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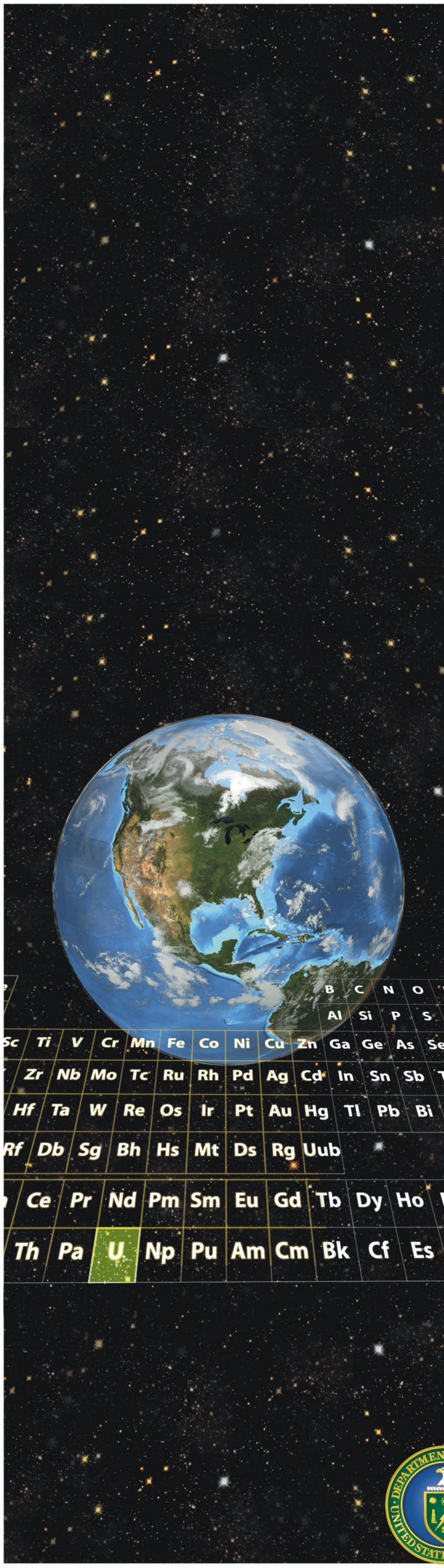
Environmental Sciences Laboratory



Applied Studies and Technology

Fiscal Year 2016 Annual Report

December 2016

U.S. DEPARTMENT OF ENERGY | Legacy Management

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Contents

Tables

Appendix

Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AC	activated carbon
ANOVA	analysis of variance
AR	activity ratio
AS&T	Applied Studies and Technology
AWP	ancillary work plan
CMU	Colorado Mesa University
COC	contaminant of concern
CRESP	DOE Consortium for Risk Evaluation with Stakeholder Participation
δD	hydrogen/deuterium ratio
$\delta^{18}O$	oxygen-18/oxygen-16 ratio
DMAV	data mining, analysis, and visualization
DOE	U.S. Department of Energy
ECAP	Enhanced Cover Assessment Project
EPA	U.S. Environmental Protection Agency
EQuIS	Environmental Quality Information System
ESL	Environmental Sciences Laboratory
ET	evapotranspiration
EVI	Enhanced Vegetation Index
FY	fiscal year
GJDS	Grand Junction Disposal Site
GMD	groundwater model domain
HDPE	high-density polyethylene
IAEA	International Atomic Energy Agency
IDL	Interactive Data Language
ISR	in situ recovery
LAI	leaf area index
LiDAR	light detection and ranging
LM	Office of Legacy Management
LMS	Legacy Management Support
LTS&M	long-term surveillance and maintenance
LTSP	Long-Term Surveillance Plan
m	meters
mg/L	milligrams per liter

mm	millimeters
mm/year	millimeters per year
MODIS	Moderate Resolution Imaging Spectroradiometer
MTL	maximum tolerance level
N	nitrogen
NAS	National Academy of Sciences
Navarro	Navarro Research and Engineering, Inc.
NDVI	Normalized Difference Vegetation Index
NRC	U.S. Nuclear Regulatory Commission
NURE	National Uranium Resource Evaluation
NVOS	Nevada Offsites
PAF	Predictive Assimilation Framework
PPT	precipitation
^{222}Rn	radon-222
SC	specific conductivity
SCT	specific conductivity/temperature
SEEPro	Site Environmental Evaluation for Projects
SLAC	Stanford Linear Accelerator Center
SOARS	System Operation and Analysis at Remote Sites
STEM	science, technology, engineering, and mathematics
TTP	Technical Task Plan
U	uranium
UA	University of Arizona
UAS	unmanned aircraft system
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	U.S. Geological Survey

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Executive Summary

The Applied Studies and Technology (AS&T) Program has a critical role in the U.S. Department of Energy (DOE) Office of Legacy Management (LM) mission to fulfill its post-closure responsibilities and to ensure the future protection of human health and the environment. Given the long half-lives of some radionuclides, LM sites will require long-term surveillance and maintenance (LTS&M) for hundreds or even thousands of years. Incorporating improvements in scientific understanding and technology applications into site management and remediation strategies improves cleanup effectiveness, protectiveness, and sustainability and can decrease long-term costs. The overriding goal of AS&T is to incorporate advances in science and technology to improve LM capabilities towards fulfilling its mission. AS&T strives to move the "state of the science" in long-term stewardship strategies and methods into the "state of the practice" at LM sites (2012 AS&T Five-Year Plan).

The AS&T program implements a disciplined management process to identify, select, and monitor AS&T studies. This management process (1) ensures that all AS&T studies support LM's long-term goals, objectives, and strategies; (2) engages LM management and Legacy Management Support (LMS) staff in the development of the AS&T study portfolio; (3) effectively documents and communicates AS&T study results and conclusions to LM and LMS management; (4) promotes the application of applicable AS&T study outcomes to LM/LMS site and task managers to improve the effectiveness of LM operations; and (5) integrates AS&T into LM-wide optimization and improvement initiatives.

The AS&T program includes a portfolio of long-term technical studies, implemented through Technical Task Plans, where the deliverables are new knowledge, enhanced technical capability, advancement of current LM/LMS operations, and new or improved technology applications. These studies are the primary focus for the AS&T program. In fiscal year (FY) 2016, AS&T technical studies included (1) Variation in Groundwater Aquifers; (2) Plume Persistence; (3) SOARS (System Operation and Analysis at Remote Sites); (4) Data Mining, Geochemical Analysis, and Project Visualization; (5) Long-Term Cover Performance; (6) Enhanced Natural Attenuation; (7) Educational Collaboration; (8) Gold King Mine Spill Impact to Uranium Mill Tailings Radiation Control Act Sites; and (9) Unmanned Aircraft System Technology Evaluation.

The AS&T program also includes a portfolio of short-term studies implemented through ancillary work plans (AWPs), requested by an LM site manager or one or more LMS subject matter experts. These AWPs are approved and performed on an as-requested basis. Examples include supporting DOE interoffice collaborations across multiple LM sites, supporting approved technical studies, performing short-term investigations, and developing white papers. In FY 2016, AS&T ancillary studies included: (1) Uranium In Situ Recovery; (2) Evaporite Sampling Phase I; (3) Well Redevelopment Evaluation; (4) Nevada Offsites (NVOS) ArcGIS Two-Dimensional Transport Modeling Assessment; (5) NVOS Three-Dimensional Visualization Project; (6) Tracer Testing Workshop; and (7) LM and Subsurface Insights Modeling Collaboration.

We made significant progress on all technical and ancillary studies, summarized here. Four examples of successful AS&T contributions to the LM mission are described below.

Well Redevelopment Evaluation: AS&T undertook an evaluation to determine whether routine well redevelopment was necessary to obtain representative groundwater samples. The study examined water quality results pre- and post-redevelopment in nearly 500 wells from 16 LM sites. Results showed that uranium, the primary contaminant of concern, generally remained unchanged pre- and post-well redevelopment. Thus, redevelopment is not required to obtain representative groundwater samples.

Plume Persistence Study: In FY 2016, AS&T initiated collaborations and cost-sharing for this study with SLAC National Accelerator Laboratory, operated by Stanford University on behalf of DOE. These collaborations led to enhanced data collection and refined interpretation of subsurface processes that control contaminant migration.

Effects of Soil-Forming Processes on Cover Engineering Properties: This new study involves collaboration with U.S. Nuclear Regulatory Commission researchers and with partners from academia. The study will improve our understanding of the effects of natural ecological and soil-forming processes on the engineering properties that control radon flux and rainwater percolation in disposal cell covers. In FY 2016, the research team conducted field studies on disposal cell covers at two LM sites.

Educational Collaborations: The AS&T Educational Collaboration initiative builds on LM's longstanding commitment to environmental science education by strengthening existing partnerships with Native American undergraduate and graduate students and by exploring opportunities for new partnerships. In FY 2016, as with prior fiscal years, this initiative was advanced through partnerships with Diné College and the University of Arizona and through planning for new educational partnerships. This initiative includes (1) development of educational modules on uranium mining and reclamation for tribal colleges, (2) creation of AS&T studies (tied to LM Goal 1) that match graduate student research requirements, and (3) cultivation of new educational partnerships with tribal and local colleges and universities linked to other stakeholder communities.

The collaboration with Diné College is recognized as a successful grassroots partnership. Many Diné College students and university graduate student partners have received recognition at tribal college science, technology, engineering, and mathematics conferences and other national technical forums. The partnership has received recognition from the U.S. Environmental Protection Agency, the DOE Consortium for Risk Evaluation with Stakeholder Participation, and the National Academy of Sciences.

Other measures of the effectiveness of the AS&T program include advances in scientific understanding through scientific and regulatory collaborations and journal publications and conference presentations in national and international recognized forums. These AS&T achievements in FY 2016 include the following:

- AS&T study results were presented at eight conferences
- AS&T study results published in five journals
- AS&T collaborated on nine studies with universities, government agencies, and national laboratories
- AS&T hosted scientists from the International Atomic Energy Commission to share study results and conduct site tours

The Environmental Science Laboratory provides laboratory services for AS&T projects and various LM sites. In FY 2016, column studies were performed in the laboratory on Riverton, Wyoming, floodplain soils. Samples were submitted to the Environmental Sciences Laboratory for analyses in FY 2016 from the Old Rifle, Rocky Flats, Durango, and Grand Junction sites in Colorado; the L-Bar and Shiprock, New Mexico, sites; the Bear Creek and Riverton, Wyoming, sites; the Monticello, Utah, sites; the Shoal, Nevada site; and the Monument Valley, and Tuba City, Arizona, sites.

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1.0 Introduction

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) Strategic Plan presents LM's goals and objectives (DOE 2016c). The objectives of Goal 1, Protect Human Health and the Environment, are to comply with environmental laws and regulations, reduce post-closure related health risks in a cost-effective manner, and improve the long-term sustainability of environmental remedies.

An overriding LM goal is to "incorporate advances in science and technology to improve our capabilities" in advancing protection of human health and the environment (DOE 2016c). Applied Studies and Technologies (AS&T) is a core component of LM's efforts to fulfill this goal. Incorporating improvements in scientific understanding and technology applications into site management and remediation strategies improves cleanup effectiveness and can decrease long-term costs. This fiscal year (FY) 2016 Annual Report documents the studies AS&T is conducting to fulfill these objectives, to continuously improve the quality of long-term surveillance and maintenance (LTS&M) and the cost effectiveness, sustainability, and protectiveness of environmental remedies at LM sites. These studies include working with other federal agencies, the environmental community, universities, national laboratories, and the international scientific community so that LM can stay informed about emerging engineering and scientific advancements that support ongoing LM studies and promote data sharing, discourse, and scientific achievements.

AS&T work consists of two categories of study. Category 1 studies enhance LM's strategic capabilities by way of new knowledge or understanding, enhanced technical capability, optimizing current Legacy Management/Legacy Management Support (LMS) operations, and advancing technology applications. Category 1 studies are documented in Technical Task Plans (TTPs). Category 2 studies consist of ancillary work requested by LM and LMS subject matter experts. This is work is considered on an ad hoc basis and can include supporting DOE interoffice collaborations across multiple LM sites, supporting active Category 1 work, performing short-term investigations, and developing white papers. Category 2 studies are documented in ancillary work plans (AWPs).

In fiscal year (FY) 2016, AS&T work included nine TTPs and seven AWPs. The TTPs focus on eight technical areas: (1) Subsurface studies, (2) Remote Environmental Monitoring Technology studies, (3) Environmental Data Mining and Visualization studies, (4) Long-Term Cover Performance studies, (5) Enhanced Natural Attenuation studies, (6) Educational Collaboration initiatives, (7) Environmental Monitoring, and (8) Data Collection. Section 5.0 of this annual report summarizes FY 16 TTPs. The seven AWPs range from work associated with sampling evaporite deposits at the Riverton, Wyoming, Processing Site to evaluating whether monitoring well redevelopment is necessary to obtain representative groundwater samples. Section 6.0 of this annual report summarizes the FY 2016 AWPs.

In addition to these long-term and short-term study areas, AS&T manages the Environmental Sciences Laboratory (ESL). The ESL includes a geochemical laboratory, an ecology laboratory, a petrography facility, and an instrument calibration facility.

2.0 Program Objectives

AS&T is at the core of LM efforts to incorporate improvements in scientific understanding and advancements in technology into site management and remediation strategies to improve remedy protectiveness, sustainability, and long-term cost effectiveness. AS&T conducts in-house studies and collaborates with other federal agencies, the environmental community, universities, national laboratories, and the international scientific community on other studies to evaluate and understand emerging engineering and scientific advancements that may prove beneficial to LM. The following AS&T objectives are presented in the *Five-Year Plan for Applied Science and Technology (AS&T) FY 2013 Through FY 2017* (Five-Year Plan) (DOE 2012) and are directly aligned with the LM Strategic Plan:

- Ensure that sound engineering and scientific principles are used to conduct LTS&M.
- Evaluate and improve the effectiveness of routine LTS&M practices.
- Evaluate the long-term performance of disposal cells, groundwater treatment systems, and institutional controls.
- Track and apply advances in science and technology to improve the sustainability of these remedies.
- Provide LM with the science and technology needed to make informed decisions regarding potential future corrective actions and modifications of selected remedies.
- Share technologies and lessons learned with stakeholders; regulators; and state, tribal, and local governments.
- Collaborate and share project costs with other DOE offices, other agencies, universities, and industry and offer "test beds" to other organizations that fund LTS&M research and development.
- Publish AS&T project results to provide a measure of credibility in defending LM decisions, to bring visibility to LM science and technology initiatives, and to enable others to utilize the results.
- Use AS&T projects to create and promote opportunities, discourse, and achievements in environmental science education.

