered controls, including caps, barriers, reactive barriers, waste packages, landfill units, caps and liners, pits, trenches, vaults, and mixed waste burial grounds
- *Facilities*—Contaminated buildings and other structures that will be deactivated and/or entombed with contamination left in place.

Sensing targets include contaminants (organics, metals, radionuclides—see Table I), diagnostic parameters (dissolved oxygen, etc.), water quality indicators (salinity, pH, Eh, oxidation-reduction potential [ORP], etc.), soil characteristics (dielectric constant, matric potential, moisture content, erosion, etc.), meteorology and climatic variables, and radiation levels.

The principal contaminants in the DOE complex identified in Table I can be combined with the media to into six monitoring categories:

- monitoring for natural or enhanced attenuation of organic compounds in the vadose zone and groundwater
- long-term monitoring of landfills or uncontained areas for the release of volatile organic compounds (VOCs) in soil and groundwater
- monitoring of landfill covers or other engineered barriers
- monitoring landfills or uncontained releases of radionuclides in the environment (both soil and groundwater)
- monitoring for metals in groundwater and soil
- monitoring biota.

Current monitoring procedures and specific sensor needs are summarized in the following sections for each of the six categories.

Table I. Principal Contaminants in the DOE Complex (4,5).

Organics	Metals	Radionuclides
Trichloroethylene (TCE)	Lead	Plutonium
Dichloroethylene	Chromium (VI)	Strontium-90
Tetrachloroethylene (Perchloroethylene (PCE))	Mercury	Cesium-137
Carbon Tetrachloride	Zinc	Uranium (various isotopes)
Chloroform	Beryllium	Tritium
Dichloromethane (methylene chloride)	Arsenic	Thorium
Polychlorinated Biphenyls	Cadmium	Technetium-99
Benzene, Toluene, Ethylbenzene, and Xylene (BTEX)	Copper	Radium
		Iodine-129

Monitored Natural (or Enhanced) Attenuation (MNA)

Many DOE sites have experienced releases of chlorinated solvents, petroleum products, or other volatile organics. Federal and state regulators usually expect that source control and long-term performance monitoring will be fundamental components of any MNA remedy (5). The long-term monitoring of natural attenuation areas should address the breakdown of contaminants and the migration of their transformation products.

In situ monitoring of natural attenuation parameters are currently being met for shallow wells (less than 250 feet) by a variety of instruments. These measurements are typically taken from monitoring wells, piezometers, or temporary wells and measure pH, temperature, dissolved oxygen, specific conductance, and salinity. Additional natural attenuation parameters are determined by periodic sampling and include the constituent of concern (BTEX or a chlorinated hydrocarbon such as TCE), breakdown products, iron, sulfate, nitrate, and Eh or ORP. Sensors to specifically measure BTEX and other hydrocarbons and halogenated hydrocarbons are needed.

The key limitations of the current commercially available instruments for monitoring groundwater are the depth to which they can be installed and the number of parameters that they can monitor. For sites with a deep water table, such as the INEEL, commercially available instruments cannot be used at the depths at which they are needed because maximum line lengths are only 250-300 feet.

In addition to groundwater, sensors or a sensor package needs to be developed to measure the in situ degradation of VOCs in the vadose zone. This sensor package would need to measure oxygen, methane, carbon dioxide, total volatile hydrocarbons, and total volatile halogenated compounds or individual compounds, such as TCE and PCE. Automatic data readings and data storage for the entire set of monitored parameters is recommended. A variety of meters exist to monitor natural attenuation parameters in the vadose zone, but they are all hand-held instruments and generally have limited or no data logging capacity. The development of these sensors could also be used for monitoring active remediation projects, such as monitoring bioventing, soil vapor extraction, and bioslurping.

