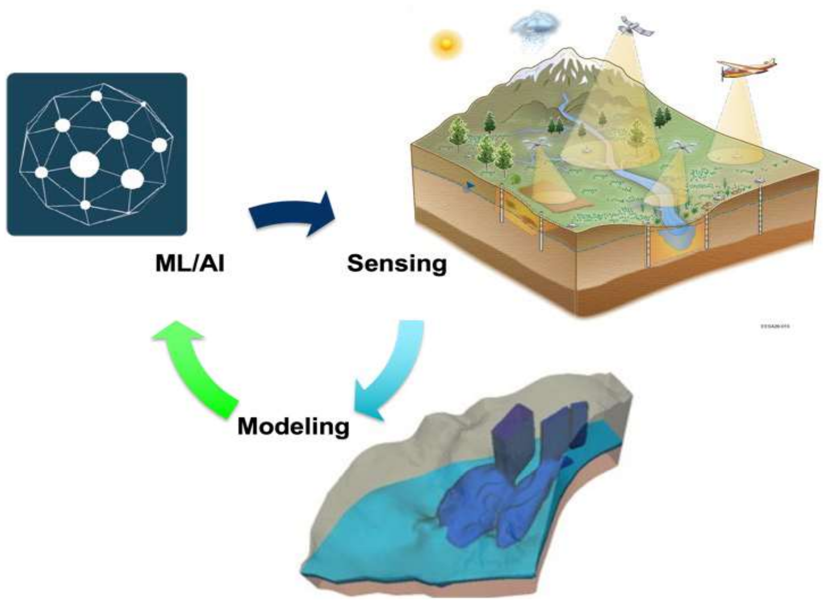
Contract No:

This document was prepared in conjunction with work accomplished under Contract No. 89303321CEM000080 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Disclaimer:

A U.S. DEPARTMENT OF ENERGY NATIONAL LAB • SAVANNAH RIVER SITE • AIKEN, SC • USA

Workshop Report: Innovative Strategies for Long-Term Monitoring of Complex Groundwater Plumes at DOE's Legacy Sites



Carol Eddy-Dilek
Jennifer Nyman
Keaton Belli
Emily Fabricatore

March 2023

SRNL-STI-2023-00103, Revision 0

Printed in the United States of America

Prepared for
U.S. Department of Energy

SRNL-STI-2023-00103
Revision 0

Keywords: *Long-term monitoring, ALTEMIS, artificial intelligence, machine learning, end state, closure*

Retention: *Varies*

Workshop Report: Innovative Strategies for Long-Term Monitoring of Complex Groundwater Plumes at DOE's Legacy Sites

Carol Eddy-Dilek
Jennifer Nyman
Keaton Belli
Emily Fabricatore

March 2023

Savannah River National Laboratory is operated by Battelle Savannah River Alliance for the U.S. Department of Energy under Contract No. 89303321CEM000080.

REVIEWS AND APPROVALS

AUTHORS:

Carol Eddy-Dilek, SRNL, Earth, Biological, and Quantitative System Science Date

Jennifer Nyman
Digitally signed by Jennifer Nyman
Date: 2023.03.22 09:46:35 -07'00'

Jennifer Nyman, Geosyntec, Inc. Date

Keaton Belli, Geosyntec, Inc. Date

Emily Fabricatore, SRNL, Environmental Sciences and Dosimetry Date

TECHNICAL REVIEW:

HANSELL GONZALEZ RAYMAT (Affiliate)
Digitally signed by HANSELL GONZALEZ RAYMAT (Affiliate)
Date: 2023.03.22 16:48:56 -04'00'

Hansell Gonzalez-Raymat, SRNL, Environmental Sciences and Dosimetry Date

APPROVAL:

BRADY LEE (Affiliate)
Digitally signed by BRADY LEE (Affiliate)
Date: 2023.03.23 14:12:07 -04'00'

Brady Lee, SRNL, Director, Earth, Biological, and Quantitative System Science Date

ACKNOWLEDGEMENTS

We appreciate the role that the following individuals took as leads of the breakout session during the workshop and responsibility for collating all breakout session findings into sections for this report:

- **In Situ Sensors/Tools for Subsurface Monitoring**
    - Tom Danielson, SRNL

- **Spatially Integrative Tools for Surface/Subsurface Monitoring and Contaminant Mapping**
    - Tim Johnson, PNNL

- **Artificial Intelligence/Machine Learning**
    - Haruko Wainwright, MIT

- **Challenges to Regulatory Acceptance**
    - Shelly Wilson, Longenecker & Associates
    - Kathy Higley, CRESP
    - Stephanie Jacobs, SRNL

- **Technical/Regulatory Path Forward for Implementation of Innovative Monitoring Strategy for the Moab Site**
    - Brian Looney, SRNL

We would also like to thank Bradley Bohr from SRS Communication & Media Services for taking videos and pictures of both the workshop and the F-Area tour.

EXECUTIVE SUMMARY

Most remaining Department of Energy (DOE) sites will require extended periods of institutional control, especially at complex groundwater sites where attenuation-based strategies have been implemented to facilitate closure. The current practice of monitoring—obtaining and analyzing contaminant concentration in groundwater samples at numerous wells—will account for a large portion of the projected life-cycle at these DOE sites unless a new approach is adopted. State-of-the-art technologies are being developed, including in situ sensors, geophysics, radiation mapping, numerical modeling and AI/ML. These technologies can optimize monitoring strategies in space and time, provide spatially extensive information at vulnerable regions and/or provide more continuous monitoring at lower cost.

As part of DOE's Office of Environmental Management (DOE-EM's) efforts to advance long-term monitoring systems, an in-person/virtual hybrid workshop was hosted by Savannah River National Laboratory (SRNL) on January 24 and 25, 2023, in Augusta, Georgia. Because DOE-EM's complex sites will eventually be transferred to DOE's Office of Legacy Management (DOE-LM), representatives of DOE-LM were important participants in the workshop. The purpose of the workshop was to identify challenges and opportunities for deploying advanced technologies for long-term monitoring at DOE sites. The key questions during the workshop were: 1) the regulatory acceptance of replacing a process that traditionally has used laboratory sampling and analysis of groundwater samples, and 2) the application of this strategy to the southwestern arid sites that include many of the remaining DOE-EM and DOE-LM complex groundwater plumes. Characteristics common to most arid sites present both limitations and opportunities for advanced technologies.