In FY 2016, AS&T studies have resulted in the advancement of LM objectives (DOE 2016c) including the following:

1. Reduce post-closure-related health risks in a cost-effective manner.
2. Improve the long-term sustainability of environmental remedies.
3. Address the environmental legacy of defense-related uranium mines and milling sites.
4. Make information more accessible.
5. Enhance sustainable environmental performance for facilities and personal property, and account for climate change in LM site management.
6. Engage the public in our program, project, and site activities.
7. Work effectively with local, state, and federal governments and nonprofit organizations.
8. Consult, collaborate, and partner with the people and governments of tribal nations.

Specific work performed by AS&T in FY 2016 that supports both AS&T and LM objectives, referenced by objective number (above), includes the following:

- Development, installation, and maintenance of remote data acquisition systems to monitor remedy performance, expedite corrective actions, reduce LTS&M costs, and increase sustainability of remedies (1, 2, 4, 5)
- Developing data mining tools to facilitate site data analysis and promote program and site understanding using LM's existing data assets (2, 3, 4, 7)
- Evaluating the long-term performance of disposal cells to improve the protectiveness and sustainability of these remedies, and evaluating or modifying proposed and existing cell designs (1, 2, 3, 4, 7)
- Providing support to LM to share information, technologies, and lessons learned with shareholders, regulators, and state, tribal, local governments and the environmental community, including the development of advanced visualization techniques that enhance communication and quality of technical information (3, 4, 6, 7, 8)
- Evaluating alternative methods of groundwater plume control and contaminant treatment (1, 2, 5, 7, 8)
- Collaborating with other agencies, universities, and industry to leverage new knowledge into AS&T studies (1, 2, 4, 5, 6, 7)
- Offering LM sites as test beds to other organizations to supplement LTS&M research and development (1, 2, 3, 4)
- Studying the mechanisms behind plume persistence to enhance our understanding of uranium behavior in the subsurface and our ability to predict long-term behavior of groundwater contaminant plumes, predict compliance issues, and potentially develop alternative cleanup levels if required (1, 2, 5, 7, 8)
- Publishing AS&T project results to provide a measure of credibility in supporting LM decisions and to enable others to utilize and build on the results (3, 4, 6, 7)
- Educational outreach to promote science, technology, engineering, and mathematics (STEM) education and opportunities and strengthen existing partnerships with tribal colleges and Native American students (3, 4, 6, 7, 8)

3.0 AS&T Program Management

AS&T implements a disciplined work management process to identify, select, and monitor AS&T studies. This process:

- Ensures that all AS&T studies support LM’s long-term strategies, objectives, and goals.
- Engages LM management and LMS staff in the development of the AS&T study portfolio.
- Effectively documents and communicates AS&T study results and conclusions.
- Integrates AS&T into LM-wide optimization and improvement initiatives.

Management: In accordance with the *Applied Studies and Technology (AS&T) Program Guidance to Identify, Select, and Monitor Applied Studies* (DOE 2014a), all potential AS&T studies are identified and evaluated against LM's long-term goals, objectives, and strategies. The selection process for adding a study to the AS&T portfolio involves the LM AS&T manager, LM site managers, LMS AS&T manager, and LMS technical sponsors. Key features of a proposed study that are considered include: (1) a demonstrated commitment to enhancing LM's strategic capabilities; (2) scientific value (e.g., whether the results of the study will be suitable for publication in a nationally recognized journal); and (3) a scope of work that documents the study plan, the estimated budget, and milestones.

Integration: AS&T's integration effort is evolving to address LM programwide challenges. This integration involves engaging LM management and LMS staff across the LM program in the development of the AS&T study portfolio. In addition, AS&T is actively supporting LM-wide optimization and improvement initiatives.

Communication: Effective documentation and communication of AS&T work is necessary to maximize the positive impacts of AS&T studies to LM objectives. To support this effort, a communication model document (Appendix A) was developed to guide communication to internal and external audiences. The communication model document provides a framework to manage and coordinate a wide variety of AS&T communications and describes who will receive AS&T communications, how the communications will be delivered, what information will be communicated, who communicates, and the frequency of the communications.

4.0 Program Effectiveness and Achievements

All AS&T studies are undertaken to improve the quality of LTS&M and environmental remedies at LM sites. AS&T shares study results by publishing reports and journal articles, giving presentations at conferences and to visiting professionals, guiding site tours, and conducting technical information exchanges. To maximize study effectiveness, AS&T routinely collaborates with other government agencies, universities, and private entities. AS&T disseminates information globally by participating in International Atomic Energy Agency (IAEA) conferences and workshops.

4.1 Overview of Technical Task Plans and Ancillary Work Plans

In FY 2016, AS&T worked on nine TTPs and seven AWPs, as presented in Table 1. Details regarding TTP and AWP activities can be found in Sections 5.0 and 6.0, respectively.

Table 1 provides a tabular summary of FY 2016 AS&T TTPs and AWPs. It is intended to guide the reader to potential areas of interest within the report. Cross-references are provided to link these summaries to sections in the report where more detail is provided.

Table 1. FY 2016 Active Technical Task Plans and Ancillary Work Plans

Title	Status	Location in Annual Report
Technical Task Plans		
Variation in Groundwater Aquifers	Ongoing in FY 2017	Section 5.1
Plume Persistence	Completed in FY 2016	Section 5.2
SOARS: System Operation and Analysis at Remote Sites	Ongoing in FY 2017	Section 5.3
Data Mining, Geochemical Analysis, and Project Visualization	Ongoing in FY 2017	Section 5.4
Long-Term Cover Performance	Ongoing in FY 2017	Section 5.5
Enhanced Natural Attenuation	Ongoing in FY 2017	Section 5.6
Educational Collaboration	Ongoing in FY 2017	Section 5.7
Gold King Mine Spill Impact to Uranium Mill Tailings Radiation Control Act Sites	Ongoing in FY 2017	Section 5.8
Unmanned Aircraft System Technology Evaluation	Ongoing in FY 2017	Section 5.9
Ancillary Work Plans		
Uranium In Situ Recovery	Completed in FY 2016	Section 6.1
Evaporite Sampling Phase I	Ongoing in FY 2017	Section 6.2
Well Redevelopment Evaluation	Completed in FY 2016	Section 6.3
Nevada Offsites (NVOS) ArcGIS Two-Dimensional (2D) Transport Modeling Assessment	Ongoing in FY 2017	Section 6.4
Nevada Offsites (NVOS) Three-Dimensional (3D) Visualization Project	Ongoing in FY 2017	Section 6.5
Tracer Testing Workshop	Completed in FY 2016	Section 6.6
LM and Subsurface Insights Modeling Collaboration	Ongoing in FY 2017	Section 6.7

Table 2 provides a tabular summary of FY 2016 AS&T TTPs and AWP that are under development.

Table 2. FY 2016 Technical Task Plans and Ancillary Work Plans Under Development

Technical Task Plans
Persistent Secondary Contaminant Sources
Pollinator Habitat Development and Sustainability
Tamarisk and Vegetation Management Study
Ancillary Work Plans
Groundwater Modeling Training

4.2 Effectiveness and Achievements

The following sections summarize AS&T past and present (FY 2016) program effectiveness and achievements.

4.2.1 Long-Term Cover Performance Studies

LM is currently responsible for the LTS&M of 91 sites, some of which will never be released for unrestricted use (DOE 2016c). To ensure long-term protectiveness of the remedies, it is critical that LM understands the long-term processes that affect performance of disposal cells and their engineered cover systems. Due to the long-term LTS&M obligations, it is also critical that cost effective and sustainable LTS&M practices are developed and implemented. AS&T has a portfolio of studies that focus on enhancing our understanding the long-term processes that affect disposal cell performance with the goal of improving performance, sustainability, and cost effectiveness. These studies are as follows.

Initiated in the 1990s, this succession of studies addresses gaps in our scientific understanding of how disposal cell covers are changing over long periods of time and if changes are altering cover performance. Knowledge gained from these studies will have significant implications for long-term protectiveness evaluations, LTS&M land management practices, and LTS&M cost reductions. These studies may also impact future disposal cell design and performance evaluation methods and policies. These studies include collaborations with U.S. Environmental Protection Agency (EPA) and Nuclear Regulatory Commission (NRC) regulators to move the regulatory framework towards risk-informed performance evaluations. The four ongoing studies align with the LM Strategic Plan goal to understand and improve the long-term sustainability of environmental remedies employed at LM sites.

- **Effects of Soil-Forming Processes on Cover Engineering Properties**
  This 4-year study, initiated in FY 2015, is a collaboration with NRC researchers and partners from academia. The study will improve our understanding of the effects of natural ecological and soil-forming processes on the engineering properties that control radon flux and rainwater percolation in disposal cell covers. In FY 2015, the research team developed new sampling, monitoring, and modeling methods for measuring and predicting changes in cover performance. In FY 2016, LMS scientists and collaborators from NRC, University of Wisconsin-Madison, University of Virginia, and University of California-Berkeley completed field sampling of the Falls City, Texas, and Bluewater, New Mexico, disposal cell covers.
- **Contaminant Uptake by Plants on Disposal Cells**
  This study, initiated in FY 2012, evaluated plant uptake of tailings elements on disposal cell covers and associated exposure risks near Native American communities. It also highlights the contribution of AS&T to LM's community outreach initiatives. The study was a thesis research project for a University of Arizona student who is a member of a stakeholder community. Results support an overall premise that LM could discontinue herbicide spraying on rock-covered disposal cells, potentially leading to a reduction in LTS&M costs at these sites. In FY 2016, the student presented a paper at the American Geophysical Union annual meeting and continued work on a manuscript for publication in a scientific journal. An LMS scientist serves as the student's advisor.
- **Water Balance Cover Monitoring**
  This multiyear study is the culmination of an effort to develop, test, construct, and monitor a water balance cover. Water balance covers are sustainable alternatives to conventional covers containing compacted soil barriers. Earlier collaborations with EPA researchers and partners from academia led to the water balance cover design for the disposal cell located in Monticello, Utah. The current study developed instrumentation and methods for large-scale

monitoring of the Monticello disposal cell cover system. Results show nearly zero percolation through the water balance cover over a 16-year period. The study has garnered national and international (International Atomic Energy Agency) recognition for innovation, and it has become a technical basis for water balance cover designs at other DOE, state, and municipal disposal sites. Cover performance monitoring continued through FY 2016. Future plans include drafting a monograph and using the unique monitoring data to calibrate, validate, and compare water balance models.

- **Enhanced Cover Assessment Project**
  This multiyear study is evaluating how natural ecological and soil-forming processes are transforming conventional covers into water balance covers, transformations that might enhance long-term protectiveness and reduce LTS&M costs. The study is using large-scale test facilities constructed at the Grand Junction, Colorado, Disposal Site (GJDS) in FY 2007 and 2010. In FY 2016, a paper was published in the *Journal of Environmental Quality* on cover soil manipulation methods, a cover revegetation study was continued, and comparison of the performance of conventional and enhanced covers was continued.

4.2.2 SOARS: System Operation and Analysis at Remote Sites

Because many LM sites are in remote locations making routine field visits costly, AS&T established SOARS to remotely collect and transmit data in real time to LM servers. SOARS supports LMs objectives to reduce post-closure-related health risks in a cost-effective manner, improve the long-term sustainability of environmental remedies, and make information more accessible. In a typical year, SOARS reduces travel to sites by 37,000 miles, saving about 1900 gallons of fuel. Approximately 19.64 pounds of carbon dioxide (CO_2) are produced from a gallon of gasoline in a typical vehicle[1]. This translates to a CO_2 emission reduction of 18.7 tons per year through the implementation of SOARS. Additionally, increased safety has been realized by reducing driving time. Many of the SOARS sites use photovoltaic solar system to power instruments and communications equipment, further reducing electrical consumption and greenhouse gas emissions. In recognition of the SOARS efficiencies, in FY 2011 LM received a DOE Management Award for cost savings related to energy, water, and vehicle fleet management. In FY 2016, the savings and efficiencies associated with SOARS continued to reduce LM program costs.

Currently SOARS is operational at 21 LM sites in eight states (Table 3). Cumulatively, SOARS maintains 113 data loggers coupled to 800 sensors of varying types. Understanding weather patterns and extremes is an important component of LTS&M. To facilitate data acquisition, SOARS currently maintains weather stations at 15 sites (Table 3). Efforts are underway to share LM weather data with the National Weather Service to provide better coverage in remote areas where weather coverage has been previously spotty or nonexistent. SOARS also allows LM scientists and engineers to remotely diagnose and fix problems with piping and electrical systems at a number of remote sites. SOARS also makes it possible to control values and pumping rates remotely from office locations. It is expected that the SOARS footprint will continue to expand with technology development and as more sites transition to LM.

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[1] U.S. Energy Information Administration, “How much carbon dioxide is produced by burning gasoline and diesel fuel?” http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11.