Monitoring for VOCs in Soil (Vadose Zone) and Water

VOCs also need to be monitored at some sites that have vadose zone contamination but little or no groundwater contamination, or at sites that have the potential for a VOC release, such as at a landfill. Monitoring requirements for VOCs in groundwater are currently met by collecting groundwater samples from monitoring or production wells. VOCs in the vadose zone are usually measured by collecting gas samples from soil gas wells. Monitoring well networks (both vadose zone and groundwater) are usually established based on regulatory requirements or site characterization results and groundwater and soil gas samples collected at frequencies varying from quarterly to every 2 years. A variety of hand-held instruments are currently available to measure oxygen and methane, carbon dioxide, and total photoionization detectable (PID) compounds at various lamp energies. Hand-held flame ionization detectors (FID) are also available. A combination PID and FID is commercially available. However, these instruments are inadequate for long-term monitoring in that they require manual operation and have limited data storage abilities and battery life. In addition, they are incapable of periodic remote operation and generally are not configured by size to fit down a well.

For VOC monitoring in groundwater and the vadose zone (gas monitoring), sensors are needed to measure total quantities of volatile hydrocarbons and halogenated compounds in each medium. The type of sensor needed will depend on the long-term monitoring needs and the characteristics of the VOC contamination. If a plume has been identified, compound specific sensors are desirable. If a plume is not present at a site and the purpose of monitoring is to detect contaminants migrating from a containment area, then general-purpose sensors would be more desirable because a single sensor would be able to detect a broad range of compounds. In addition, the bulk of the solvent contamination at many sites is predominantly one or two compounds, such as TCE, PCE, or carbon tetrachloride. A general purpose VOC sensor could be used for those sites as well. A sensor for total hydrocarbons may be desirable because hydrocarbon contamination from fuels typically consists of BTEX and dozens of other compounds. In the instances that BTEX compounds were used as solvents, this general hydrocarbon sensor would be applicable. Sensors for total hydrocarbons and total halogenated compounds could be useful as sentinel type monitors that precede contaminant specific monitoring. A multi-sensor capability (both hydrocarbon and halogenated hydrocarbons) could be used for sites with mixed fuel and solvent contamination.

Monitored Landfill Caps or other Engineered Barriers

Most of the DOE sites have landfills, capped areas, burial vaults, or other structures where there is a need to monitor the migration of water and contaminants. Soil erosion, moisture changes, slope stability, subsidence/settlement, and changes in the vegetative cover will be the primary indicators of the long-term performance of the cover system. These parameters can be assessed by collecting and evaluating data on surface erosion (such as gullets and/or deposition of sediment); conditions of surface water runon, runoff, and drainage layer system; changes in the moisture content profile in the vegetative layer;

changes in the elevation contours, location, and extent of the cover surface, changes in the vegetative cover, vegetative layer thickness, and penetration depth of the root system; and the extent of subsurface burrows produced by fauna.

Many of the new cap designs (especially in arid environments) incorporate a capillary break design that relies on soil capillary pressure to hold infiltration out of the waste. Monitoring the type and amount of water movement is critical to ensuring that water does not infiltrate the waste and contaminants do not migrate. The purpose of such sensors is to detect the potential for infiltration to cause movement of contaminants in the vadose zone before they migrate into the groundwater.

Real-time monitoring is required to capture spatial heterogeneity and temporal variation of hydraulic gradients. Current methods for estimating infiltration and recharge (leakage) include moisture monitoring, hydraulic gradient monitoring, water balance analysis, lysimetry, and tracers. Data from moisture monitoring or hydraulic gradient monitoring along with precipitation, runon and runoff data are used in estimating cover leakage using water balance analysis. Moisture monitoring at landfills is currently being met with time-domain reflectometry (TDR) monitoring, neutron probe monitoring, or tensiometers. TDR monitoring saves data to a data logger, which can be downloaded by phone. Monitoring the hydraulic gradient requires installation of sensors within the cover soil profile to directly measure soil water potential or tension (e.g., tensiometers). A variety of other moisture sensors and matric potential sensors (tensiometers) are available. Post-closure evaluation of covers intended to last hundreds of years will involve a combination of monitoring soil and water movement as well as predictive modeling. In addition to water balance analysis, the data from the moisture sensors or matric potential are often plugged into an unsaturated zone model, such as UNSAT-H (6,7), to calculate infiltration.