DOE-EM has funded a National Laboratory team from SRNL, Lawrence Berkeley National Laboratory (LBNL), and Pacific Northwest National Laboratory (PNNL) to establish the overarching framework of long-term monitoring by systematically combining advanced hardware and software technologies. This project is titled "Advanced Long-Term Environmental Monitoring Systems (ALTEMIS)" and is sponsored by the DOE-EM Technology Development Program. The multi-laboratory team is currently developing and testing innovative monitoring strategies, including the use of in situ groundwater sensors, geophysics, drone/satellite-based remote sensing, reactive transport modeling, and artificial intelligence/machine learning (AI/ML). The project's demonstration testbed is at the Savannah River Site (SRS) F-Area Seepage Basins, where a well-characterized complex groundwater plume composed of uranium and other radionuclides is in the latter stages of remediation.

The workshop included more than 70 participants, presentations, a field visit to F-Area, breakout working groups, and large group discussion. Participants developed recommendations on five topics: in situ sensors, spatially integrative tools, challenges to regulatory acceptance, AI/ML strategies, and transitioning sites to DOE-LM. The recommendations are summarized below.

In situ sensors:

- Compare results from F-Area with conventional monitoring results.
- Document performance, protocols, and best practices.
- Continue to explore optimization of the use of sensors.
- Adopt a consistent framework for managing and retaining heterogeneous datasets and develop a data management plan (including for long-term sustainability, automation, and metadata).
- Increase the use of water level sensors; water level sensors are of particular importance to most sites, especially the sites with interactions with rivers and significant evapotranspiration and/or precipitation.
- Continue to evaluate the robustness and maintenance of all types of sensors, which are critical to cost reduction.

Spatially integrative tools:

- Consider several additional, emerging, spatially integrative tools at the F-Area demonstration, including light detection and ranging (LiDAR), infrared and hyperspectral imaging, and fiber-based distributed temperature and strain sensing.
- For DOE sites in the west, consider drone-based (land or air) electromagnetic (EM), LiDAR, infrared, hyperspectral, and satellite remote sensing, which could provide large-scale monitoring information including the changes associated with climatic changes (e.g., such as vegetation change, erosion, preferential flow paths) and the changes in land use that may alter site boundary conditions and subsurface behavior over time.
- Along with the deployment of spatially integrative tools, invest in automated data collection, processing, analysis, and reporting, for which AI/ML may play a significant role.
- Consider joint multi-physical inversion to integrate spatial results into subsurface models.

Challenges to regulatory acceptance:

- Work from an established regulatory relationship base to gain trust and acceptance for changes.
- Highlight benefits and other stakeholder impacts, including more frequent/continuous data, early warning capabilities, climate predictions/resilience (a United States Environmental Protection Agency [EPA] priority), reduced worker risk, student interaction, and public availability and transparency.
- Seek regulatory acceptance of changes in phases, for example, reducing frequency first and number of wells second, while showing side-by-side correlations in traditional or historical data and new approaches.
- Ensure that the regulatory documentation is updated/accurate and covers legal responsibilities.
- Increase the awareness of new tools, for example, through the Environmental Council of the States and the DOE Intergovernmental Meeting.
- Promote local awareness so the public is aware of the end state vision and risk impacts as well as how a revised monitoring approach is beneficial/transparent.
- Compile and provide a toolbox for sites undertaking use of new long-term monitoring approaches. The toolbox could consist of structured protocols, case studies, regulatory approvals, information on vulnerability zone assessments, an example implementation plan, a description of machine learning processes, and best practices for moving towards closure.

AI/ML strategies:

- To increase acceptance of AI/ML, start with established and traceable AI/ML tools and use AI/ML for its strengths, including for: 1) optimization of sampling frequency, using more data from tools for continuous monitoring, 2) change (or anomaly) detection, outside of natural fluctuation, and 3) data mining of historical datasets.
- Further explore ML algorithms using the F-Area testbed, including for change detection coupled with continuous in situ sensor monitoring.
- Thoroughly document AI/ML processes and their applications.
- Use virtual datasets or systems to evaluate AI/ML strategies as well as train/educate workers/regulators.

Transitioning sites to DOE-LM:

- Start collaboration early and carefully consider regulatory requirements and details of engineering controls.
- Provide thorough documentation and data management, including regulatory agreements, data inputs to and processes for models, data quality objectives, and consistently formatted databases.

TABLE OF CONTENTS

LIST OF FIGURES ... viii
LIST OF ABBREVIATIONS ... ix
1.0 Introduction and Background ... 1
1.1 ALTEMIS ... 1
1.2 Workshop Objective ... 2
2.0 Workshop Summary—Day 1 ... 2
2.1 Value of Information Analysis ... 2
2.2 Supporting Closure of DOE-EM's Complex Groundwater Sites ... 2
2.3 The ALTEMIS Testbed and Field Trip ... 3
2.4 Regulatory Acceptance ... 5
3.0 Workshop Summary—Day 2 ... 6
3.1 LM Perspective on Site Transition ... 6
3.2 Working Group 1—In-Situ Sensors/Tools for Subsurface Monitoring ... 6
3.3 Working Group 2—Spatially Integrative Tools for Surface/Subsurface Monitoring and Contaminant Mapping ... 7
3.4 Working Group 3—Challenges to Regulatory Acceptance ... 8
3.5 AI/ML Strategies ... 9
3.6 Technical/Regulatory Path Forward for Implementation of Innovative Monitoring Strategy for the Moab Site ... 9
4.0 Conclusions and Recommendations ... 10
4.1 Workshop Recommendations ... 10
4.2 Path Forward for ALTEMIS ... 12
4.3 Conclusion ... 12

LIST OF FIGURES

Figure 2-1. Hansell Gonzalez-Raymat presented on the ALTEMIS demonstration at F-Area. ... 3
Figure 2-2. Integrated sensor array network installed at SRS F-Area. ... 4
Figure 2-3. Zones of vulnerability at SRS F-Area. ... 4
Figure 2-4. Tom Danielson described the sensor network at the SRS F-Area ... 5

LIST OF ABBREVIATIONS

AI/ML	artificial intelligence/machine learning
ALTEMIS	Advanced Long-Term Environmental Monitoring Systems
AS&T	Applied Studies and Technology
bgs	below ground surface
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
DIVER	Data Information Value to Evaluate Remediation
DOE	Department of Energy
DOE-EM	Department of Energy's Office of Environmental Management
DOE-LM	Department of Energy's Office of Legacy Management
EM	electromagnetic
EMI	electromagnetic conductivity meter
EPA	United States Environmental Protection Agency
ERT	electrical resistance tomography
GCAP	Groundwater Compliance Action Plan
GPR	ground penetrating radar
LBNL	Lawrence Berkeley National Laboratory
LiDAR	light detection and ranging
PNNL	Pacific Northwest National Laboratory
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
SURF	Sustainable Remediation Forum
UAV	unmanned aerial vehicle
UMTRA	Uranium Mill Tailings Remedial Action