Table 3. Sites with SOARS Instrumentation

Site Name and State	Number of Data Loggers	Weather Station
Bluewater, New Mexico	11	Yes
Grand Junction Disposal, Colorado	3	Yes
CNTA, Nevada	2	No
Crested Butte, Colorado	3	Yes
Durango, Colorado	2	Yes
Fernald, Ohio	1	No
Grand Junction, Colorado	4	Yes
Lakeview, Oregon	6	Yes
L-Bar, New Mexico	2	Yes
Monticello, Utah	7	Yes
Monument Valley, Arizona	5	Yes
Mound, Ohio	1	No
New Rifle, Colorado	9	Yes
Old Rifle, Colorado	7	Yes
Rifle Disposal, Colorado	5	Yes
Rocky Flats, Colorado	8	Yes
Shiprock, New Mexico	30	Yes
Tuba City, Arizona	2	No
Weldon Spring, Missouri	5	Yes

4.2.3 Plume Persistence Study

This multiyear study, initiated in FY 2014, is focused on improved scientific understanding of why contaminant plumes at many LM sites persist for time frames that are much longer than those predicted by traditional groundwater modeling. This goal aligns with the LM objective to improve the long-term sustainability of environmental remedies employed at LM sites by advancing the scientific understanding of subsurface processes. Outcomes from this study may affect the analyses of long-term performance of disposal cells, groundwater treatment systems, alternative concentration level discussions, and institutional controls.

In FY 2016, AS&T initiated collaborations and cost sharing associated with this study with SLAC National Accelerator Laboratory (SLAC), operated by Stanford University on behalf of DOE. These collaborations led to enhanced data collection and refined interpretation of subsurface processes that control contaminant migration.

4.2.4 Variation in Groundwater Aquifers Study

This multiyear study, initiated in FY 2014, is focused on advancing scientific understanding of mechanisms responsible for major chemical variations in groundwater that could impact traditional plume migration rate estimations as well as interpretations of historical contaminant trends, both of which affect the compliance strategy selected for a site. This study supports the LM objective to understand and improve the long-term sustainability of environmental remedies at LM sites. Outcomes from this study will affect future groundwater monitoring-well design, groundwater monitoring protocols, and the analyses of groundwater sample analytical data.

Preliminary study results indicate that some sites have considerable vertical stratification in some monitoring wells, so much so that the entire temporal variation in chemical concentrations observed over 10 or more years in an individual monitoring well could be reproduced in a single day by sampling at different vertical intervals within the well. To accurately interpret cleanup trends, vertical stratification impacts will need to be considered and future sampling methods revised accordingly.

4.2.5 Enhanced Natural Attenuation

Enhanced Natural Attenuation studies seek to understand and then enhance physical, ecological, and microbiological processes as alternatives to conventional remedies for contaminated soil and near-surface groundwater. The goal is to improve remedy effectiveness and sustainability and reduce LTS&M costs for soil and groundwater remedies. Five studies are addressing remediation options at several sites and include components of collaboration, cost sharing, and educational outreach. The Enhanced Natural Attenuation studies include (1) evapotranspiration to control soil leaching and dispersion of groundwater plumes at the Tuba City, Arizona, site; (2) phytoremediation to support the hydraulic control of shallow groundwater at the Shiprock, New Mexico, site; (3) microbial attenuation of soil contaminants at the Monument Valley, Arizona, site; (4) land-farming techniques to remediate groundwater contaminants at the Monument Valley, Arizona, site; and (5) the use of unmanned aircraft system (UAS) imagery to monitor phytoremediation and evapotranspiration (ET) on a landscape scale at the Shiprock, New Mexico, and Moab, Utah, sites.

- **Tuba City Evapotranspiration**
  This study, initiated in FY 2015 as a collaboration with USGS) and partners from academia, refined a remote-sensing method for landscape-scale estimates of evapotranspiration. ET can greatly influence both groundwater recharge and discharge in desert environments. In FY 2016, collaborators published a paper in *Journal of Arid Environments* on effects of rangeland ET on groundwater flow at the Tuba City, Arizona, site. This study was completed in FY 2016.

- **Shiprock Phytoremediation: Hydraulic Control**
  This multiyear pilot study, initiated in FY 2006, evaluated the feasibility of growing native deep-rooted plants called phreatophytes to transpire groundwater and thereby control groundwater flow and contaminant transport at the Shiprock, New Mexico, disposal site. Students and faculty from University of Arizona and Diné College, a Navajo-owned community college, supported field sampling activities and data analysis. In FY 2016, collaborators drafted a report that included estimates of ET discharge of groundwater for a hypothetical large planting of phreatophytes.

- **Monument Valley Subpile Soil Phytoremediation**
  This study is also a collaboration with students and faculty from the University of Arizona and Diné College. This is a follow-up study of a multiyear evaluation of soil phytoremediation and bioremediation as alternatives for remediating contaminated soil that was a source of groundwater contamination at the Monument Valley processing site. This study produced evidence that a combination of native transplants and microorganisms had isolated, through evapotranspiration, and removed, through denitrification, most of the soil

contamination—the pilot study was the remedy. In FY 2016, collaborators published a paper in the journal, Land Degradation & Development, and used the results of the study to support the overall groundwater remedy for the site. This study was completed in FY 2016.

- **Monument Valley Land-Farm Phytoremediation of Groundwater**
  This multiyear study produced an option for groundwater remediation at the Monument Valley processing site. The study demonstrated land-farm phytoremediation: pumping groundwater contaminated with ammonia and nitrate to irrigate and fertilize crops of native plants and produce abundant seed that Navajo entrepreneurs could harvest for mine-land reclamation and rangeland restoration.
- **USGS UAS Evapotranspiration Assessment**: This study will use UASs to acquire high-resolution spectral data needed to estimate spatial and temporal variability in ET in floodplain ecosystems for input to groundwater flow evaluations. This study will combine UAS imagery, Landsat and MODIS imagery, ground measurements of LAI, and an empirical ET algorithm to estimate ET in tamarisk-dominated riparian ecosystems adjacent to the Shiprock, New Mexico, Disposal and Moab, Utah, Processing sites. Data will be scaled from ground measurement to UAS and satellite imagery to refine the empirical ET algorithm, and then to estimate seasonal and annual variation in ET for the different riparian zones at the two sites and in adjacent reference areas.

4.2.6 Educational Collaborations

The AS&T Educational Collaboration initiative was created to support the Secretary of Energy's commitment to tribal education partnerships with an emphasis on STEM education. This initiative builds on our longstanding commitment to environmental science education by strengthening existing partnerships with Native American undergraduate and graduate students, and by exploring opportunities for new partnerships.

- **Diné College Partnership**
  This multiyear partnership supports classroom instruction and creates hand-on field experiences for environmental science students at Diné College. In FY 2016, an AS&T scientist presented a seminar on ecological remedies for uranium mill tailings; taught classes and labs covering phytoremediation, environmental sampling designs and statistics, and effects of climate change on the performance of environmental remedies; and led students on a field trip and soil sampling activity.
- **University of Arizona Partnership**
  This partnership was created in FY 2013 with a University of Arizona faculty member who serves as an environmental science extension specialist to Native American communities and recruits Native American graduate students. An AS&T scientist serves as an adjunct faculty advisor for students who have secured non-DOE grants to collaborate on LM studies. In FY 2016, students continued their work on two studies: long-term success of revegetation practices at the Tuba City site, and uptake of contaminants by deep-rooted plants growing on uranium mill tailings disposal cells near Native American communities.
- **Grow Higher Education Collaboration**
  LM developed this program plan to grow and expand higher education collaborations with a continued emphasis on STEM education for Native American students and on fostering new educational partnerships. The plan included (1) development of educational modules on uranium mining and reclamation for tribal colleges, (2) creation of AS&T studies tied to LM

Goal 1 that match graduate student research requirements, and (3) cultivation of new educational partnerships. An AS&T scientist gave a public seminar and taught an Environmental Science class at Colorado Mesa University in Grand Junction.

Table 4 provides a FY 2016 summary of Education Collaboration activities (See Section 5.7 for details).

Table 4. FY 2016 Educational Outreach Summary

College/University	AS&T Activity
Diné College, Tsaile, Arizona	Lecture: "Using Plants to Clean Up Uranium Mill Tailings Contamination at Monument Valley, Arizona" (November 11, 2015)
	Lab: "Environmental Statistics: Land Farm Phytoremediation at Monument Valley" (November 11, 2015)
	Seminar: "Helping Mother Earth Heal: Ecological Remedies for Uranium Mill Sites" (November 18, 2015)
	Lecture: "Climate Change: Design and Long-Term Performance of Engineered Covers for Uranium Mill Tailings" (March 15, 2016)
	Lecture and Lab: "Using Plants to Clean Up Uranium Mill Tailings Contamination at Monument Valley, Arizona" (March 17, 2016)
	Field Trip: Tour of Monument Valley phytoremediation pilot studies and student participation in soil sampling (March 18, 2016)
University of Arizona, Tucson, Arizona	Master Thesis Advisor
University of Arizona, Tucson, Arizona	PhD Committee Member
Colorado Mesa University, Grand Junction, Colorado	Guest instructor to an Environmental Sciences class

4.3 Conference and Workshops

To acquire and disseminate information related to LM issues, AS&T staff participate in conferences and workshops as attendees and presenters, summarized in Tables 5 and 6.

Table 5. Conferences Attended in FY 2016

Conference/Workshop	Location	Date	AS&T Activity	Location in Annual Report
Interstate Technology and Regulatory Council Annual Meeting	Minneapolis, Minnesota USA	April 18–22, 2016	Management	Appendix A
Unmanned Aircraft Systems Technologies LiDAR Demonstration	Castle Rock, Colorado USA	February 25, 2016	TTP: Unmanned Aircraft System Technology Evaluation	Section 5.9

Table 6. Conferences Presented in FY 2016

Conference or Workshop	Location	Date	Title	Conference Item	AS&T Activity	Location in Annual Report
American Geophysical Union 2015	San Francisco, California USA	12/16/2015	Column Testing and 1D Reactive Transport Modeling to Evaluate Uranium Plume Persistence Processes	Presentation	TTP: Plume Persistence	Section 5.2
American Geophysical Union 2015	San Francisco, California USA	12/16/2015	Uptake of Elements of Concern by Plants Growing on Remediated Uranium Mill Tailings Near Native American Communities	Poster	TTP: Enhanced Natural Attenuation	Section 5.6
National Groundwater Association Summit	Denver, Colorado USA	4/26/2016	Column Testing and 1D Reactive Transport Modeling to Evaluate Uranium Plume Persistence Processes	Presentation	TTP: Plume Persistence	Section 5.2
International Mine Water Association	Leipzig, Germany	7/14/2016	Column Testing and 1D Reactive Transport Modeling to Evaluate Uranium Plume Persistence Processes	Proceedings Article and Presentation	TTP: Plume Persistence	Section 5.2
International Mine Water Association	Leipzig, Germany	7/12/2016	Persistent Secondary Contaminant Sources at a Former Uranium Mill Site, Riverton, Wyoming USA	Proceedings Article and Poster	TTP: Plume Persistence	Section 5.2
International Atomic Energy Agency 2016	Madrid, Spain	5/25/2016	Applications of Ecological Engineering Remedies for Uranium Processing Sites	Presentation	TTP: Enhanced Natural Attenuation	Section 5.6
Geological Society of America	Denver, Colorado USA	9/28/2016	Contribution of Uranium-Bearing Evaporites to Plume Persistence Issues at a Former Uranium Mill Site, Riverton, Wyoming	Poster	AWP: Evaporite Sampling Phase I	Section 6.2
Geological Society of America	Denver, Colorado USA	9/28/2016	Water-Quality Issues Related to Uranium In Situ Recovery Sites	Presentation	AWP: Uranium In Situ Recovery	Section 6.1

Abbreviation:
1D = one-dimensional

4.4 Journal Articles

In FY 2016, AS&T scientists authored or coauthored five journal articles (Table 7). AS&T uses journal articles as a means of vetting LM study results and sharing LM study outcomes with the scientific community.

Table 7. Journal Articles by AS&T Scientists Published in FY 2016

Article	AS&T Activity	Location in Annual Report
Glenn, E.P., C.J. Jarchow, and W.J. Waugh, 2016. "Evapotranspiration dynamics and effects on groundwater recharge and discharge at an arid waste disposal site," *Journal of Arid Environments* 133:1–9.	TTP: Enhanced Natural Attenuation	Section 5.6
Glenn, E.P., F. Jordan, and W.J. Waugh, 2016. "Phytoremediation of a nitrogen-contaminated desert soil by native shrubs and microbial processes," *Land Degradation and Development*, DOI:10.1002/ldr.2502.	TTP: Enhanced Natural Attenuation	Section 5.6
Johnson, R.H., R.A. Truax, D.A. Lankford, and J.J. Stone, 2016. "Sorption testing and generalized composite surface complexation models for determining uranium sorption parameters at a proposed uranium in-situ recovery site," *Mine Water and the Environment*, http://link.springer.com/article/10.1007/s10230-016-0384-6.	TTP: Plume Persistence	Section 5.2
Johnson, R.H., and H. Tutu, 2016. "Predictive reactive transport modeling at a proposed uranium in situ recovery site with a general data collection guide," *Mine Water and the Environment,* http://link.springer.com/article/10.1007/s10230-015-0376-y.	AWP: Uranium In Situ Recovery	Section 6.1
Waugh, W.J., C.H. Benson, W.H. Albright, G.M. Smith, and R.P. Bush, 2015. "Evaluation of soil manipulation to prepare earthen waste covers for revegetation." *Journal of Environmental Quality* 44(6):1911-1922.	TTP: Long-Term Cover Performance	Section 5.5

4.5 Collaborations

AS&T collaborated with a number of universities, government agencies, and national laboratories during FY 2016 (Table 8). Collaboration takes multiple forms including intellectual teaming, cost sharing, and LM providing site access for research purposes.