There are numerous limitations to the current soil moisture and soil tension methods. For instance, some tensiometer designs require maintenance, and the quality and usability of the data can be questionable. For TDRs, an important limitation is the depth that they can be placed in the ground. Drilling costs to emplace moisture sensors or tensiometers can limit the aerial and vertical coverage that can be obtained. The amount of neutron probe data that can be acquired is further limited by the need for a person to go to the site with the neutron probe to make the measurements.

For landfill cover/cap monitoring, an integrated system that combines moisture monitoring with contaminant monitoring is needed. Monitoring of hydrologic properties and processes in the vadose zone includes measurement of state variables such as moisture content, matric potential, temperature, and the description of flow and migration (8). The variety of sensors that such a system would need include moisture, temperature, Eh, conductivity, gross alpha/gross beta, total halogenated hydrocarbons (TOH), BTEX and other hydrocarbons (TOC), and pH. There is a need for improved novel emplacement approaches for invasive vadose zone monitoring through boreholes, trenches, and other excavations.

Monitoring for Radionuclides in Soil and Water

Radionuclides in groundwater, including tritium, iodine-129, and technetium, are typically monitored by collecting samples at a set frequency from monitoring wells and sending sample to a laboratory for analysis. This frequency varies from quarterly to every two or more years depending on regulatory requirements. Radionuclide characterization of soil samples consists of taking samples for laboratory analysis, which can take one to two weeks to produce results. Radionuclide screening of soil samples can be performed with a variety of instruments.

Limitations to the current approach are related to the frequency and the cost of sampling. The current periodic monitoring and sampling methodologies are inadequate to define the periodic slug releases of radionuclides due to seasonal or event-related weather changes. For example, radionuclide releases may occur during the wet season or during a snow melt event as increased infiltration carries radionuclides from the vadose zone and landfill sources. Rising water levels can release tritium from the vadose zone sources, and moisture pulses from storm events may enhance colloidal transport of plutonium. By placing dedicated downhole groundwater probes in wells proximal to sources and performing measurements at more frequent intervals than quarterly, periodic or seasonal releases of radionuclides can be better monitored. Periods of more frequent measurements can be triggered when dedicated water level probes indicate that the water levels are rising into vadose zone source areas. Additionally, dedicated in situ probes could identify pulses that might otherwise be missed by conventional methods.

For radionuclide monitoring, a system that can monitor gross indicators of contamination, such as gross alpha and gross beta, is needed for both the groundwater and vadose zone. There are currently no sensors for long-term in situ monitoring of gross alpha/beta or radionuclides, such as tritium or technetium-99. Once the radionuclide contamination has been characterized, gross alpha and beta monitoring may be all that is needed to confirm or question levels between confirmatory sampling events. Continued periodic sampling will probably still be required by State and Federal agencies, even after a sensor has been shown to be reliable. However, the number and frequency of sampling events could be decreased, allowing for cost savings.

Monitoring for Metals in Soil and Groundwater

Groundwater monitoring for metals is currently performed by collecting groundwater samples from monitoring or production wells. The transport of metals in the vadose zone can be monitored by collecting liquid samples using lysimeters. A groundwater and vadose zone monitoring network is usually established based on site characterization results and samples collected at a frequency varying from quarterly to every 2 years. The distribution of metals in soil can be characterized by taking surface and core samples. A variety of portable x-ray fluorescence instruments is currently available to measure metals with an atomic number higher than potassium in soils for characterization purposes. The bulk movement of dissolved solids in the groundwater and vadose zone, including common metals and priority pollutant metals, can be monitored using conductivity or salinity measurements. If pH and Eh measurements are also taken, the redox state, solubility, and transport of metals can be estimated.

The limitations of conductivity or salinity measurements are that data for individual metals, such as arsenic, mercury, and cadmium, are not obtained. Sensors that can measure individual metals as well as the total dissolved metal load are needed. The limitations of using lysimeters are that usually only a few point readings are obtained and that the lysimeters must be located beneath a source area.