1.0 Introduction and Background

After more than three decades of remedial activities, many of the Department of Energy's Office of Environmental Management (DOE-EM) complex groundwater sites have or will soon transition from active to passive remedies which will require an extended period of institutional control before site closure is achieved. There is growing concern that the cost of long-term monitoring will soon dominate the projected life-cycle cleanup cost. In addition, robust monitoring data is critical to provide assurance to the surrounding communities that residual contamination does not pose a risk to surrounding communities. As part of DOE-EM's efforts to advance long-term monitoring systems, an in-person/virtual workshop was hosted by Savannah River National Laboratory (SRNL) on January 24 and 25, 2023, in Augusta, Georgia. Because DOE-EM's complex sites will eventually transfer to DOE's Office of Legacy Management (DOE-LM), representatives from DOE-LM were important participants in the workshop. The objective of the workshop was to document the implementation of the innovative monitoring strategy at SRS and to develop strategies and relevant tools that can be used to transition the innovative to other complex groundwater plumes throughout DOE.

Over 70 participants attended the workshop, including representatives of the following organizations:

- DOE-EM and DOE-LM Headquarters
- National laboratories including SRNL, Lawrence Berkeley National Laboratory (LBNL), and Pacific Northwest National Laboratory (PNNL)
- The DOE-EM Moab Uranium Mill Tailings Remedial Action (UMTRA) Project Site which is scheduled for transition to LM in the next 5 years.
- Academia, including the Massachusetts Institute of Technology, Florida International University, and Clemson University
- Industry, including Geosyntec Consultants, Inc., the Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Longenecker & Associates, Panoramic Environmental Consulting, Subsurface Insights, and the Sustainable Remediation Forum (SURF)
- The Sellafield Site in the United Kingdom

1.1 <u>ALTEMIS</u>

Since 2020, DOE-EM's Office of Technology Development (DOE-EM TD) has funded a National Laboratory team from SRNL, LBNL, and PNNL to develop and implement an innovative framework for long-term monitoring at DOE's complex plumes that combines advanced hardware and software technologies. This project is titled "Advanced Long-Term Environmental Monitoring Systems (ALTEMIS)." The ALTEMIS team has developed and installed an integrated sensor network at the Savannah River Site (SRS) and is now evaluating and testing the monitoring system that includes state-of-the-art technologies, including in situ groundwater sensors, geophysical methods, reactive transport modeling, and artificial intelligence/machine learning (AI/ML). The objective of the project is the development of improved monitoring systems for residual contaminants that will improve the quality of monitoring while simultaneously reducing costs.

The project demonstration testbed is located at the SRS F-Area Seepage Basins where a well-characterized complex acidic groundwater plume composed of radionuclides such as tritium, uranium isotopes, iodine-129, strontium-90 and other metals is in the latter stages of remediation. The team first identified key objectives for the monitoring which included identification of the controlling variables for plume movement and areas where residual contamination will be present over the next several decades. The identification of these 'zones of vulnerability' provided the basis for the layout of the sensor network. Installation of the integrated sensor network and electrical resistance tomography (ERT) array was recently completed at the site. The new long-term system is focused on monitoring the leading indicators (e.g., conductivity, pH, redox, temperature, and water level) that indicate or control migration and mobilization of attenuated contaminants rather than collection and laboratory analysis of groundwater. This system has the potential to significantly reduce costs (by 50 to 75%) by reducing the number or frequency of laboratory sampling while improving the quality of long-term monitoring. In addition, the use of sensors that monitor the leading indicators for plume movement will allow proactive response to unexpected plume movement before the plume has actually migrated.

1.2 Workshop Objective

Two key challenges remain for acceptance of new long-term monitoring approach, specifically: 1) regulatory acceptance of a process that traditionally has used laboratory sampling and analysis of groundwater samples, and 2) the application of this strategy to the southwestern arid sites that include many of the remaining DOE-EM and DOE-LM complex groundwater plumes. Hydrologic driving forces may be lower at arid sites, which can extend plume flushing times. Also, western sites are typically characterized by large, remote, relatively unvegetated monitoring areas that are accessible to the public and may experience changes in use over time (e.g., agriculture, development).

The purpose of the workshop was to share the innovative paradigm and to identify challenges and opportunities for transferring advanced technologies for long-term monitoring to other DOE sites, including strategies to obtain regulatory acceptance of the new approach to long-term monitoring and closure. The first day of the workshop included a series of presentations on value of information analysis, ALTEMIS, and regulatory acceptance, as well as a visit to F-Area. The second day included a presentation by DOE-LM, working groups, and a working session on an example site. This report summarizes both days and presents a summary of recommendations from the workshop.

2.0 Workshop Summary—Day 1

2.1 Value of Information Analysis

Dr. Mike Kavanaugh of Geosyntec Consultants, Inc., opened the workshop with a review of value of information analysis and long-term monitoring optimization. The presentation introduced several key concepts that were referenced throughout the workshop:

1. Optimization of long-term monitoring programs can significantly reduce life-cycle costs and carbon emissions while still demonstrating containment of residual contamination.
2. Processes can be used to maximize the net value of new data collection efforts.
3. Virtual datasets are useful tools for developing optimization processes.

The presentation included results of Mike's Department of Defense-sponsored research, the Data Information Value to Evaluate Remediation (DIVER) project. The project concluded that data analysis/interpretation is as important to optimization as data collection. Increased use of value of information analysis will require investments in mining of site data, for which AI/ML may be useful.

2.2 Supporting Closure of DOE-EM's Complex Groundwater Sites

A significant portion of DOE-EM's liability for environmental cleanup is associated with complex groundwater plumes, which will require monitoring for decades after active remediation is complete. Carol Eddy-Dilek presented on the ongoing process to provide DOE-EM headquarters recommendations on a consistent and expedited closure strategy for DOE's complex contaminant plumes as well as recommendations to shrink the remaining cleanup footprint significantly over the next decade.