Table 8. AS&T Collaborating Partners

Collaborative Entity	AS&T Activity	Location in Annual Report
SLAC National Accelerator Laboratory	TTP: Plume Persistence	Section 5.2
University of Virginia	TTP: Long-Term Cover Performance	Section 5.5
University of Wisconsin-Madison	TTP: Long-Term Cover Performance	Section 5.5
University of California	TTP: Long-Term Cover Performance	Section 5.5
U.S. Nuclear Regulatory Commission	TTP: Long-Term Cover Performance Projects	Section 5.5
U.S. Geological Survey	TTP: Enhanced Natural Attenuation and Unmanned Aircraft System Technology Evaluation	Sections 5.6 and 5.9
Office of Science and Technology Policy	Rifle Site	Sections 5.3 and 7.0
Los Alamos National Laboratory	AWP: Tracer Testing Workshop	Section 6.6
Lawrence Berkeley National Laboratory	SOARS: System Operation and Analysis at Remote Sites	Section 5.3

4.6 AS&T Reports

In FY 2016, AS&T prepared two project summary reports (Table 9). These reports can be found at https://www.osti.gov/.

Table 9. FY 2016 AS&T TTP and AWP Summary Reports

Report	AS&T Activity	Location in Annual Report
Uranium–Bearing Evaporite Mineralization Influencing Plume Persistence: Literature Review and DOE-LM Site Surveys	AWP: Evaporite Sampling Phase I	Section 6.2
Evaluation of Pre- and Post-Redevelopment Groundwater Chemical Analyses from LM Monitoring Wells	AWP: Well Redevelopment Evaluation	Section 6.3

4.7 Technical Educational Exchanges

AS&T conducts technical exchanges to communicate LM/LMS study findings and evaluation techniques to LM/LMS managers and scientists and engineers. In FY 2016, AS&T presented five technical educational exchange presentations to LM/LMS (Table 10).

Table 10. Technical Educational Exchanges

Educational Exchange Topic	Presentation Title	Date
Data Visualization	ArcGIS Visualization	June 2, 2016
	Data Mining/IDL	
	R/ggplot2 Applications	
Uranium Isotopes	Application of Uranium Isotopes to the Evaluation of the Origin of Contamination in a Desert Arroyo: Many Devils Wash, Shiprock, New Mexico	July 12, 2016
Multivariate Analysis	Multivariate Statistical Analysis	July 12, 2016

4.8 International Atomic Energy Agency Scientific Visit

On June 27 through June 30, 2016, Brazilian scientists with the International Atomic Energy Agency visited the LM office at Grand Junction, Colorado. AS&T scientists gave presentations and conducted site tours of LM sites (Tables 11 and 12). During the week of September 26, 2016, an IAEA Technical Meeting of Uranium Mining and Remediation Exchange Group was held in Grand Junction. AS&T scientists were invited to give technical presentations to the exchange group (Table 11).

Table 11. IAEA Presentations

Presentation	
June 30, 2016	AS&T Overview
	Plume Persistence Status Update and Collaborative Efforts
	Legacy Management Groundwater, Solute Transport and Geochemical Modeling
	Modeling of Flow and Transport Induced by Production of Hydrofracture Stimulated Gas Wells Near the Rulison, Colorado, Nuclear Test Site
September 26, 2016	Landscape Scale Evapotranspiration Groundwater Recharge and Discharge at a Uranium Processing Site
	An Evaluation of Nitrate Remediation in Soils and Groundwater at DOE UMTRCA Sites with an Emphasis on the Monument Valley, Arizona USA Site

Table 12. IAEA Site Tours

Tour
Grand Junction Disposal Site – Enhanced Cover Assessment Project: Lysimeter Setup
Monticello Site – 7.5 Acre Evapotranspiration Cover and Lysimeter Setup

4.9 Environmental Science Laboratory

The ESL, located at the LM office at Grand Junction, operates a fixed-base laboratory and a mobile laboratory with capabilities to conduct geochemical and ecological studies. (Details regarding ESL are presented in Section 7). In FY 2016, the ESL made significant contributions to AS&T studies. ELS personnel performed specialized analyses including petrographic interpretation and fission track radiography to better understand subsurface mineralogy and uranium sequestration and column studies to evaluate contaminant transport rates and the mechanisms controlling contaminant migration. In addition, ESL performed laboratory analyses in support of numerous LM sites including the Rocky Flats site, the Rifle, Colorado, site subsurface focus area; and the Tuba City, Arizona, disposal site.

5.0 FY 2016 Technical Task Plans

In FY 2016, AS&T conducted a variety of long-term studies in support of the LM mission that relate to subsurface processes, remote environmental monitoring technologies, data mining and visualization, disposal cell cover performance, natural attenuation, groundwater monitoring, unmanned aircraft systems (UAS) data collection, and education collaborations. TTP study details and results are presented in the following sections.

5.1 Variation in Groundwater Aquifers

Overview: This study, also called the Variation Study, is focused on evaluating variation in concentrations of dissolved constituents in groundwater monitoring wells. Preliminary investigations indicated that concentrations of dissolved ions and contaminants vary with depth in some LM wells. For example, uranium concentrations in samples collected from a well on a floodplain at the Shiprock, New Mexico, site were highly dependent on the depths from which the samples were collected. In some cases, the range in uranium concentrations observed over a decade or more in a well can be reproduced at a single point in time by simply sampling the well at different depths. This stratification in wells could be caused by stratification in the aquifer, by dead zones in the well that retain older groundwater, or by some as-yet unidentified process.

All samples collected from a well contain information about the aquifer because they are all ultimately derived from the groundwater. An investigator must skillfully evaluate the meaning of the concentration data and ascribe a measure of uncertainty to the interpretation. For example, the observation of a decade-long downward trend in uranium concentrations might be interpreted as a sign that an aquifer is cleaning up. However, if the samples were collected from stratified wells using low-flow sampling techniques, the trend may be uncertain.

The need to understand concentration stratification is tied to the need to accurately predict groundwater plume migration and cleanup rates. Contour maps of contaminant plumes are often the principal tool used to evaluate the extent of contamination in an aquifer and the rate of groundwater cleanup. Implicitly, the use of contour mapping assumes that the concentration measured in a well represents the average concentration in the aquifer at that time. By making sequential measurements over time, the rate of cleanup can be inferred. However, if concentrations vary with depth in the well bore, time trends might instead reflect changes in sampling methodology. The LM standard sampling protocol changed from three-bore-volume purge to low-flow sampling in 2002. Using low-flow sampling, the chemical concentration in a sample collected from a stratified well depends on the depth from which the sample was collected. Thus, one objective of this study is to determine how pervasive well stratification is at LM sites. To meet this goal, we conducted specific conductivity/temperature (SCT) profiling at 15 sites.

Specific conductivity is a function of the concentration of dissolved ions. The SCT profiles are made by slowly lowering a sonde through the water column. Because no pumping is required, this method has minimal disruption to the water column and provides a semicontinuous set of concentration data that can be used to evaluate the degree of well stratification. The simplicity of the method allows a large quantity of data to be collected at relatively low cost. A related objective of this Variation Study is to determine if there is a correlation between specific conductivity (SC) and contaminant concentrations (e.g., SC versus uranium). A goal of this effort would be to test the assumption that stratification in SC indicates similar stratification in contaminant concentrations. Also, if a suitable correlation exists, then specific conductivity might be a viable surrogate that could be measured in lieu of more costly sampling and analysis of chemical concentrations.

A final component of this study involved chemical and radon-222 (^{222}Rn) profiling at the sites exhibiting the greatest degree of stratification based on the Phase I SC profiling results (Shiprock floodplain and Durango processing sites). At each of these sites, wells were chosen to represent a range of SC magnitudes and degrees of stratification. Initial wells selected for chemical profiling were those displaying high variation in the specific conductivity profiles. To eliminate bias, several wells exhibiting moderate or little to no stratification were also profiled to test the assumption that no stratification based on SC measurements correlates with similar homogeneity in the vertical chemical profiles. Radon-222, which is produced within an aquifer by emanation from uranium-series isotopes, was included in this study because the ^{222}Rn activity measured in well samples reflects the length of time that the water has resided in the well (i.e., the degree of stagnation). This information may be useful in interpreting the SC and chemical profile results.

Prior Activities: Between July 2013 and October 2014, SC profiles were taken at 400 monitoring wells at 15 LM sites. The central activity in FY 2015 consisted of analysis and preliminary interpretation of those data. This evaluation culminated in the submittal of the draft report titled *Applied Studies & Technology, Variation in Groundwater Aquifers: Results of 2013–2014 Phase I Field Investigations* (DOE 2015). Analysis and preliminary interpretation of the SC profiles taken at 400 monitoring wells at 15 LM sites between July 2013 and October 2014 that Phase I field effort report. Findings of this study served as the basis for the Phase II (chemical and ^{222}Rn profiling) scope. While Shiprock ranked high in terms of overall variation based on the Phase I results, the Durango, Colorado, Processing Site (including the raffinate ponds area and the mill tailings area) also has many wells with high variation. Although most wells profiled in this investigation (about 70%) had low variation, every site has at least one well with high enough variation in the SC profile to warrant further examination. An overview of the Variation Project was included in the third quarter (July–September 2015) LM Program Update.[2]

FY 2016 Activities: The central activity in FY 2016 consisted of chemical and ^{222}Rn profiling of wells at the Shiprock disposal (floodplain) and Durango processing sites.[3] We profiled 25 wells at the Durango processing sites (13 at the mill tailings site and 12 at the raffinate processing site) and 36 wells on the Shiprock floodplain. At each well profiled, we collected samples at approximate 1-foot intervals using low-flow purge methods for the analysis of uranium, nitrate, iron, organic carbon (total and dissolved), and major ions (calcium, chloride, magnesium, potassium, sodium, and sulfate). Field parameters (alkalinity, SC, and temperature) were also measured. In a subset of these samples (10 of the 36 Shiprock wells, and 11 of the 25 Durango wells), we also profiled for ^{222}Rn. Samples were analyzed at the ESL in Grand Junction and then entered into AS&T's data mining, analysis, and visualization database (Section 5.4) for visualization and interpretation.

To verify well construction information, especially screen placement (critical to the interpretation of study results), we conducted downhole video camera surveys of wells on the Shiprock floodplain (April 2016) and Durango processing sites (July 2016).

Phase II data compilation and analysis is ongoing. Our preliminary evaluation of vertical profiles of ^{222}Rn in Shiprock and Durango samples verified that this method is useful in discerning zones with high groundwater influx and zones that are relatively stagnant. Initial profiling results also indicate that these stagnant or "dead zones" in a well may account for some chemical stratification.

[2] "Applied Studies and Technology: The Third Dimension—Variation in Groundwater Aquifers," http://www.energy.gov/lm/articles/applied-studies-and-technology-third-dimension-variation-groundwater-aquifers.

[3] Durango wells were profiled in late FY 2015, after the FY 2015 annual report was written.

5.2 Plume Persistence

5.2.1 Overview

The impetus for the Plume Persistence study is that contaminant plumes at many LM sites persist longer than predicted by traditional groundwater modeling. The goal of this investigation is to provide a scientific foundation for this observation and information that can be used to improve model accuracy and model predictions in support of site remedies and regulatory compliance. To accomplish this goal, the study is divided into three study areas: (1) contaminant residence, (2) rate-limited processes, and (3) modeling. These three study areas were recommended in the Five-Year Plan (DOE 2012). LM approved the original TTP for the Plume Persistence study in 2013.

5.2.2 Prior Activities

5.2.2.1 Contaminant Residence

Geoprobe coring was conducted at 22 locations in 2012 over the uranium plume at the Grand Junction site (near the LM office) to determine the location and amounts of mill-related contaminants (mainly uranium). Core samples were collected at 1-foot depth intervals for a total of 366 samples. We conducted batch tests on the core samples to determine the mass of uranium removed by four different extracting media. The different extractants are intended to release uranium that is bound in different forms. The extractants (in order of those expected to release only loosely held uranium to those expected to release more tightly bound uranium) are (1) bicarbonate/carbonate solution (labile fraction), (2) 5% nitric acid, (3) concentrated nitric acid (microwave digestion), and (4) lithium metaborate fusion (total digestion). The results of these extractions are being used in conjunction with data from petrography and column testing to evaluate the mineralogical residences of the uranium. The results provide information to help determine how tightly the uranium is bound to the aquifer solids.

Polished thin sections were prepared for a subset of the samples. Fission-track maps of the polished thin sections were prepared on mica detector plates affixed to the thin sections. The mica–thin-section packages were subjected to a prescribed flux of slow neutrons to fission the uranium, which produces tracks in the detector plates. To analyze the fission-track maps, significant improvements were made to the ESL petrography laboratory. Two existing petrographic microscopes were outfitted with digital cameras. Software was purchased that allows images of the polished thin section and the fission-track map to be projected side by side so that fission tracks can be accurately mapped to the mineral and textural feature in the thin section. These techniques provide a unique means to identify the mineralogical associations of uranium. Our fission-track analyses indicated that uranium resides in mineral coatings on grain surfaces. Fission tracks are also concentrated in the fine-grained matrix of composite sedimentary grains. The grain coatings and the fine-grained matrix containing the uranium appear to be associated with iron oxide or oxyhydroxide.

5.2.2.2 Rate-Limited Processes

It is expected that aging processes during the 6 decades between groundwater uranium contamination and the present have caused some uranium to become more closely associated with the sediment in a manner that causes its release to be rate-limited. We conducted 12 “small” column tests. The small column tests help determine the prevalence of rate-limited uranium desorption from a uranium plume at the Grand Junction site (near the LM office). These column tests involved passing simulated groundwater through the columns at a constant flow rate. The flow was intentionally interrupted twice during each column test. Uranium released from the sediment during the flow interruptions indicates the presence of rate-limited desorption.

The water flux from the small columns was insufficient to conduct analyses other than for uranium. To better understand the desorption processes, analyses of major ions, pH, and alkalinity are required. Therefore, we conducted a larger column test in FY 2014 with these additional analyses. The uranium results from the large column matched well with the results from the small column, including the increased uranium concentrations following flow interruptions. The consistency between the large and small column results provides confidence in the column test methodology.