Monitoring Biota

The ecological monitoring of the flora and fauna habitat and assessment of the overall health of the ecosystem can indicate the effectiveness of engineered designs. Innovative monitoring techniques for assessing the effectiveness of passive remediation technologies, such as phytoremediation techniques that use plants or bacteria to remediate waste, are needed. If sensors could be developed to aid in the determination of contaminant removal rates, then the time period needed for passive remediation could be determined more accurately. Monitoring parameters may include plant or bacterial conditions and performance as an indicator of remediation effectiveness. "Self-sensing" techniques, those that provide a measurement of the contamination state indirectly through the performance of the remediation techniques, may reduce the cost and complexity involved with deploying additional instrumentation.

SENSOR APPLICATIONS

Sensors are needed to serve as sentinels for event-related phenomena, monitoring at fixed intervals, early warning systems, or for system validation at a fixed point in time. Sensors have been categorized as follows based on how the sensor will be used:

- *Monitoring for Natural Attenuation/VOCs* – System validation for remediation via natural attenuation is needed for many sites. For example, the INEEL has a need for long-term sensors to monitor a suite of parameters during a natural attenuation remedial action. Monitoring is necessary to ensure that the aquifer continues to support biodegradation of chlorinated solvents and hydrocarbons (such as BTEX) in groundwater and that key parameters are maintained such as the bio-availability of sulfate, nitrate, iron, and dissolved oxygen. For the vadose zone, methane, carbon dioxide, and oxygen content need to be monitored.
- *Landfill Cap or Engineered Barrier Monitoring* – Sensors should be capable of monitoring event-related data on a real-time and/or as-needed basis, such as after a major storm. The ideal system would be one that could be remotely pulsed for real-time or stored data on an as-needed basis. For example, the INEEL needs sensors that will detect and monitor on a real-time basis, sporadic infiltration events that might occur through a cap. The sensor network would ideally be able to measure and track infiltration through the entire area of concern. Some sensors would be needed simply as alert devices to signal appropriate personnel when a

threshold has been exceeded, such as breakthrough of a reactive barrier, leaching from a landfill, a significant break in a cover, etc.

- *Periodic Groundwater or Vadose Zone Monitoring* – In many instances, periodic monitoring, as opposed to continuous monitoring, is sufficient to meet regulations. The frequency of monitoring for contaminants left on a site will be determined by the final regulatory agreements. Currently, monitoring frequencies range from quarterly to annual. However, the system should also be able to provide data on an as-needed basis. An example may be low cost sensors that are able to sample and transmit periodic monitoring events, such as quarterly groundwater samples. A sensor that could automatically turn on at daily, weekly or monthly interval could be useful in examining the impacts of recharge on radionuclide concentrations in the groundwater.
- *Screening for Soils and Water* – Sensors used for screening are not intended to give results with lab accuracy and, thus, could potentially be lower-cost and less complex. Such sensors could provide early indicators of a problem requiring remedial action. Examples are conductivity sensors to indicate the migration of metals or soil gas sensors to indicate migration of volatile organics.

SENSOR DESIGN AND PERFORMANCE CONSIDERATIONS

The working group defined general design and performance considerations for sensors for long-term monitoring applications at DOE sites. When designing a sensor system for a specific application, the following elements should be addressed:

- *Operating Conditions* – Ability to withstand harsh environments and provide reliable data over the expected range of environmental conditions and events, including temperature, pH, humidity, lightning strikes, etc. For example, the operating temperature range in the vadose zone is -20°C to 45°C, whereas for groundwater it is -2°C to 30°C. A concern is how long the sensor will last if the media is corrosive to the sensor. Is the sensor subject to fouling? (8). Can the sensor have exposed electrodes or must it operate within a sealed package?
- *Power Source* – Low power requirements; batteries recharged by solar energy for remote site monitoring.
- *Measurement Frequency* – Ability to take measurements on an hourly, daily, weekly or monthly basis, as needed.
- *Sensitivity* – Are the sensors sensitive enough to meet detection limits? Instruments designed for other applications (i.e., characterization of high-level waste) may not have the required sensitivity to detect contaminants at the ppb or ppt level and usually require a trained operator and frequent calibration.
- *Selectivity* – Ability to measure parameters as well as changes in parameters (e.g., changes in hydraulic gradients, etc.), ability to distinguish between valence states (i.e., Cr-III vs. Cr-VI), high dynamic range, ability to detect low concentrations of

constituents of interest in a difficult or varied solution matrix, non-contact detection, etc.