The process has been divided into three phases. Phase 1 was to develop updated Technical Targets for DOE-EM. This effort was completed in 2021 by a multi-disciplinary team of technical experts. The collaborative process identified 15 topic areas where technical research and development should be targeted to support site management and cleanup. ALTEMIS addresses many of these areas. In Phase 2, teams from nine DOE-EM sites were interviewed to identify critical challenges and assess common themes and best practices for achieving site closure. This phase of the groundwater strategy development again involved a multi-disciplinary team of reviewers and included experts in stakeholder interaction, regulatory engagement, risk assessment, and site management as well as representatives from the Technical Targets development team. Phase 3 is converting core themes identified in Phase 2 into recommendations, prioritizing technical issues within the Technical Targets, and developing specific plans to be implemented by DOE-EM to encourage progress towards closure and transition to DOE-LM. Phase 3 will produce a clear, complex-wide end state vision for groundwater cleanup.

2.3 <u>The ALTEMIS Testbed and Field Trip</u>

Dr. Hansell Gonzalez-Raymat presented on the ALTEMIS testbed at the F-Area Seepage Basins of SRS (Figure 2-1), and Dr. Haruko Wainwright discussed early successes and accomplishments of ALTEMIS. At the F-Area of the SRS, the ALTEMIS project is demonstrating how to establish a new paradigm of long-term monitoring based on the implementation of state-of-the-art technologies (Figure 2-2).

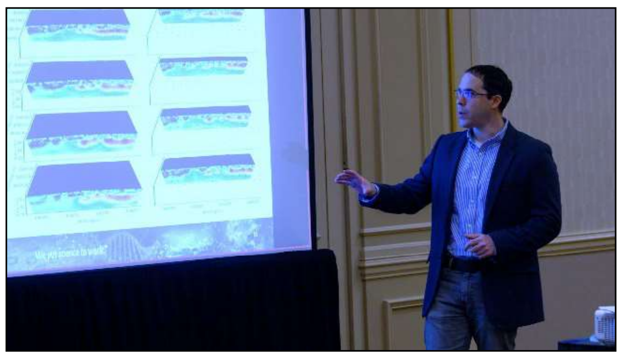


Figure 2-1. Hansell Gonzalez-Raymat presented on the ALTEMIS demonstration at F-Area.
Photo Credit: Bradley Bohr

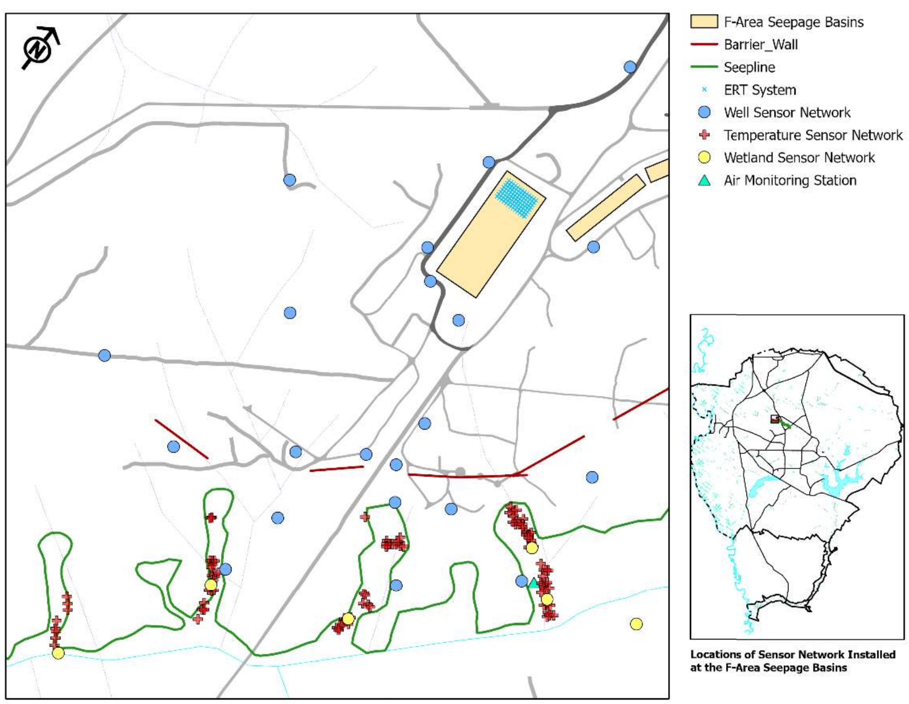


Figure 2-2. Integrated sensor array network installed at SRS F-Area.

The F-Area seepage basins consisted of three unlined, earthen surface impoundments that received acidic, low-level waste (average influent pH of 2.9) that originated from uranium processing from 1955 through 1988. The groundwater plume currently extends from the basins approximately 600 meters downgradient to a stream and contains many contaminants, of which the most hazardous, based on risk to potential receptors, are uranium isotopes, Sr-90, I-129, Tc-99, tritium, and nitrate.

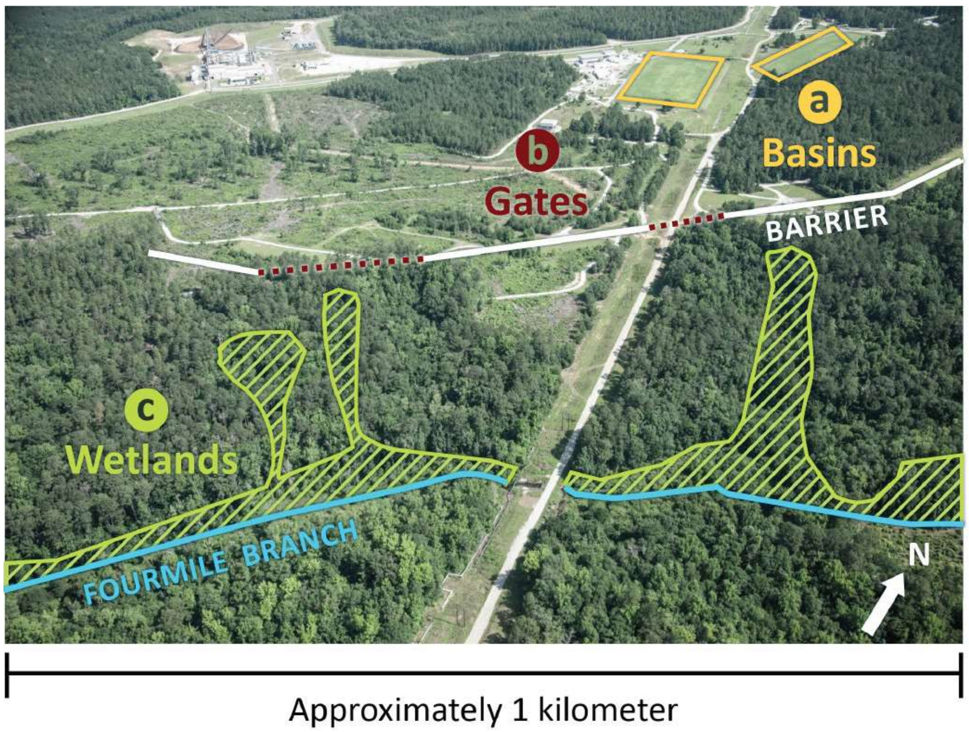


Figure 2-3. Zones of vulnerability at SRS F-Area.