5.2.2.3 Modeling

The larger column test data were simulated using one-dimensional (1D) numerical models that incorporate multispecies chemical equilibrium and rate-limited desorption. Our 1D reactive transport modeling was completed using the PHREEQC computer program and was calibrated to the column test data manually and using PEST (an inverse modeling calibration routine). Processes of sorption, dual porosity with diffusion, mineral dissolution, dispersion, and cation exchange were evaluated separately and in combination. The calibration results indicate that sorption and dual porosity are major processes in explaining the column test data, which provide rate-limited desorption processes. These processes are also supported by the fission-track photographs discussed above that show solid-phase uranium residing in less mobile pore spaces. These procedures provide valuable information on plume persistence and secondary source processes that might be used to better inform and evaluate remedial strategies, including natural flushing.

We developed and provided an in-house presentation (for LM and LMS personnel) on the results of the 1D reactive transport modeling of the larger column test. In addition, we developed and submitted abstracts on the results of this modeling for consideration as invited presentations to the American Geophysical Union for their fall 2015 meeting in December 2015 and the National Groundwater Association’s Groundwater Summit 2016 in April 2016. These abstracts are included in prior activities because they were completed and submitted in FY 2015.

5.2.3 SLAC Collaboration

LM invited SLAC personnel to collaborate on the AS&T Plume Persistence study to integrate the influence of natural reduced zones into LM’s experience with uranium plume persistence issues. This integrated collaboration has provided leveraged funding and site access to SLAC personnel that would not have been otherwise possible. We have provided support in arranging site access and core drilling for solid-phase sample collecting. In return, SLAC personnel are providing analytical results, summary reports, and discussions on how their findings might influence plume persistence. Much of their work relates to identifying the types of naturally occurring carbon in the natural reduced zones and what microbial populations support the associated reducing conditions.

This collaborative effort has included (1) core collection at the Grand Junction site (near the LM office), the Naturita, Colorado, Processing Site, and the Shiprock site and (2) geophysical survey support at two sites (at Shiprock and at the Gunnison, Colorado, Processing Site). In addition, we supported trench and hand auger sampling at the Riverton, Wyoming, Processing Site in the spring, with follow-up sonic drilling and core collection in the fall (this work overlapped with the Plume Persistence study but was supported using Riverton site funds). Additional AS&T collaboration included LMS sampling using temporary water sampling devices installed by SLAC personnel at the Naturita processing and the Riverton sites, with analyses being done at SLAC. Preliminary results from the SLAC work were presented at the Goldschmidt2015 conference in Prague, Czechoslovakia (Noel et al. 2015a).

5.2.4 FY 2016 Activities

In FY 2016, the focus was on the modeling study area for this project. The abstracts mentioned above on the 1D reactive transport modeling of the larger column test were accepted and presented at the American Geophysical Union 2015 Fall Conference in San Francisco, California, in December 2015 and the National Ground Water Association's Groundwater Summit in Denver, Colorado, in April 2016. The talk title was "Column Testing and 1D Reactive Transport Modeling to Evaluate Plume Persistence Processes" (Johnson et al. 2015; Johnson et al. 2016b). This same talk was presented at the International Mine Water Association 2016 Annual Conference in Leipzig, Germany, in July 2016 with an associated proceedings article (Johnson et al. 2016c). A journal article on the plume persistence column testing and 1D reactive transport modeling is currently in preparation for submission in FY 2017.

A final plume persistence LMS series report is in preparation. The completion of a journal article on column testing and 1D reactive transport modeling, along with the final plume persistence project report, will complete this TTP.

Additional work on plume persistence in FY 2016 focused on the Riverton site. In 2015, additional characterization was completed at the site (DOE 2016b). While much of the work at the site was completed with Riverton site funds, plume persistence is an important issue at the site. Given that, the plume persistence TTP has funded work on better understanding the link between persistent secondary contaminant sources, such as evaporites and naturally reduced zones that occur at the Riverton site. Riverton site funds provided for the collection of the majority of solid-phase and water-phase samples in 2015. AS&T funding has then provided for (1) preparation of thin sections, (2) irradiation of those thin sections for fission-track radiography, (3) X-ray diffraction analyses of solid-phase samples, and (4) analyses of water samples from multilevel monitoring wells. Thorough analyses of sample results, along for reports and presentations, will be part of the Persistent Secondary Contaminant Sources TTP as a logical follow-on project from the Plume Persistence project. However, presentations on initial findings were completed at the International Mine Water Association's 2016 Annual Conference (IMWA 2016) in Leipzig, Germany, in July 2016 and the Geological Society of America's 2016 Annual Conference (GSA 2016) in Denver, Colorado, in September 2016. The IMWA 2016 presentation was a poster along with a proceedings article "Persistent Secondary Contaminant Sources at a Former Uranium Mill Site, Riverton, Wyoming, USA" (Johnson et al. 2016d). This poster took a second-place award for the best poster presentation. The GSA 2016 presentation was a poster entitled “Contribution of Uranium-Bearing Evaporites to Plume Persistence Issues at a Former Uranium Mill Site, Riverton, Wyoming” (Johnson et al. 2016e).

5.2.4.1 SLAC Collaboration

Collaboration with SLAC at the Riverton site continued in FY 2016 through the coordination of field work, sampling analyses, and co-authored publications. SLAC presentations in FY 2016 included abstracts and posters at the American Geophysical Union 2015 Fall Conference in San Francisco in December 2015 (Noel et al. 2015b) and the American Chemical Society 2016 Spring Conference in San Diego, California, in March 2016 (Noel et al. 2016). In addition, several abstracts by SLAC scientists with LM and LMS co-authors are being submitted to the American Geophysical Union 2016 Fall Conference. The SLAC research was initially focused on naturally reduced zones at the Riverton site, but the influence of evaporites in the unsaturated zone has also become an important issue. Current and future collaboration with SLAC on plume persistence issues related to secondary contaminant sources is an integral part of the Persistent Secondary Contaminant Sources TTP.

5.3 SOARS: System Operation and Analysis at Remote Sites

Overview: The SOARS system was established in 2006 to improve data collection at LM sites. The system fulfills a need to collect data from LM sites nationwide and transmit the data to a central processing site for real-time use. It has saved money by reducing the number of trips to sites and has improved site evaluations by affording immediate access to detailed data sets.

This AS&T program function has demonstrated the feasibility of collecting data remotely in real time and transmitting it to LM computer servers. Many LM sites are in remote locations, and collecting data by regular field visits is costly. Implementation of SOARS has numerous benefits:

- Reduced fuel consumption and greenhouse gas emission reduction
- Cost reductions
- Real-time data are available
- Improved ability to diagnose problems and make timely repairs and adjustments
- Expedited corrective actions

Project teaming efforts are improved because project personnel based at LM sites across the nation can access the data in real time. Vista Data Vision software is used to automatically produce real-time graphs that are available to any authorized personnel connected to the Internet. A comprehensive operation and maintenance manual titled *Operation and Maintenance of the System Operation and Analysis at Remote Sites (SOARS) Network* (LMS/PRO/S08736) is available as a level 3 controlled document on the LM Intranet.

A Google Earth file that shows the locations of all SOARS stations is maintained. Parameters measured by field sensors include flow rate, water level, in-line pressure, pH, oxidation–reduction potential, conductivity, unsaturated-zone moisture content, wind speed and direction, relative humidity, solar radiation, rainfall, current and voltage, digital photos, and water infiltration rate. Electrical relays and variable-frequency drives are used for remote control of more than 20 well pumps. The SOARS field systems are powered by 88 solar panels. Data are downloaded daily through 15 Internet protocol (IP) cell modems, 6 landline IP connections, and 1 analog landline. Onsite communication with the modems is accomplished using 105 radios. Approximately 300,000 data points are transmitted and graphed daily.

Prior Activities: This is a continuation of the SOARS program that has been active since 2006.

FY 2016 Activities: We operated SOARS continuously through FY 2016 with relatively few issues. Web access to the SOARS system was functional more than 98% of the time. Data loggers and radio links functioned well. We updated and maintained study documentation, including SOARS notes, Job Safety Analyses, Plan of the Day meetings, procurement logs, instrument inventories, metrics, and calibration logs. Improvements were made to postprocessor graphs and data storage and retrieval programs. We added new graphs to better accommodate site reporting or analysis needs. Alarm settings that provide notifications of site-related issues (such as pump failure) or problems with the instrumentation were regularly updated. The SOARS calibration database was improved and adapted to support the data mining and visualization programs (see Section 5.4). Calibration checks were conducted on field instruments at many sites. Most of the instruments maintained calibration and functioned successfully. Instruments were regularly lab tested and calibrated prior to installation at field sites. We replaced outdated or nonfunctional equipment during maintenance trips. New technology was lab tested so that SOARS stays current and ahead of the curve, including but not limited to wireless bridges, multiparameter sensors, and higher-resolution remote digital cameras. Software for data collection and data-logger operating systems was kept up to date with the latest versions. Support for site activities and operations is a top priority, and these were always given immediate attention so as to maintain the flow of quality data.

A continuing emphasis in FY 2016 was on the preparation of data mining and visualization programs (Section 5.4) for refining the SOARS data. The data mining and visualization programs are used to remove and revise erroneous SOARS data. Erroneous data result from field issues such as power interruptions. We made a significant effort during FY 2016 to populate the corrections database that the data mining and visualization programs use to produce the requested data. This effort has entailed methodically reviewing historical SOARS data for corrections that need to be made to the data to make it suitable for interpretation of groundwater applications. Currently, this database is over 20,000 lines long. Our effort is resulting in a high-quality database that can be used with confidence to make groundwater interpretations. We will continue to work on this corrections database until all historical data have been reviewed and corrected. We will then continually correct the incoming data as anomalies and erroneous data arise. Prior to data mining and visualization programs, data had to be refined for each project, which was a time-consuming effort. Data mining and visualization programs also provide data reformatting algorithms and visualizations tailored to LM projects.

SOARS continues to work with DOE Cyber Security to implement security features on all publically facing Internet connections. Multiple new security measures were instituted during FY 2016 at the request of Cyber Security that will assist the SOARS system to operate correctly. Continued cooperation with Cyber Security will ensure a secure and robust system across sites.

5.4 Data Mining, Geochemical Analysis, and Project Visualization

Overview: The motivation for developing data mining, analysis, and visualization (DMAV) computer applications was the need to rapidly visualize large amounts of data from multiple databases. Databases currently used by LM project personnel include SEEPro (Site Environmental Evaluation for Projects), EQuIS (Environmental Quality Information System), SOARS, Supplemental, SOARS calibrations, and data from field data loggers. Data also come from offsite repositories such as the USGS National Water Services and the National Uranium Resource Evaluation (NURE) programs. Benefits are realized by assessing the full range of data that are available for a specific evaluation or scientific pursuit. LM databases contain several billion data values. Sorting, extracting, and utilizing data sets that can be utilized to test specific scientific hypotheses can be an overwhelming task. The DMAV study addresses this need by providing user-friendly computer applications to streamline these data acquisitions and visualizations.

Often, interpretations of subsurface data are based on small subsets of data. Using a larger data set provides additional constraints that can improve interpretations. The human mind is better able to process and interpret large data sets if the data are crafted into suitable visualizations. Statistical approaches can also be used to help make sense of large data sets. Although there are many computer programs available commercially that can produce visualizations and perform statistical data operations, the DMAV study endeavors to provide applications that are tailored to specific LM needs. The applications address specific data acquisition, manipulation, and visualization methods that are rapid, user-friendly, and directly tailored to interpreting LM data.

To satisfy study needs, DMAV applications (apps) are written in-house, and source code development is directed by end users. The Interactive Data Language (IDL) was selected as the DMAV programming language. The rationale for choosing IDL included the following:

- Relatively easy language that was designed for scientific programming
- Used by scientists worldwide
- Has a long history, first developed in the mid-1980s
- Many useful functions and procedures are available
- Well suited to visualizations
- Has a data-mining module
- Interfaces with other common programming languages
- Training opportunities are available at the vendor's Boulder, Colorado, headquarters
- Well-suited for future LM use because it specializes in rapid (cloud-based) analysis of geospatial imagery including multispectral, hyperspectral, and light detection and ranging (LiDAR) imagery

The following four databases are mined to provide data to the DMAV apps: (1) the SEEPro Oracle database, (2) the Vista Data Vision mySQL database (SOARS data repository), (3) the SOARS Calibration Access database, and (4) the Supplemental Database in Excel spreadsheets. The SEEPro database contains more than 1 billion data values with, among other things, all of the groundwater chemical data collected by the LM program. These data are used by DMAV apps to provide rapid analysis and visualizations that support the interpretation of groundwater processes. SOARS maintains a database containing more than 1.4 billion real-time data values (Section 5.3). The SOARS data include (1) downhole data (e.g., water levels, specific conductivity, and temperature), (2) flow and pressure (mostly from pump-and-treat operations), (3) weather data, (4) soil moisture (time-domain reflectometry) data, and (5) energy usage. The SOARS Calibration Access database has calibration data that is regularly collected by SOARS field personnel. The Supplemental Database contains data that are not available in the other databases. Currently, the Supplemental Database contains profiling data collected through the AS&T Variation in Groundwater Aquifer TTP (Section 5.1). The Supplemental Database also contains well information (e.g., easting, northing, top of casing, screen depth) that is either not available or is deemed incorrect in SEEPro. DMAV apps search SEEPro initially but override or supplement, if needed, with the Supplemental Database data.

Since its inception in 2006, SOARS has maintained electronic databases containing field notes that detail activities relevant to data quality. These notes provide a basis for making unbiased decisions on data refinement. DMAV apps mine these notes and provide them to the end user in the SOARS maintenance application. The information provided in the SOARS maintenance app (which provides one-stop shopping for data, field notes, and calibrations) is used to “correct” the database to reflect true groundwater conditions (Section 5.3). The raw data are always maintained so that refined data can be readily compared to the original. This corrections database should be regularly maintained. Without these corrections, the SOARS data are difficult to interpret because of “noise” that often compromises data quality. Corrections should be made immediately following any field or data logging activity that could cause disruption to the data. Site leads are responsible for ensuring that these corrections are timely and that SOARS personnel regularly assist in this process.