- *Size* – For subsurface monitoring, a small diameter (less than 4 inches, in some cases less than 2 inches) to insert in a borehole.
- *In-situ* – Preferred to drawing samples ex-situ for analysis and, thus, creating secondary waste.
- *PARC Parameters (precision, accuracy, representativeness, and calibration)* – Are measurements reproducible? Does the sensor generate representative data and exhibit long-term stability? A key concern for vadose zone monitoring is that the procedure or method by which a sensor is installed enables the collection of representative data. Sensors must meet regulatory standards for accuracy and calibration, and maintain calibration over long periods of time (many years). Can the sensor be "factory" calibrated or is site-specific or in-field calibration required?
- *Maintainability* – Low or no maintenance required. The sensors are intended to be left in place for extended periods.
- *Durability and Reliability* – The sensors should be rugged and capable of maintaining functionality, calibration, and accuracy for years without replacement or repair. Built-in failure sensing would indicate a sensor malfunction.
- *Depth* – How deep can the sensor be buried? Depths of 500 ft or more are needed at certain sites.
- *Data acquisition and transmission* – How easy is it to access the collected data? Can the sensor be adapted to handle data access needs? Many commercially available instruments have manual or limited data storage with limited battery life. Need to be able to save data to a data logger and download data via telemetry. Output from the sensor must directly connect to a commercially available data logger system. Can the sensor provide a real-time assessment of environmental conditions? Data acquired by contaminant monitoring sensors could be made available to stakeholders via the Internet.
- *Timeframe* – When will sensor be available for deployment? How long must it operate?
- *System platform* –How many parameters can be monitored? Will an ensemble of sensors be needed? Integrate combination of sensors on one platform where multiple contaminants are present. What type of platform is required to support the sensor? Output from sensor should be compatible with industry standards. There is emerging interest in developing "swarms" of low-cost sensor networks, which need high reliability to be effective. An integrated package of networked sensors is a powerful tool for on-line remedial action; cost-effective, long-term monitoring; and timely information to support analytical models and decision-making.
- *Portability* – Sensors may need to be moved from location to location (i.e., near waste packages).

- *Smart sensors* – Sensor capability that triggers a secondary response to an actuator on mechanical or electronic systems.
- *Accessibility* – Can the sensor be nonintrusively placed in a remote area and transmit information? Retractable and serviceable, if necessary. Can the sensor be easily emplaced, removed, serviced, or replaced? Modeling can be used to optimize the placement of sensors.
- *Life cycle cost* – System must be more cost effective than traditional sampling methods. Consider capital cost, installation, operation and maintenance, data collection, and data transfer as opposed to periodic sampling, operator training, labor requirements, laboratory equipment and analysis, and production of investigation-derived waste.
- *Regulatory acceptance* – Regulatory acceptance of the data is critical. Newly developed sensors will need to be verified by comparing the sensor data with data collected by traditional means. Full comparisons over a wide range of conditions will also be required (e.g., tests at low, neutral, and high pH, Eh, conductivity, etc.). Because regulators will probably require a verification period, it may be necessary for sensors to be placed in a well along with a groundwater pump in such a manner that the sensors or the pump do not need to be pulled out for sampling.

SPECIFIC SPECIFICATIONS FOR SENSORS

Specific sensor specifications are based on regulatory requirements and data needed to model the fate and transport of contaminants. Because regulators will probably require a verification period for newly developed sensors, it may be necessary for sensors to be emplaced in a well along with a groundwater pump so that the sensors do not need to be removed during groundwater sampling. Specific sensor requirements to meet critical sensor needs are outlined in Table II. The basis for the sensor requirements is described in the following paragraphs.

Table II. Sensor requirements for critical sensor needs at DOE sites.