Three locations, or zones, of vulnerability were identified at F-Area: the cap on the former basins, the area of a funnel-and-gate subsurface treatment barrier, and the wetlands at the downgradient end of the plume (Figure 2-3). These zones are potentially vulnerable to changes in infiltration, chemical conditions, or physical conditions that could result in the mobilization of attenuated contaminants. Tools employed at the F-Area testbed include

- the geophysical method ERT to monitor moisture content in the cap clay layer and beneath basin soils, which is providing continuous data to image and detect anomalies.
- multiparameter sonde with interchangeable sensors in wells that monitor pH, conductivity, redox potential, temperature, and water level.
- AI/ML approaches, which were used to optimize well locations for the sensors and will be used for data analysis.
- a geophysical survey in the wetlands using three instruments: an electromagnetic conductivity meter (EMI), ground penetrating radar (GPR), and a hand-held gamma-ray detection sensor, which delineated the subsurface structure, including the peat thickness and interfaces, and produced a geolocated radiological map.
- a distributed temperature sensor network at the wetlands using depth-discrete temperature probes at 97 locations and multiparameter sonde with interchangeable sensors at 13 locations, which is

already showing complex dynamics in biogeochemical conditions and characterizing surface-subsurface water interactions, and
- an air monitoring system to be installed at the wetlands for I-129 to refine the conceptual site model.

Most components at the ALTEMIS F-Area testbed will be operational for five years, during which time data will be collected and analyzed and compared to traditional monitoring results.

Dr. Wainwright discussed multiple modeling efforts that are part of the ALTEMIS project, including the reactive flow and transport model that incorporates geochemistry and impacts of climate change, a physics-informed deep learning surrogate model, and AI/ML. Goals for AI/ML include improving real-time monitoring and developing early warning systems for tracking groundwater contamination. An ML framework, PyLEnM, for long-term monitoring was developed in Python and has been published. PyLEnM includes both supervised and unsupervised learning and can be used for optimization of monitoring location placement.

During the afternoon of Day 1 of the workshop, participants went to F-Area to observe the ERT array at the cap and the groundwater well sensor setup. Dr. Tim Johnson of PNNL led a discussion of the ERT array implementation and initial results, and Dr. Tom Danielson described the sensor installation and setup (Figure 2-4).

Figure 2-4. Tom Danielson described the sensor network at the SRS F-Area.

Photo Credit: Bradley Bohr

2.4 Regulatory Acceptance

Shelly and David Wilson, of Longenecker and Associates, provided considerations for gaining regulatory acceptance for new long-term monitoring approaches. Both were with the South Carolina Department of Health and Environmental Control; David was formerly its Acting Director. They reviewed the major regulatory frameworks for long-term groundwater monitoring and noted that most frameworks include four subjects: constituents, wells, frequency, and quality assurance. Of these, frequency is most often easiest to change as a first step. Shelly and David noted the importance of consistency and requirements for regulators, but also noted that innovation and flexibility are possible if confidence can be built. They suggested approaches for developing confidence and trust with regulators:

- Correlating data from new approaches with data from traditional or existing approaches
- Using a phased approach, instead of making large changes at once
- Building a site-specific regulatory team, including DOE, technical experts, and regulators, and schedule ongoing meetings for trust building

While recommending a site-specific regulatory team approach, Shelly and David also suggested building a toolbox of documents for use at new sites. It could include

- descriptions of long-term monitoring tools,
- case studies of successful site deployments,
- analysis showing correlation of traditional and ALTEMIS data,
- previous regulatory approvals, and/or
- journal articles.

Shelly and David emphasized the importance of formal documentation of accepted changes to the long-term monitoring program in applicable regulatory documents.

3.0 Workshop Summary—Day 2

3.1 LM Perspective on Site Transition

Dr. Darina Castillo, Annette Moore, and Kate Whysner of DOE-LM presented expectations for transitioning sites to DOE-LM. Dr. Castillo explained that it is a multi-year process that includes a group of subject matter experts from DOE-LM and the site predecessor. The process must capture all requirements for long-term surveillance and maintenance and the responsible transition of all regulatory agreements.

DOE-LM is currently developing a site transition framework that includes 10 requirements, all of which are to be included in a site transition plan (Appendix A). Two important requirements were discussed in detail: engineered controls and information/records management.

For engineering controls, emphasis was placed on having regulatory acceptance of engineering controls documented in a formal decision document and DOE-LM fully understanding the path to compliance. The following special considerations for ALTEMIS long-term monitoring tools, within the context of engineered controls, were highlighted:

- AI/ML is a new technology to the DOE-LM team. DOE-LM suggests providing manuals, field training, full documentation, and the opportunity for review prior to transition.
- DOE-LM has special considerations for sensors, including equipment maintenance, details of the associated network architecture, and cybersecurity requirements, since DOE-LM values consistency and dependability.
- Recommendations for transitioning aerial imagery data to DOE-LM include establishing land survey data quality standards, documenting data quality objectives, identifying change thresholds to become action levels for change detection, and documenting algorithms.

Information and records to be transitioned to DOE-LM include email and legal records, permanent records, and an asset database, all of which have requirements. Environmental data, including sufficient information to recreate models, and geospatial information warrant specific consideration. DOE-LM is standardizing geospatial data and needs metadata, data quality objectives, and the involvement of subject matter experts.

3.2 Working Group 1—In-Situ Sensors/Tools for Subsurface Monitoring

A key focus of the ALTEMIS project is in situ monitoring sensors for monitoring master variables that control or are associated with contaminant plume mobility and direction. Sensors for groundwater monitoring were installed at F-Area in fiscal year 2022 to monitor the plume and to support AI algorithms.

For the demonstration at F-Area, Working Group 1 identified the following opportunities and challenges related to sensors:

- The results from F-Area should be compared with conventional monitoring. Performance, protocols, and best practices should be documented, and the documentation should be used to seek regulatory approval.