Prior Activities: Two software licenses for IDL and six data-miner licenses were procured. Eighteen DMAV apps were completed and were partially beta tested. Calibration data were mined from the SOARS Microsoft Access-based calibration database and the SEEPro database. All apps had menu-driven, user-friendly interfaces. Apps were put on Citrix so that they can be accessed by LM/LMS personnel through the Internet.

FY 2016 Activities: In FY 2016, eight new apps were written and partially beta tested: (1) ReportsWind, (2) ReportsMonticelloTreatmentSystem, (3) Timelines, (4) SearchMaster, (5) WellConstruction, (6) BaselineComparisons, (7) UraniumIsotopes, and (8) WaterIsotopes. A few former apps were discontinued or replaced. There are currently 23 apps in the DMAV app store (Table 13). These apps use network connections to the databases and are retrieving the most currently available data. Maintenance of networks and Citrix needed for DMAV apps continued in FY 2016. Beta testing and bug fixes continued.

Table 13. DMAV Apps

Program Name	Snapshot
BaselineComparisons	Compares results for 2 years to assess cleanup rates
EquisHistograms	Histograms
EquisProfilesSpatial	Mining of three-dimensional (3D) contour and bubble plots
EquisProfilesStickball	Mining of 3D stickball plots
EquisProfilesVertical	Mining of 3D *XY* plots
EquisSpatialChem	Contour and bubble plots of groundwater chemical data
EquisTimelines	Chemical and water level data versus time
EquisXYplot	Correlation *XY* plots of any two parameters
ProfilesStats	Box plots and statistics tables of well profile data
ReportsEnergy	Report of energy consumption in LM facilities
ReportsRainfall	SOARS real-time reports of rainfall at LM facilities
ReportsPumping	SOARS real-time reports of pumping rates and masses of contaminants removed at LM pump-and-treat systems
ReportsMonticello TreatmentSystem	Water levels in wells, pond depths, and calculates evaporation rates from the pond
ReportsWind	Rose plots of SOARS wind data
SearchMaster	Searches SEEPro, EQuIS, SOARS, and the Supplemental Database and writes data to a file
SOARSElevs	SOARS groundwater elevation contours
SOARSElevsPlus	SOARS groundwater elevation, specific conductivity, and temperature contours
SOARSMaintenance	Quality assurance program to refine the SOARS database
SOARSTimelines	SOARS concentrations versus time
Timelines	Time plots using data from SEEPro, EQuIS, SOARS, and the Supplemental Database. Will replace SOARSTimelines and EquisTimelines
UraniumIsotopes	Activity ratios (uranium-234 to uranium-238) versus uranium concentration. Compares with standard mixing curves.
WaterIsotopes	Plots $\delta^{18}O$ versus δD and compares to meteoric water curves
WellConstruction	Depicts multiple well constructions hung by elevation

Abbreviation:
δD = hydrogen/deuterium ratio
$\delta^{18}O$ = oxygen-18/oxygen-16 ratio
3D = three-dimensional

Two apps were requested by the Monticello project team: ReportsWind and ReportsMonticelloTreatmentSystem. The ReportsWind app mines wind data from the SOARS database. It creates current wind rose diagrams for the 10 sites (including Monticello) that have SOARS wind data. The ReportsMonticelloTreatmentSystem app helps with evaluation of a pump-and-evaporate system constructed in 2015 at the Monticello disposal. Water-elevation data from 16 monitoring wells, 8 pumping wells, and the evaporation pond are mined and plotted. Flow rates from the eight pumping wells and the flow entering the pond can be plotted. The pond geometry and depth of pond water is used, along with the flow rates, to calculate pond evaporation by difference. Project notes can be plotted on the graphs. Many of these data come from the SOARS database and are much more useful when the corrections database is kept up to date.

The Timelines app mines data from the following sources: SEEPro, SOARS, Supplemental, and USGS river gages. It also plots computed values including (1) uranium (U) using both chemical and radiometric analytical results, (2) nitrate using all forms of analytical results for nitrate (e.g., nitrate, nitrate as N, nitrate plus nitrite as N), (3) total inorganic carbon from the various analytical reporting values of alkalinity and pH, (4) uranium activity ratios from the individual analytical results of ^{238}U, ^{234}U, and $^{233}U + ^{234}U$, (5) calcite and gypsum saturation indices and other values calculated by an embedded version of the geochemical speciation program PHREEQC. Timelines is more comprehensive than the EquisTimeline and SOARSTimelines apps, and after thorough beta testing of the new app those two apps will be retired.

The SearchMaster app is a prototype for future apps. It is restructuring many of the object classes, functions, and program flow elements to enhance readability for mining of the multiple databases. It is the first app to incorporate data from EQuIS. When completed, it will access the following: (1) SEEPro, (2) EQuIS, (3) data logger data, (4) SOARS, (5) Supplemental, (6) USGS river gages, and (7) NURE. The app mines each database and writes key data parameters to a file. The next generation of apps will build off the programming in this app.

The WellConstruction app was requested by an LMS scientist working on the AS&T Variation project. The app helps to rapidly visualize the vertical locations of well features. The app mines well construction data from SEEPro. Data include vertical locations of top of casing, current water level, well screen top and bottom, and bedrock. It portrays the well constructions on a cross section referenced to elevation.

The BaselineComparisons app was requested by an LMS modeler reviewing data for the Tuba City project. The app mines chemical data from SEEPro. It displays 2 years of data for a single analyte on an *XY* plot. For example, a common use is to plot a baseline year (e.g., 2000 for Tuba City) against a later year (e.g., 2016) to see if a contaminant (e.g., uranium) is cleaning up. If the data plot along the “no change” line, then it is concluded that little or no cleanup is occurring. Lines for “one order of magnitude change,” and “two orders of magnitude change” can also be plotted for reference.

Uranium isotopic data (the activity ratio [AR] of ^{234}U to ^{238}U) are becoming widely used by LM/LMS site personnel to help define the origin of uranium in groundwater. The UraniumIsotopes app was engineered to allow scientists to rapidly compare site-specific uranium isotopic data with all other uranium isotope data in the SEEPro and Supplemental databases. Data can be viewed by the traditional-style ($\log_{10}$ uranium concentration versus AR) or by a method used by Bob Zielinski (USGS) that plots the inverse of the uranium concentration versus AR. Various mixing lines can be plotted for reference.

The isotopic ratios of oxygen-18/oxygen-16 ($\delta^{18}O$) and hydrogen/deuterium (δD) are used by scientists to help determine the provenance of groundwater. More than 40 LM sites have water isotope data available. Because water isotopes are influenced by many factors, importantly evaporation, comparison to a variety of data and to global databases portrayed as meteoric water lines helps improve site-specific interpretations. The WaterIsotope app was designed to enhance the ability of LM/LMS scientists to make accurate interpretations of their water isotope data by making it easy to plot a set of site-specific data with other data sets.

Although there is a wealth of data in the SEEPro/EQuIS database, scientists often require supplemental data that are not in these databases. For example, chemical data from published literature were used to help interpret background concentrations for the Bluewater site. A large number of data from samples collected at various (non-LM) sites around the Colorado Plateau (the Natural Contamination project) were used to help formulate LM's position on contamination in Many Devils Wash near the Shiprock site. Studies conducted by other agencies and individuals (e.g., Paul Garvin's thesis and USGS work on Many Devils Wash, IFRC work at the Old Rifle site) often produce data that are useful to LM projects but are not commonly entered into the SEEPro/EQuIS databases. The Supplemental Database can be used to house these data. Once in the Supplemental Database, they can be mined and displayed by any of the DMAV apps. Entries to the Supplemental Database this fiscal year includes portions of (1) Paul Garvin's nitrogen isotope data, (2) USGS isotopic and chemical data from Many Devils Wash, (3) the Natural Contamination study from sites on the Colorado Plateau, and (4) New Mexico Environment Department data from near the Bluewater site. If these data are subsequently entered into EQuIS, they can be removed from the Supplemental Database. No changes to the DMAV apps would be needed as a result of this data transfer.

5.5 Long-Term Cover Performance

Introduction: LM is responsible for post-closure stewardship of Uranium Mill Tailings Radiation Control Act (UMTRCA) disposal cells. LM regularly inspects and maintains disposal cells as directed in Long-Term Surveillance Plans (LTSPs) approved by NRC. Recognizing that natural processes are changing the engineering properties of disposal cell covers, LM made commitments to evaluate these changes and to study options that enhance long-term protectiveness (DOE 2016c).

Long-Term Cover Performance consists of four interrelated studies:

- Study 1: Effects of Soil-Forming Processes on Cover Engineering Properties
- Study 2: Contaminant Uptake by Plants on Disposal Cells
- Study 3: Water Balance Cover Monitoring
- Study 4: Enhanced Cover Assessment Project

Long-Term Cover Performance studies will help managers answer the following types of questions regarding LTS&M of disposal-cell covers:

- Have changes in cover engineering properties increased radon flux and soil water percolation? If so, what are the regulatory risks, and are covers *currently* protective of human health and the environment?
- Will natural processes increase radon flux, soil water percolation, or erosion over the design life of a cover? If so, will covers be protective in the *long term*?
- Under what conditions should vegetation be allowed to grow on disposal cells?
- Are disposal cell covers at Title II transition sites acceptable as designed or as built, or will they require modification before or after transfer to LM?
- How would water percolation and radon flux through in-service covers be monitored if regulatory requirements change and place greater emphasis on performance monitoring?
- What technologies could be used to modify a cover if a corrective action is necessary?

Cover Designs: UMTRCA disposal cells were covered with engineered earthen layers designed to contain tailings contaminants for the long term. Most engineered covers include a "low-permeability radon barrier," which is a layer of compacted soil designed to limit the surface flux of radon and to protect groundwater by controlling rainwater percolation. Some covers have a thick soil "protection layer" (overlying the radon barrier) that is designed to prevent damage from freeze-thaw and wet-dry cycles. Most covers are also armored with a durable rock "riprap layer" that withstands water and wind erosion. The riprap layer is usually placed on a "bedding layer" that also sheds rainwater. Disposal cell covers were designed to control radon flux, protect groundwater, and withstand erosion "for a period of 1,000 years to the extent reasonably achievable" (Title 40 *Code of Federal Regulations* Section 192).

Natural Changes in Covers: The as-built engineering properties of covers are subject to change by natural ecological and soil-forming processes over relatively short time periods. A rock-armored surface can create favorable habitat for deep-rooted plants in all climates by reducing soil evaporation, increasing soil water storage, and trapping windblown dust, thereby providing water and nutrients for plant germination and establishment. Tap roots often extend vertically through armor and bedding layers and then branch and spread laterally at the interface with underlying compacted soil layers. Secondary and tertiary roots often extend vertically into and through compacted layers where they become fibrous root mats following soil structural planes.

Within 5 to 10 years, natural soil-forming processes create larger pores in compacted soil layers, increasing saturated hydraulic conductivity, sometimes by several orders of magnitude. Percolation and gas fluxes may also increase. Soil formation begins with freeze-thaw and desiccation cracking, retention of borrow soil structure during construction, and biointrusion. Post-construction changes in hydraulic properties are generally greater in less permeable, highly compacted clayey layers than in more permeable, less compacted, less clayey layers. Over time, the hydraulic properties of cover soils become similar to the original undisturbed borrow soil properties regardless of the as-built condition.

These natural changes in engineered soil properties may also introduce an alternative means for controlling percolation in the long term. Relatively low precipitation, high potential evapotranspiration, and thick unsaturated soils often limit percolation and recharge in arid and semiarid ecosystems. Disposal cell covers designed to mimic this natural soil water balance, often referred to as water balance covers or evapotranspiration covers, can provide hydraulic isolation in these settings. Therefore, natural soil-forming and ecological processes that slowly transform engineered earthen covers with compacted fine-textured layers into vegetated soil profiles resembling water balance covers may provide long-term advantages compared with the original compacted soil designs.

5.5.1 Study 1: Effects of Soil-Forming Processes on Cover Engineering Properties

Overview: This study will improve our understanding of the effects of natural soil-forming and ecological processes on cover engineering properties. Previous research demonstrated how soil-forming processes create cracks in compacted soil layers thereby increasing saturated hydraulic conductivity. Changes in soil hydraulic properties have been well-documented in the upper meter of cover profiles. However, we currently have a poor understanding of (1) effects of soil formation on radon flux, (2) depths at which soil-forming processes are changing engineering properties, (3) relationships between changes in soil morphology and soil engineering properties, and (4) how and at what rate plant-soil-microbial feedbacks evolve in cover systems and implications for changes in engineering properties over the long term.

Soil formation (pedogenesis) is inevitable and ubiquitous in all soil profiles, natural and engineered. The morphology of a soil is the collection of observable properties that reflect both in situ conditions and local soil-forming processes. This study is characterizing the morphology of cover soil profiles and natural analog soil profiles to understand (1) the processes that are changing soil engineering properties and (2) the degree of change that occurs in both the near-term (decades) and long-term (millennia). Soil morphology is characterized in test pits on selected disposal cell covers and at applicable natural analog sites. Natural analogs sites have undisturbed soil profiles, similar to cover soils, and late-successional vegetation.

This study is also measuring and modeling radon and percolation fluxes in selected disposal cell covers that have undergone pedogenesis. We use both large-scale and conventional-scale radon flux chambers. The large scale is necessary to ensure that radon flux measurements are made over an area sufficiently large to encompass radon movement through macropore structure in the radon barrier. We are also evaluating depth-dependent effects of soil-forming processes on engineered soils by measuring soil hydraulic properties and gas diffusivity in large soil monoliths extracted from disposal cell cover profiles.

Prior Activities: In FY 2015, LM and NRC began collaboration and formed an interdisciplinary research team (Table 14). The team developed and tested methods for measuring soil-gas diffusivity and hydraulic properties, measuring and modeling radon and water percolation flux rates, and characterizing soil morphology. We also developed a process for screening UMTRCA disposal cells as possible test sites, ranked sites, selected the first two, and began obtaining DOE and NRC approval for field work at the first test site.