Requirements for Landfill cover or barrier monitoring/leachate monitoring sensors
Diameter – less than 2 inches, preferably one inch
Moisture sensor – moisture content 0.0 to 0.5 percent
Radius of influence for moisture sensor- 2 to 5 inches
Tensiometer – no maintenance – range –1000 to +100 cm
Length – less than 1 foot
pH – 0 to 14
Eh - -1500 to 1500 mV
Conductivity - 0 μS/cm to 100 S/cm
TOC (Total hydrocarbons) – 0.05 mg/L to 500 mg/L
TOH (Total halogenated) - 0.01 mg/L to 50 mg/L
Gross Alpha – 2 pCi/L, detection limit (DL)
Requirements for a groundwater monitoring/natural attenuation sensor package.
Diameter – less than 4 inches, preferably two inches
Total Sensor probe length – less than 3 feet
Cable length – 800 to 1000 feet
Data logger with telemetry capability
DO sensor – 0 to 10 mg/L, automatic salinity and temperature correction
pH – 0 to 14
Eh - -1500 to 1500 mV
Conductivity - 0 μS/cm to 100 S/cm
TOC (Total hydrocarbons) – 0.05 mg/L to 500 mg/L
TOH (Total halogenated) - 0.01 mg/L to 50 mg/L
Water level – reads ±0.01 feet up to 800 to 1000 feet below ground surface
Requirements for a Vadose zone vapor monitoring/natural attenuation sensor package.
Diameter – less than 4 inches, preferably two inches
Total Sensor probe length – less than 3 feet
Sensors enclosed in a box (2 x 2 x 1 feet) at surface and only an intake placed at the screen level.
Cable length – up to 500 to 800 feet
Data logger with telemetry capability
Air Pump to purge well
Oxygen sensor – 0 to 30 percent by volume
Methane – 0 to 50 percent by volume
Carbon dioxide – 0 to 20 percent by volume
TOC (Total hydrocarbons) – 0.010 mg/L to 500 mg/L
TOH (Total halogenated) - 0.005 mg/L to 50 mg/L
Requirements for Groundwater Radionuclide sensor
Diameter – less than 4 inches, preferably two inches
Total Sensor probe length – less than 2 feet
Gross Alpha – 3 pCi/L, DL
Gross Beta – 10 pCi/L, DL
Optional sensors: I-129 – 0.5 pCi/L, tritium – 400 pCi/L, Sr-90 – 4 pCi/L, and uranium – 20 μg/L

Sensor moisture monitoring requirements for landfill barriers are based on moisture ranges for soils. The requirements for leachate monitoring are based on standard ranges for pH, Eh, and conductivity. The detection limits for TOH are about twice the groundwater Federal Maximum Contaminant Level (MCL) for common solvents, such as TCE and PCE, because the leachate concentration usually needs to be considerably above an MCL to affect groundwater due to diluting effects with the groundwater. The TOC sensor should be most sensitive to hydrocarbons in the C_5 to C_{10} range because BTEX and many other hydrocarbons commonly found in fuels are in this range.

The sensor requirements for MNA and groundwater monitoring are based on MCLs and the data needed to quantify the estimated time period of natural attenuation or the fate and transport characteristics of groundwater contaminants. Sensors exist for many of the MNA parameters, but some sites cannot use available equipment because the depth to water extends beyond the maximum depth of these instruments. The sensor configuration for groundwater monitoring could be used to monitor potential impacts from landfills or other buried waste sites on groundwater even if groundwater contamination does not occur at the present time.

The requirements for vadose zone MNA gas monitoring are based on data needs to determine degradation rates. For landfill or disposal site monitoring, the detection limits for TOC and TOH are set at levels so that gas concentrations that could potentially affect groundwater could be monitored.

The detection limits for gross alpha and gross beta in groundwater are set at one-fifth of their respective MCLs so that increases above background levels can be determined. Some sites may need detection limits of only half of the MCL because of high background levels. The detection limits for Sr-90 and I-129 are set at half of their respective MCLs so that concentration changes within plumes can be monitored.