- Sensors are an important tool to improve cost-effectiveness of monitoring. They can provide additional lines of evidence for measures such as reducing the frequency of sampling, or the number of wells sampled. Assuming that sensors are robust and do not require significant maintenance, sensors will reduce cost when compared to conventional monitoring well sampling while maintaining the ability to ensure regulatory compliance.
- In addition to sensors for contaminants, water level sensors are also very important to monitor plume flow dynamics. Other types of sensors may be considered, including radiation sensors and fiber optic-based sensors. Conventionally available data/parameters can also be considered for innovative uses, such as distributed sensing of temperature for monitoring surface water/groundwater interactions.
- Data processing can be explored for multiple purposes, including change/anomaly detection.
- Virtual datasets or systems could be beneficial for evaluating AI/ML strategies as well as training/educating workers/regulators. This approach could help address the identified gap between AI/ML expertise and domain science.
- Aspects of the use of sensors over the long term can be further evaluated, including the robustness of hardware, calibration frequencies, and maintenance frequencies and difficulties. Optimization of the use of sensors could also continue to be explored.
- The challenge of managing and retaining heterogeneous datasets over time could be supported by early adoption of a consistent framework and data management plans (including for long-term sustainability, automation, and metadata).

With respect to application of the technologies to other sites, including arid sites, the sensors working group identified the following opportunities and challenges:

- Monitoring strategies can be developed for different sites by identifying the different vulnerabilities and requirements. The first step in the system design should be identification of site-specific master variables for the specific plume.
- Interactions of groundwater with surface water is important at many sites. Water level sensors could be important for measuring dynamic hydrological changes and interactions, including assessment of boundary conditions and potential re-mobilization of sequestered contaminants. AI/ML may be a tool for optimizing sampling frequency.
- Evapotranspiration and/or precipitation could have a large impact on groundwater systems at other sites. Near-surface sensors for these variables should be integrated with groundwater sensors.
- Site-specific data should be integrated with publicly available data, such as that from the USGS. The ALTEMIS project has developed a python package to download and analyze publicly available climate datasets (pipy.org/climate-resilience).
- As for SRS, the robustness of sensors is critical for reducing the maintenance needs and cost.

3.3 Working Group 2—Spatially Integrative Tools for Surface/Subsurface Monitoring and Contaminant Mapping

Spatial monitoring methods remotely detect surface and subsurface properties that can help assess system behavior and performance. Spatial monitoring of the subsurface is primarily limited to geophysical sensing approaches (electrical, electromagnetic [EM], seismic, etc.). Examples of surface spatial monitoring approaches include hyperspectral and infrared cameras, LiDAR sensing, and satellite remote sensing. Their primary utility in monitoring of complex plumes is to identify significant anomalous changes over time that provide early warning to prompt more detailed investigations and to provide diagnostic information regarding the long-term performance of closure measures. Given the spatial and temporal scales required for long-term monitoring of remediated DOE-EM sites, spatial sensing systems must be autonomous enough to limit costs by reducing human effort and robust enough to operate for long periods without maintenance in remote areas that may be open to the public. Ideal spatial monitoring methods have feasible installation costs, robust field instrumentation, and can be automated from data collection through analysis and reporting.

Several additional emerging spatial sensing technologies could be used at the F-Area demonstration with some moderate developments in data infrastructure and autonomous data processing:

1. LiDAR. Commercial off-the-shelf LiDAR systems could be used to precisely monitor the stability of engineered structures using a modest array of stationary LiDAR sensors. For example, they could be deployed on the perimeter of a waste landfill cap to monitor for subsidence and/or changes in topography associated with animal burrowing, erosion, or other abnormal conditions.
2. Infrared and Hyperspectral Imaging. Commercial outdoor-rated infrared and hyperspectral cameras could be mounted on stationary platforms within the seep zone to identify changes and corresponding impacts over time.
3. Fiber-Based Distributed Temperature and Strain Sensing. Hardened fiber optic cables deployed along the surface or subsurface can be used to sense temperature and strain along the cable. A single cable can provide meter-scale resolution over many kilometers. Possible applications include shallow deployments in the seep zone to continuously monitor for temperature anomalies associated with groundwater discharge, or shallow deployments within the landfill cap to monitor for subsidence-induced strain. Temperature and strain cables could be co-deployed with ERT cables.

Characteristics common to most arid sites present both limitations and opportunities for spatial sensing technologies. Specifically, western sites are typically characterized by large, remote, relatively unvegetated monitoring areas that are accessible to the public or adjacent to public lands that may experience changes in use over time (e.g., agriculture, development). The spatial scale of many western disposal cells may make ERT monitoring as deployed on the F-Area Basin 3 cap infeasible. However, the lack of nearby metallic infrastructure and trees may make drone-based (land or air) EM sensing feasible for the same purpose. Although drone-based EM sensing is not currently available commercially, the capability is being developed within the national laboratory system. Drone-based LiDAR, infrared, and hyperspectral sensing are applicable to arid sites for the same reason (i.e., lack of trees). Satellite remote sensing is also anticipated to be more useful at arid sites than forested sites like SRS and could provide large-scale monitoring information including climatic changes and changes in land use that may alter site boundary conditions and subsurface behavior over time. To be cost-effective in the long-term, each of these approaches will likely require investments to automate data collection, processing, analysis, and reporting. The rapid advancement of AI/ML capabilities can likely play a significant role in this regard.

Predictive uncertainty, originating from insufficient data, is one of the most pervasive challenges in the subsurface sciences, resulting in increased cost and risk of remedies. Spatial monitoring data implicitly contain significant information regarding the evolution of subsurface behavior that could help address the subsurface information gap. However, spatial sensing results generally cannot be easily assimilated by existing subsurface simulators. Recent advancements in joint multi-physical inversion, aided by massively parallel computing, are poised to make significant progress on this front. In addition, emerging AI/ML approaches, including approaches yet to be developed, offer new avenues for comprehensive assimilation of data to reduce predictive uncertainty.

3.4 Working Group 3—Challenges to Regulatory Acceptance

Working Group 3 identified two main challenges in the regulatory realm: 1) acceptance of new, desired tools, and 2) reducing the long-term cost of monitoring, for example with reductions in the number of wells.

The working group developed the following suggestions:

1. Work from an established regulatory relationship base to gain trust and gain acceptance for changes. An example is the Core Team Process at SRS.