Table 14. Research Team for the AS&T Study Area—Effects of Soil-Forming Processes on Cover Engineering Properties

William Albright, PhD[a] Division of Hydrologic Sciences Desert Research Institute	Nicholas Stefani, Graduate Student[b] Geological Engineering University of Wisconsin-Madison
Craig Benson, PhD, Dean[b] School of Engineering and Applied Science University of Virginia	Kuo Tian, PhD[b] Civil and Environmental Engineering University of Virginia
David Dander[a] Project Services Navarro Research and Engineering, Inc.	Xiadong Wang[b] Geological Engineering University of Wisconsin-Madison
Mark Fuhrman, PhD[b] Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission	William Waugh, PhD[a] Environmental Sciences Laboratory Navarro Research and Engineering, Inc.
William Likos, PhD[b] Geological Engineering University of Wisconsin-Madison	Morgan Williams, PhD candidate[a] Department of Geography University of California-Berkeley

Notes:
[a] Funding through Office of Legacy Management, U.S. Department of Energy
[b] Funding through Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission

Large-scale and conventional-scale radon flux chambers were tested at the Wisconsin Geotechnics Laboratory. The large-scale chambers (1.5 × 1.5 meters [m] squared) were adapted from the inner "ring" of sealed-double ring infiltrometers that we used previously to measure effects of pedogenic processes on soil hydraulic properties. The following two methods for measuring radon were compared: (1) activated carbon sorbent and (2) a solid-state electronic radon detector (also called a RAD7 unit). Researchers modeled radon diffusion to determine the appropriate sorption/detection period and chamber size to ensure the accuracy of radon flux measurements. A one-dimensional analytical model permitted variable source concentration, back diffusion, and decay.

The research team compiled relevant information on UMTRCA Title I and II sites, ranked sites, and proposed the first test sites. Site attributes included priority to NRC, climatic influence, vegetation, radon barrier vulnerability, source activity, depth to source, presence of natural analogs, and urban proximity. The team developed criteria for assigning high, medium, or low scores for each attribute based on the propensity for radon flux (a high score corresponded to a higher probability for an increase in radon flux). Rankings of sites were based on the average total score for a site.

FY 2016 Activities: Radon flux, soil engineering properties, and soil morphology were sampled for ranges of conditions on disposal cells at Falls City and Bluewater (Table 15). LMS and the research team (1) calibrated radon flux sensors, (2) developed a laboratory diffusion apparatus, (3) developed field work control plans for the Falls City and Bluewater sites, and (4) completed field sampling at Falls City and Bluewater for soil engineering and morphology parameters.

<u>Sensor Calibration</u>. Alternative measurement techniques for measuring radon flux in the field were examined through literature review. Two sensor types were identified for use at LM sites: activated-carbon (AC) canisters and an electronic radon detection (RAD7) system. Prior to the field site visits, a suite of laboratory tests was conducted to develop protocols for the field measurements and to characterize variables that could potentially affect the measurements, including relative humidity, flux chamber size, and measurement duration. Significant and consistent differences were observed between radon concentrations measured using the RAD7 and concentrations measured using AC. The ratio of measured concentrations averaged 0.58, meaning AC canisters measured 42.0% less radon than the RAD7 system.

<u>Field Work Plans</u>. LMS organized work control project teams and completed field work plans for Falls City and Bluewater (DOE 2016c, DOE 2016d). Project teams prepared National Environmental Policy Act documentation, Project/Activity Evaluations, Job Safety Analyses, and other safety, health, and compliance documents as required. Field work plans included (1) descriptions of research and test site restoration tasks, (2) calculations of potential dose to field workers, (3) job safety analyses, training requirements, dosimetry, and other safety and health documentation, and (4) cultural resource evaluation, waste management, and other environmental management requirements.

Table 15. Disposal Cell Conditions Tested in Test Pits at Falls City, Texas, and Bluewater, New Mexico

Test Pit No.	Disposal Cell Condition Tested
Falls City, Texas, Site	
1	High tailings radium activity Mesquite tree and perennial grasses
2	High tailings radium activity No mesquite tree (control) Perennial grasses
3	Mature mesquite tree Perennial grasses Medium tailings radium activity
4	Perennial grasses and no mesquite tree (control) Medium tailings radium activity
5	Rock armor on top slope apron High tailings radium activity
6	Rock armor on side slope High tailings radium activity
Bluewater, New Mexico, Site	
1	Main tailings pile Seasonal water ponding Slimes tailings
2	Main tailings pile No seasonal water ponding (control) Slimes tailings
3	Main tailings pile High tailings radium activity Sands tailings
4	Main tailings pile No fourwing saltbush (control) Sands tailings
5	Main tailings pile Mature fourwing saltbush Sands tailings
6	Main tailings pile Ant mound Sands tailings
7	Carbonate tailings pile Fourwing saltbush Thick radon barrier
8	Carbonate tailings pile No fourwing saltbush (control) Thick radon barrier
9	Acid tailings pile Vegetated cover design Thin radon barrier

Field Instrumentation and Soil Engineering Sampling. Field activities at the Falls City and Bluewater sites included soil sampling and installation of instrumentation to measure radon flux at six (Falls City) and nine (Bluewater) test pits locations. Most tests pits were paired with a corresponding control test pit selected to isolate potential influences of site-specific variables on measured radon flux and material properties, for example, ponded location versus location without ponding, vegetated location versus nonvegetated location, high activity versus low activity. Radon flux at each test pit was measured using flux chambers and electronic RAD7 devices to obtain radon buildup curves at the top surface of the radon barrier. Flux chambers with four different cross-sectional areas were installed to assess potential scaling effects associated with soil structure. At the Bluewater site, replicate measurements were obtained with each chamber to evaluate measurement repeatability. Additional radon flux measurements were obtained at the approximate contact between the top surface of the tailings and the radon barrier. Sampling at the test pits included at least one large-diameter block sample of radon-barrier material and at least two thin-walled Shelby tube samples of the radon-barrier material. Continuous (stacked) block samples of radon-barrier material were taken at test pit locations characterized by relatively a thick barrier to assess depth-dependent changes in soil properties. The block and tube samples will be used for laboratory determination of water retention characteristic curves, saturated hydraulic conductivity, radon diffusion coefficient, grain size, plasticity, and in situ water content profiles at the time of sampling.

Soil Morphology. Soil morphology was also characterized in each test pit and at radon-barrier analog sites using conventional soil survey methods, digital soil morphometrics, thin-section micromorphology, and microbial community assay/nutrient cycling. Analog test pits were excavated at the edge of radon-barrier borrow areas. The morphology of analog soil profiles provides clues as to how soil-forming processes might continue to change the cover in the long term (100s to 1000s of years).

In FY 2016, cover system soil morphology and characterization methods were optimized, and detailed in situ soil studies were performed on a total of 16 cover cell pits and 4 analog soil pits at the two sites. A total of 196 bulk soil samples and 60 core samples were collected and analyzed to allow for a spatially resolved understanding of rates and qualities of soil change (notably the distribution of carbon, nitrogen, biota, physical architecture, and mobile solutes) with implications of cover system performance and future evolution.

Work to date suggests that soil change on the two disposal cells are contingent not only on cover design strategy but also on site-specific spatially and temporally variable factors including microclimate, topography, organismal influence, and environmental additions (namely, dust and seeds). Additionally, lingering microheterogeneities from the construction process (i.e., retained borrow structure) may play a role in initial cover system evolution.

The total extent of cover system soil morphological development (in the radon barrier, specifically) was far greater at the Bluewater site than at the Falls City site. The Bluewater disposal cell is currently composed of an emergent assemblage of morphologically distinct soil systems that have very different soil structure and morphology. Some of these soil processes have resulted in considerable structural transformations through the entire depth of the radon barrier to tailings. At this time, the research group is still in the early stages of determining how cover evolution impacts system performance (radon flux and water percolation through preferential flow to the depth of tailings) and how covers might be managed for sustained performance over their design life.

5.5.2 Study 2: Contaminant Uptake by Plants on Disposal Cells

Overview: LM site managers want a consistent policy for managing vegetation on UMTRCA disposal cell covers. LTSPs currently require vegetation removal on many covers, whereas on others, LTSPs were written to allow or even foster plant growth. This study adds to our understanding of the complex tradeoffs of potential detrimental and beneficial effects of plants growing on disposal cell covers. Results will support a rational and consistent vegetation management policy.

We designed this study to determine if plants growing on disposal cells create exposure pathways by taking up and disseminating tailings constituents through animal foraging on stems and leaves. The literature suggests that plant uptake of tailings contaminants occurs, but levels can vary widely depending on plant species, tailings and soil chemistry, and cover soil hydrology. Hence, we chose to conduct an empirical field study that includes a range of UMTRCA sites with wide applicability. The study has four objectives:

1. Compare levels of tailings constituents in plants currently rooted in covers with plants growing in reference areas (undisturbed areas with soil and vegetation matching the disposal cell cover).
2. Evaluate several UMTRCA sites near Native American communities that represent a broad range of climates, cover designs, cover soil types, and vegetation types. (The study was conducted in part by a Native American graduate student.)
3. Assess an animal-foraging pathway for contaminant transport by comparing plant levels to dietary tolerance levels set for livestock.
4. Gauge, on the basis of existing literature, the potential for long-term bioaccumulation of tailings constituents in plant litter and soil organic matter.

Prior Activities: AS&T and University of Arizona researchers compared concentrations of uranium, molybdenum, selenium, manganese, lead, and arsenic in aboveground tissues harvested from plants growing on and near seven UMTRCA cells in the western United States. We screened risks of an exposure pathway through grazing animals by comparing analyte levels in plant tissues to maximum tolerance levels (MTLs) set for livestock by the National Research Council and to analyte levels in aboveground tissues harvested from plants growing in reference areas (background or control samples) in the vicinity of the disposal cells.

We used analysis of variance (ANOVA) to compare element concentrations for different species growing on cells and in reference areas. For some comparisons, concentrations in plants growing on the disposal cells were higher than those in plants growing in reference areas, indicating possible mobilization of these elements from the tailings into plant tissues. However, with one exception, concentrations in all plants were well below MTLs. The only element that exceeded its MTL was selenium, which was present in plants growing on disposal cells at the Bluewater and L-Bar, New Mexico, sites. The region is known for soils that are naturally seleniferous, and because plants growing both on these disposal cell covers and in reference areas had elevated selenium levels, the contamination likely originated from local borrow soils rather than the underlying tailings.

FY 2016 Activities: A University of Arizona graduate student and collaborators (Table 16) revised a manuscript for publication. The student completed ANOVA and regression analyses for uranium, radium, and the other elements of concern in leaf and stem tissues and a literature survey of potential long-term bioaccumulation of tailings elements in plant litter and organic soil that forms beneath plant canopies. The draft paper includes (1) statistical comparisons of tissue concentrations for uranium and other metals in plants rooted in covers with plants growing in reference areas, (2) analyses for radium-226 activity in plant tissues, and (3) a review of cultural and medicinal uses of these plants by Native Americans.

Table 16. Collaborators on the Plant Uptake Study

Edward Glenn, PhD[a,c] Soil, Water, and Environmental Science University of Arizona	David Moore[a,c] Soil, Water, and Environmental Science University of Arizona
Carrie Joseph, PhD candidate[b,c] Soil, Water, and Environmental Science University of Arizona	William Waugh, PhD[c] Environmental Sciences Laboratory Navarro Research and Engineering, Inc.

Notes:
[a] In-kind funding through the University of Arizona.
[b] Funding through Alfred P. Sloan Foundation Indigenous Graduate Partnership.
[c] Funding through Office of Legacy Management, U.S. Department of Energy.

5.5.3 Study 3: Water Balance Cover Monitoring

Overview: LM's plan for continuous improvement of LTS&M includes strategies to "improve the long-term sustainability of environmental remedies" (DOE 2016c). Studies funded by LM and others over the past 20 years have shown that natural processes are changing the engineering properties of disposal cell covers. A goal of the Long-Term Cover Performance study area is to understand the long-term consequences of these changes and to develop and test new technologies that LM could use to improve the LTS&M of engineered covers. This study is monitoring the performance of an alternative cover design at the Monticello, Utah, Disposal Site.

Most UMTRCA disposal cell covers include a compacted soil layer (low-permeability radon barrier) designed to limit radon exhalation and rainwater percolation. Research by DOE, EPA, NRC, and others has shown that within 5–10 years, natural soil-forming processes (1) create structure in compacted soil layers, (2) increase porosity and saturated hydraulic conductivity, sometimes by several orders of magnitude, and (3) can increase percolation through covers. Research has also shown that alternative cover designs called evapotranspiration (ET) covers, or water balance covers, may provide a sustainable alternative to compacted soil barriers with respect to controlling percolation.

Water balance covers consist of thick, fine-textured soil layers that store precipitation in the root zone where it can be removed seasonally by ET. Capillary barriers composed of coarse-textured sand and gravel placed below this soil "sponge" can enhance soil water-storage capacity and limit unsaturated flow. The sustainability of alternative covers will depend, in part, on the establishment and resilience of a diverse plant community. Changes in the plant community inhabiting a cover will influence ET rates and the soil–water balance. However, plant community dynamics are complicated, and effects are difficult to predict. Even in the absence of large-scale disturbances, seasonal and yearly variability in precipitation and temperature will cause changes in species abundance, diversity, biomass production, and soil water extraction rates.

This study has four objectives:

1. Demonstrate methods for the large-scale, long-term monitoring of an in-service water balance cover.
2. Characterize changes in the soil engineering properties of a water balance cover.

3. Monitor the water balance response, including percolation, to soil formation, ecological succession, and climatic variability.
4. Transfer LM's water balance cover technology to other agencies, nationally and internationally.

The Monticello site is an ideal setting for a long-term evaluation of a water balance cover because of the relatively short growing season and the semiarid to subhumid climate—the site is at the cool-wet climatic fringe for locations where water balance covers might work. The study is providing DOE, other federal and state agencies, and international agencies with unprecedented, large-scale, long-term performance monitoring of an in-service water balance cover.