EMSP RESEARCH WITH LONG-TERM MONITORING APPLICATIONS

EMSP research projects provide basic research to improve current environmental monitoring methods or provide solutions to problems that are currently intractable. Applied and developmental research is needed to transform the findings of basic research and innovative concepts into functioning, reliable instruments and methodologies for confronting the challenges and demands of in situ applications in the field or within closed facilities. There is a need to bridge the gap between the laboratory prototype and the field deployable sensor. EMSP research projects with applications to long-term monitoring are listed in Table III.

Table III. EMSP sensor research projects with long-term monitoring applications.

EMSP Project Number	Project Title	Principal Investigator	Targeted DOE Problem
54639	Development of an In-Situ Microsensor for the Measurements of Chromium and Uranium in Groundwater at DOE Sites	Joseph Wang, New Mexico State University	Chromium, uranium, and toxic metals in groundwater
54674	Design and Development of a New Hybrid Spectroelectrochemical Sensor	William R. Heineman, University of Cincinnati	Radionuclides in water and the vadose zone
55247	Ion and Molecule Sensors Using Molecular Recognition in Luminescent, Conductive Polymers	Michael R. Wasielewski, Argonne National Laboratory	Metals and organics
59882	Measurements of Radon, Thoron, Isotopic Uranium and Thorium to Determine Occupational & Environmental Exposure & Risk at Fernald Feed Materials Production Center	Naomi H. Harley, New York University	Rads in air
60231	Novel Miniature Spectrometer for Remote Chemical Detection	Andrew C. R. Pipino, National Institute of Standards	Halogenated organics in the vadose zone and groundwater
60247	Miniature Nuclear Magnetic Resonance Spectrometer for In-Situ and In-Process Analysis and Monitoring	Gennady Friedman, U of Illinois at Chicago	Rads in soil and groundwater
60370	Rational Design of Metal Ion Sequestering Agents	Kenneth N. Raymond, University of California at Berkeley	Rads in water
64982	Metal Ion Analysis Using Near-Infrared Dyes and the "Laboratory-on-a-Chip"	Greg E. Collins, Naval Research Laboratory	Rads in soil and groundwater
65001	Development of Novel, Simple Multianalyte Sensors for Remote Environmental Analysis	Sanford A. Asher, University of Pittsburgh	Rads in soil and groundwater
65340	Detection and Characterization of Chemicals Present in Tank Waste	P. G. Datskos. Oak Ridge National Laboratory	VOCs in air
65421	Correlation of Chemisorption and Electronic Effects for Metal/Oxide Interfaces: Transducing Principles for Temperature-Programmed Gas Microsensors	Stephen Semancik, National Institute of Standards	VOCs in air
70010	Spectroelectrochemical Sensor for Technetium Applicable to the Vadose Zone	William R. Heineman, U of Cinn	Radionuclides in the vadose zone
70050	Novel Optical Detection Schemes for In-Situ Mapping of Volatile Organochlorides in the Vadose Zone	S. Michael Angel, U of SC	VOCs in the vadose zone
70179	Radionuclide Sensors for Water Monitoring	Jay W. Grate, Pacific Northwest National Laboratory	Radionuclides in water
73808	Microsensors for In-Situ Chemical, Physical, & Radiological Characterization of Mixed Waste	Thomas G. Thundat, Oak Ridge National Laboratory	Hg in air, hydrogen in air

73844	Miniature Chemical Sensor Combining Molecular Recognition with Evanescent-Wave Cavity Ring-Down Spectroscopy	Andrew C. R. Pipino, National Institute of Standards	TCE, VOCs in water
55328	Novel Analytical Techniques Based on an Enhanced Electron Attachment Process	Lal A. Pinnaduwage, University of Tennessee at Knoxville	VOCs in air

SUMMARY AND FUTURE WORK

This paper has provided a preliminary evaluation of critical sensor needs and site conditions for LTS monitoring and validation applications, summarized current monitoring processes, discussed categories of sensors, provided general design and performance considerations for the sensors, and outlined applications for current EMSP sensor research. The next steps in the Sensor Initiative are to create a database of sensor needs and match those needs to current sensor capabilities, emerging technologies, and promising research. This will enable the identification of technical gaps that require further research and development to meet site needs. Certain EMSP projects may require applied research and development to progress to the field testing stage and ultimately to operational scale deployment.

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