2. Make a business case for the change. Highlight benefits and other stakeholder impacts, including more frequent/continuous data, early warning capabilities, climate predictions/resilience (a United States Environmental Protection Agency [EPA] priority), reduced worker risk, student interaction, and public availability and transparency.
3. Seek regulatory acceptance of changes in phases, for example with frequency first and number of wells second, while showing side-by-side correlations in historical data and data using new approaches.
4. Ensure the regulatory documentation is updated/accurate and covers legal responsibilities.
5. Increase awareness of new tools, for example, through the Environmental Council of the States and the DOE Intergovernmental Meeting.
6. Seek local awareness so the public is aware of the end state vision and risk impacts and how a revised monitoring approach is beneficial/transparent, for example through citizens advisory board meetings, public outreach, and technical assistance teams.
7. Compile and provide a toolbox to sites undertaking use of new long-term monitoring approaches. The toolbox could consist of structured protocols, case studies, regulatory approvals, information on vulnerability zone assessments, an example implementation plan, a description of machine learning processes, and best practices for moving towards closure.

3.5 AI/ML Strategies

Workshop participants emphasized their certainty that AI/ML is the next generation for environmental data analysis and will increase in use. They pointed out that while AI/ML can seem new and unknown, many machine learning approaches are well-established and have been in use for some time. To increase acceptance of AI/ML, the group suggested starting with established and traceable AI/ML tools and using AI/ML for its strengths.

Two specific ideas were suggested. The first was optimization of sampling frequency. Sampling frequency, as Shelly and David Wilson pointed out, may be one of the easier modifications to negotiate with regulators. In hand with AI/ML, optimization would be to reduce the frequency of groundwater sampling, by acknowledging and taking the credit of the more continuous monitoring that in situ sensors and spatially integrative tools can provide. The second idea was change (or anomaly) detection, outside of natural fluctuation. Important examples include the start of erosion on a tailings cell cover or detecting hydrologic flow and water table anomalies that could lead to a change in plume mobility or plume direction. Anomaly detection is categorical in ML, which is usually more accurate and highly performing than quantitative estimation. The challenge is that training sets are limited, since such anomalies have never occurred or happened only a few times. A potential approach, which is the current practice in earth science, is to create hypothetical training sets based on model simulations. ML algorithms could be explored using the F-Area testbed, including for change detection for potential future disturbances.

The group discussed the importance of thoroughly documenting AI/ML processes and their applications, particularly for promoting regulatory acceptance. Because AI/ML is not as well-known as traditional monitoring approaches, training and education may be needed for both DOE staff and regulators.

3.6 Technical/Regulatory Path Forward for Implementation of Innovative Monitoring Strategy for the Moab Site

Dr. Brian Looney presented an overview of the DOE-EM Moab UMTRA Project site, with input from Liz Moran, who is part of the Moab site contractor team. The site, located adjacent to the Colorado River, is a former uranium ore-processing facility approximately 3 miles northwest of the city of Moab in Grand County, Utah. Throughout the lifetime of the facility, an estimated 16 million tons of uranium mill tailings accumulated in an unlined impoundment (pile) in the floodplain of the Colorado River, which resulted in contamination of groundwater in the alluvium that discharges to the river. DOE's goal is a final, approved

Groundwater Compliance Action Plan (GCAP) by the completion of surface remediation activities. Ammonia is the primary contaminant of concern, and uranium is a contaminant of potential concern. The floodplain and Colorado River segment adjacent to the site are designated as critical habitat for endangered fish species. DOE has committed to active remediation as well as interim actions to protect the river. Freshwater in the unconfined alluvial aquifer is underlain by a brine zone that varies seasonally in elevation but is often encountered at approximately 55 feet below ground surface (bgs). Challenges at the site include multiple sources with different behavior; secondary sources, including solid-associated uranium and ammonia in the saturated and vadose zones; high hydrologic influence from the Colorado River; and the river habitat for endangered species. Surface remediation at the site is expected to be completed by 2028, at which time responsibility for the site will be transitioned from DOE-EM to DOE-LM.

After the presentation on site background, Brian led workshop participants in a discussion of potential monitoring objectives and tools. The following suggestions were identified:

- Add to monitoring of water levels using sensors, particularly along the river; these can provide data for model calibration targets and can capture oscillations of the river stage and its impact on the brine.
- Identify high-flow and/or high-flux channels that are discharging to the river using distributed temperature sensing, potentially with fiber-optic cable, or other high-resolution site characterization techniques along the river.
- Consider using ERT to characterize hydraulic interfaces in the subsurface and guide placement of sensors.
- Use a groundwater flow model to do a data worth assessment for potential monitoring approaches and locations.
- Consider characterization of contaminant flux, to the river and/or from the brine, and use flux reduction as an initial remedial goal; sensors for ammonium and conductivity were discussed.

Mark Kautsky presented on the DOE-LM Applied Studies and Technology (AS&T) Program, which is a core component in incorporating advances in science and technology to improve DOE-LM's capabilities in advancing the protection of human health and the environment. Incorporating improvements in scientific understanding and technology applications into site management and remediation strategies improves cleanup effectiveness, protectiveness, and sustainability, which can result in long-term cost savings. Of relevance to the workshop was AS&T's work on unmanned aerial vehicle (UAV)-based multispectral remote sensing, which can map and track evapotranspiration, landcover change (plants, wetlands, etc.), plant health, and other environmental factors.

4.0 Conclusions and Recommendations

4.1 Workshop Recommendations

The workshop yielded recommendations on five topics: in situ sensors, spatially integrative tools, challenges to regulatory acceptance, AI/ML strategies, and transitioning sites to DOE-LM. The recommendations are summarized below.

In situ sensors:

- Compare results from F-Area with conventional monitoring results.
- Document performance, protocols, and best practices.
- Continue to explore optimization of the use of sensors.
- Adopt a consistent framework for managing and retaining heterogeneous datasets and a data management plan (including for long-term sustainability, automation, and metadata).
- Increase use of water level sensors; water level sensors are of particular importance to most sites, especially sites with interactions with rivers and significant evapotranspiration and/or precipitation.

- Continue to evaluate the robustness and maintenance of all types of sensors, which are critical to cost reduction.

Spatially integrative tools:

- Consider several additional emerging spatially integrative tools at the F-Area demonstration, including LiDAR, infrared and hyperspectral imaging, and fiber-based distributed temperature and strain sensing.
- For DOE sites in the west, consider drone-based (land or air) EM, LiDAR, infrared, hyperspectral, and satellite remote sensing, which could provide large-scale monitoring information including climatic changes and changes in land use that may alter site boundary conditions and subsurface behavior over time.
- Along with deployment of spatially integrative tools, invest in automated data collection, processing, analysis, and reporting, for which AI/ML may be significant.
- Consider joint multi-physical inversion to integrate spatial results into subsurface models.

Challenges to regulatory acceptance:

- Work from an established regulatory relationship base to gain trust and gain acceptance for changes.
- Highlight benefits and other stakeholder impacts, including more frequent/continuous data, early warning capabilities, climate predictions/resilience (an EPA priority), reduced worker risk, student interaction, and public availability and transparency.
- Seek regulatory acceptance of changes in phases, for example with frequency first and number of wells second, while showing side-by-side correlations in traditional or historical data and new approaches.
- Ensure the regulatory documentation is updated/accurate and covers legal responsibilities.
- Increase awareness of new tools, for example, through the Environmental Council of the States and the DOE Intergovernmental Meeting.
- Seek local awareness so the public is aware of the end state vision and risk impacts and how a revised monitoring approach is beneficial/transparent.
- Compile and provide a toolbox to sites undertaking use of new long-term monitoring approaches. The toolbox could consist of structured protocols, case studies, regulatory approvals, information on vulnerability zone assessments, an example implementation plan, a description of machine learning processes, and best practices for moving towards closure.

AI/ML strategies:

- To increase acceptance of AI/ML, start with established and traceable AI/ML tools and use AI/ML for its strengths, including for: 1) optimization of sampling frequency, using more data from tools for continuous monitoring, 2) change (or anomaly) detection, outside of natural fluctuation, and 3) data mining of historical datasets.
- Further explore ML algorithms using the F-Area testbed, including for change detection for potential future disturbances.
- Thoroughly document AI/ML processes and their applications.
- Use virtual datasets or systems to evaluate AI/ML strategies as well as train/educate workers/regulators.

Transitioning sites to DOE-LM:

- Start collaboration early and carefully consider regulatory requirements and details of engineering controls.
- Provide thorough documentation and data management, including regulatory agreements, data inputs to and processes for models, data quality objectives, and consistently formatted databases.

4.2 Path Forward for ALTEMIS

Ongoing and future work for the ALTEMIS project includes monitoring various sensors that have been installed at F-Area (Section 1.1) and developing and launching a data management system to house the transmittal, storage, and access of the continuous sensor data. Fieldwork will include sampling to better understand the speciation of iodine in the wetlands to support the recalculation of the risk model for iodine at F-Area. Data collection and experiments will seek to better understand how the geochemistry of the plume has evolved with time and potentially identify the geochemical conditions that influence the contaminant behavior within the zones of vulnerabilities. An air monitoring system for iodine will also be installed at F-Area. Communication efforts will support the development of a regulatory communication strategy and technology transfer documents.

4.3 Conclusion

Most remaining DOE sites will require extended periods of institutional control, especially for groundwater sites where attenuation strategies have been implemented to facilitate closure. The current practice of monitoring—obtaining and analyzing the contaminant concentrations in groundwater samples at numerous wells—will account for a large fraction of the projected life-cycle cleanup costs at these DOE sites, unless a new approach is adopted. State-of-the-art technologies are being developed by DOE that can optimize existing monitoring approaches and/or provide more continuous monitoring at lower cost. These technologies can detect changes earlier and with greater effectiveness and improve performance assessment. Implementation of new approaches will require improved data analysis and integration (for which AI/ML may be useful), thoughtful and deliberate regulatory interactions, and thorough documentation. Workshop participants emphasized their certainty that AI/ML is the next generation for environmental data analysis.

Distribution: *Appropriate customer contacts should be added at author's discretion.*

DOE-EM
Latrincy Bates latrincy.bates@em.doe.gov
Skip Chamberlain grover.chamberlain@em.doe.gov
Kurt Gerdes kurt.gerdes@em.doe.gov
John Moon john.moon@em.doe.gov
JP Pabon jean.pabon@em.doe.gov
Robert Seifert robert.seifert@em.doe.gov
Karen Skubal karen.skubal@em.doe.gov
Aaron White aaron.white@em.doe.gov

DOE-LM
Darina Castillo darina.castillo@lm.doe.gov
Mark Kautsky mark.kautsky@lm.doe.gov
Nick Kiusalaas nicholas.kiusalaas@lm.doe.gov
Tania Smith Taylor tania.taylor@lm.doe.gov
Diana Trettin diana.trettin@lm.doe.gov

SRNL
Marion Cofer marion.cofer@srnl.doe.gov
Tom Danielson thomas.danielson@srnl.doe.gov
Carol Eddy-Dilek carol.eddy-dilek@srnl.doe.gov
Emily Fabricatore emily.fabricatore@srnl.doe.gov
Hansell Gonzalez-Raymat hansell.gonzalez-raymat@srnl.doe.gov
Connie Herman connie.herman@srnl.doe.gov
Brady Lee brady.lee@srnl.doe.gov
Brian Looney brian02.looney@srnl.doe.gov
Holly VerMeulen holly.vermeulen@srnl.doe.gov

DOE-SR
Angelia Holmes angelia.holmes@srs.gov
Tony Polk philip.polk@srs.gov

SRNS-ACP
Mark Amidon mark.amidon@srs.gov
Kevin Boerstler kevin.boerstler@srs.gov
Rohit Goswami rohit.goswami@srs.gov
Seth Miller seth.miller@srs.gov
Phil Prater m.prater@srs.gov
Jeff Ross j.ross@srs.gov
Jeffrey Thibault jeffrey.thibault@srs.gov

SRS
Bradley Bohr bradley.bohr@srs.gov

Geosyntec
Keaton Belli kbelli@geosyntec.com
Michael Kavanaugh mkavanaugh@geosyntec.com
Jennifer Nyman jnyman@geosyntec.com

PNNL
Chris Johnson cd.johnson@pnnl.gov
Tim Johnson tj@pnnl.gov

LBNL
Baptiste Dafflon bdafflon@lbl.gov
Brian Quiter bjquiter@lbl.gov
Zexuan Xu zexuanxu@lbl.gov

MIT
Haruko Wainwright hmwainwright@lbl.gov

Longenecker & Associates
David Wilson dwilson@la-inc.com
Shelly Wilson swilson@la-inc.com

CRESP
Kathryn Higley kathryn.higley@oregonstate.edu

Industry
Miles Denham mdenham@panoramic.consulting
Roelof Versteeg roelof.versteeg@subsurfaceinsights.com

Moab/RSI
Ron Kent ron.kent@lm.doe.gov
Liz Moran liz.moran@moabem.doe.gov
Peter Schillig peter.schillig@lm.doe.gov

FIU
Ravi Gudavalli gudavall@fiu.edu
Pieter Hazenberg phazenbe@fiu.edu
Leonel Lagos lagosl@fiu.edu
Angelique Lawrence alawrenc@fiu.edu
Himanshu Upadhyay upadahyay@fiu.edu

Note: Bolded names on distribution list indicate those who attended in person.