Prior Activities: Beginning in 1990, predecessors of AS&T conducted research and prototype tests that led to the water balance cover design for the Monticello site. The design includes a low-permeability radon barrier, directly above the tailings, overlain with a geomembrane. The water balance cover rests on the geomembrane. This study is evaluating the hydraulic performance of the water balance cover independent of the radon barrier and geomembrane. The water balance cover design relies on the water-storage capacity of a thick, fine-textured soil sponge overlying a coarse sand capillary barrier. We designed the thickness of the sponge layer to retain precipitation until it is seasonally removed by plants. Water movement into the capillary barrier should occur only if water accumulation at the soil–sand interface approaches saturation and soil water tensions decrease sufficiently for water to enter the larger pores of the sand layer. A gravel admixture at the surface controls both wind and water erosion and, by functioning as mulch, enhances seedling emergence and plant growth. The design also includes frost protection, deterrents for biointrusion, and other attributes for plant establishment and growth.

We installed instrumentation for a large lysimeter within the cover during construction of the Monticello repository and began monitoring soil–water balance parameters and vegetation in 2000. Monitoring is ongoing. Lysimetry offers the only direct means for measuring percolation at field scale and allows comprehensive evaluation of the soil–water balance. We designed and imbedded instrumentation for a 3-hectare lysimeter within the Monticello disposal cell cover. The instrumentation directly measures precipitation, percolation, runoff, and water storage changes; ET is estimated by difference. The high-density polyethylene (HDPE) geomembrane made it possible to collect percolation through the capillary barrier. An HDPE channel directs water collected on the membrane to a sump. Surface runoff is collected in a test plot within the 3-hectare lysimeter. Soil water storage is determined by integration of water content profiles, as monitored with time-domain reflectometry, and meteorological parameters are monitored onsite.

Revegetation goals for the Monticello cover included plants that (1) are well-adapted to the engineered soil habitat, (2) are capable of high transpiration rates, (3) limit soil erosion, and (4) are structurally and functionally resilient. Diverse mixtures of native and naturalized plants are thought to maximize water removal and remain resilient given variable and unpredictable changes in the environment. We seeded and planted the cover in September 2000 with a mixture of native plants in an attempt to mimic the potential natural vegetation of the cover soil source. We annually measure species composition, percent cover, shrub density, and leaf area index (LAI). Monitoring results show that the percent cover of desirable species did not satisfy LM's revegetation goal until 2006. It takes many years for vegetation to mature in these environments. The cover was also a test site for research on the use of hyperspectral imagery to map species composition, LAI, and ET on a landscape scale.

In 2008 we evaluated changes in soil morphology and soil engineering properties in the cover soil layers. The soil engineering properties have changed significantly in compacted soil covers. We wanted to know if soil-forming processes are also changing water balance covers. We characterized soil structure and root density, collected undisturbed soil block samples, and measured saturated conductivity and soil water characteristic curves on soil blocks in the lab. The results suggest greater-than-expected changes in soil morphology but only minor changes in soil hydraulic properties 7 years after construction. Variability in soil morphology and engineering properties were manifested on the surface as differences in shrub abundance and growth.

FY 2016 Activities: AS&T scientists and collaborators (Table 17) continued monitoring the 3-hectare lysimeter and changes in vegetation, gave a tour of the test site for scientists with IAEA, and gave a presentation on possible international applications of water balance covers at an IAEA conference in Madrid, Spain.

Table 17. Collaborators (Past and Present) on the Monticello Water Balance Study, 2000–2016

William Albright, PhD[a,b] Division of Hydrologic Sciences Desert Research Institute	John Jensen, PhD (emeritus)[c] Department of Geography University of South Carolina
Craig Benson, PhD, Dean[a,b] School of Engineering and Applied Science University of Virginia	Steve Rock, PhD[b] Office of Research and Development Environmental Protection Agency
Glendon Gee, PhD (emeritus)[b] Hydrology Technical Group Pacific Northwest National Laboratory	Gregory Smith, PE[a] Geo-Smith Engineering Grand Junction, CO
John Gladden, PhD (emeritus)[c] Environmental Sciences and Biotechnology Savannah River National Laboratory	William Waugh, PhD[a] Environmental Sciences Laboratory Navarro Research and Engineering, Inc.

Notes:
[a] Funding through Office of Legacy Management, U.S. Department of Energy.
[b] Funding through Office of Research and Development, U.S. Environmental Protection Agency.
[c] Funding through Office of Science, U.S. Department of Energy.

Water balance monitoring within the 3-hectare drainage lysimeter continues to provide convincing evidence that the cover has performed well in limiting percolation. As of July, lysimeter instrumentation had recorded zero percolation in 2016, for a percolation rate of about 0.4 millimeter per year (mm/year) over almost 16 years of monitoring, or about 0.1% of annual precipitation. More than 50% of the total percolation over the 16 years occurred in 2005, the second wettest winter on record. Zero percolation occurred during the year with the highest annual precipitation, 607 mm in 2015. In contrast, average percolation in conventional low-permeability covers located in similar environments, as measured during EPA's Alternative Cover Assessment Program using large lysimeters, was about 35.0 mm/year, or 9.1% of precipitation.

The following keynote session paper was presented May 25, 2016, in Madrid, Spain.

Waugh, W.J., E.P. Glenn, C.H. Benson, W.H. Albright, M.L. Brusseau, R.P. Bush, and J. Dayvault, 2016. "Applications of Ecological Engineering Remedies for Uranium Processing Sites, USA," Session 4B: Technical and Technological Aspects of Implementing Environmental Remediation Programmes, in proceedings of International Conference on Advancing the Global Implementation of Decommissioning and Environmental Remediation Programmes, 23–27 May, 2016, Madrid, Spain.

The following tasks are planned for FY 2017 and out years:

- Continue monitoring percolation and the hydraulic performance of the Monticello water balance cover.
- Continue monitoring changes in the plant community on the cover.
- Replace old and outdated percolation and runoff monitoring instrumentation in the embedded lysimeter.
- Draft a proposal to use the long-term monitoring data to evaluate different water balance models used to design disposal cell and landfill covers.
- Draft a monograph for publication on all components of the Monticello water balance cover study: small monolith lysimeter test of concept, caisson lysimeter comparison of range of cover materials, embedded lysimeter monitoring of in-service cover performance, changes in soil engineering properties, plant succession on the cover, climate change scenarios, and natural analogs of long-term performance.

5.5.4 Study 4: Enhanced Cover Assessment Project

Overview: LM plans to "record and analyze data on long-term performance" and "explore and advance innovative technical approaches that improve LTS&M quality and inform remediation strategies" and thereby "improve the long-term sustainability of environmental remedies" (DOE 2016c). AS&T scientists designed the Enhanced Cover Assessment Project (ECAP) to help LM fulfill these commitments with respect to UMTRCA disposal cell covers. ECAP studies are (1) developing technologies to evaluate the hydraulic performance of covers, (2) acquiring cover performance monitoring data, and (3) testing methods to enhance long-term cover protectiveness.

Assessment project objectives:

1. Develop methods to directly monitor the soil water balance, including percolation, of a conventional UMTRCA cover with a rock-armored, low-permeability radon barrier.
2. Evaluate natural changes in the soil engineering properties of a conventional UMTRCA disposal cell cover.
3. Demonstrate and evaluate soil manipulation and revegetation methods designed to transform a conventional UMTRCA cover into a water balance cover.
4. Monitor and compare the water balance (including percolation) of a conventional UMTRCA cover and an enhanced (transformed) cover for 10 or more years.

Prior Activities: Two test facilities were constructed at the Grand Junction disposal site to achieve the study objectives. One facility consists of two large lysimeter test sections; the other is a large test pad. We selected the GJDS because (1) it is near the LM office at Grand Junction, Colorado, (2) a large section of the disposal cell will need to be capped in the future, (3) the GJDS cover includes a protective soil layer overlying the low-permeability radon barrier, and (4) soil and rock stockpiles for all cover layers were available at the site.

Lysimeter Test Facility: The test facility resembles two large, buried plastic swimming pools containing highly instrumented disposal cell test covers. These test sections include large drainage lysimeters for direct measurement of surface runoff and percolation, instruments to monitor soil water content and soil water tension within the cover profiles, and a weather station to monitor meteorological conditions. Evapotranspiration is calculated as the difference. Placement of soil and rock layers in the lysimeters matched the engineering design, materials, and construction of the in-service GJDS disposal cell cover. The instrumentation monitors the water balance of the simulated covers: how much water (1) falls on the soil surface as precipitation, (2) sheds to the edge as runoff, (3) becomes stored in the soil sponge layer, (4) evaporates and transpires out of the soil sponge by plants (evapotranspiration or ET), and (5) most importantly, how much water percolates through the cover. Cover enhancement options (i.e., transformation to a water balance cover) are evaluated in one lysimeter, the "enhance" lysimeter. The other "control" lysimeter is maintained to simulate conditions on the operational GJDS cover.

Research suggests that the as-designed engineering properties of cover soils may change in less than 5 years. However, changes in as-built hydraulic properties of rock-armored UMTRCA covers have not been evaluated. The rock riprap can act as mulch and may reduce evaporation and limit the amount of soil cracking caused by soil-forming processes. In 2013, we repeated field tests first conducted in 2007 to determine changes in key soil hydraulic properties since construction of the test covers. We measured soil hydraulic properties in the field and in the laboratory. Results show that the geometric mean for saturated hydraulic conductivity in both the radon barrier and the frost protection layer increased by about 2 orders of magnitude over the 5-year period.

Test Pad: We constructed the test pad to demonstrate and evaluate cover enhancement methods, including soil manipulation and revegetation options. The test pad was constructed on a stockpile of fine-textured soil that DOE used to construct the protection layer of the GJDS disposal cell cover. As with the lysimeter test sections, the test pad was built to match the engineering design, materials, and construction of the full-scale GJDS cover. Soil manipulation treatments ranged from shallow ripping into the surface of the protection layer to deep ripping and blending of the riprap, bedding, and protection layers.

FY 2016 Activities: AS&T scientists and collaborators (Table 18) published a paper on the results of the cover soil manipulation study on the test pad, monitored a revegetation study on the test pad, and continued monitoring the ECAP lysimeters.

Table 18. Collaborators on the AS&T Enhanced Cover Assessment Project

William Albright, PhD[a,b] Division of Hydrologic Sciences Desert Research Institute	Linda Sheader[a] Environmental Services Navarro Research and Engineering, Inc.
Craig Benson, PhD, Dean[a,b] School of Engineering and Applied Science University of Virginia	Gregory Smith, PE[a] Geo-Smith Engineering Grand Junction, CO
Marilyn Kastens[a] Environmental Services Navarro Research and Engineering, Inc.	William Waugh, PhD[a] Environmental Sciences Laboratory Navarro Research and Engineering, Inc.

Notes:
[a] Funding through Office of Legacy Management, U.S. Department of Energy
[b] Funding through DOE Consortium for Risk Evaluation with Stakeholder Participation III (CRESP III)

Publication: The cover soil manipulation study was published in November 2015. The published abstract follows.

> Waugh, W.J., C.H. Benson, W.H. Albright, G.M. Smith, and R.P. Bush, 2015. "Evaluation of soil manipulation to prepare earthen waste covers for revegetation," *Journal of Environmental Quality* 44(6):1911–1922.
>
> Seven ripping treatments designed to improve soil physical conditions for revegetation were compared on a test pad simulating an earthen cover for a waste disposal cell. The field test was part of study of methods to convert compacted-soil waste covers into evapotranspiration covers. The test pad consisted of a compacted layer of fine-textured soil simulating a barrier protection layer overlain by a gravelly sand bedding layer and a cobble armor layer. Treatments included combinations of soil-ripping implements (conventional shank [CS], wing-tipped shank [WTS], and parabolic oscillating shank with wings [POS]), ripping depths, and number of passes. Dimensions, dry density, moisture content, and particle size distribution of disturbance zones were determined in two trenches excavated across rip rows. The goal was to create a root-zone dry density between 1.2 and 1.6 g/cm^3 and a seedbed soil texture ranging from clay loam to sandy loam with low rock content. All treatments created V-shaped disturbance zones as measured on trench faces. Disturbance zone size was most influenced by ripping depth. Winged implements created larger disturbance zones. All treatments lifted fines into the bedding layer, moved gravel and cobble down into the fine-textured protection layer, and thereby disrupted the capillary barrier at the interface. Changes in dry density within disturbance zones were comparable for the CS and WTS treatments but were highly variable among POS treatments. Water content increased in the bedding layer and decreased in the protection layer after ripping. The POS, operated at a depth of 1.2 m and with two passes, created the largest zone with a low dry density (1.24 g/cm^3) and the most favorable seedbed soil texture (gravely silt loam). However, ripping also created large soil aggregates and voids in the protection layer that may produce preferential flow paths and reduce water storage capacity.

Lysimeter Monitoring: In FY 2016, percolation rates continued to increase in both lysimeter test sections, volunteer plants began establishing on the enhanced lysimeter test section, and the enhanced test section was seeded.

We began monitoring the soil water balance and percolation in lysimeter test sections in November 2007. Annual precipitation ranged between 94 and 388 mm. Percolation remained relatively low in both test sections for 5.5 years, ranging between 0% and 3.1% of precipitation. In contrast, between July 1, 2015, and June 30, 2016, percolation was 17.3% of precipitation in the control test section, compared to 12.0% of precipitation in the enhanced test section. During this time, pulses of percolation followed large precipitation events without associated changes in water content, which is evidence of preferential flow.

Lower percolation rates in the enhanced test section may be attributable to plant transpiration. We began allowing volunteer plants to establish on the enhanced test section in 2015 but continued to keep the control test section denuded with herbicides. By spring of 2016, a sparse stand of primarily annual grasses and forbs was growing on the enhanced test section. We seeded the enhanced test section in spring of 2016 using the most promising seed mix based on the test pad revegetation study and with the objective of accelerating ecological succession, increasing ET rates, and reducing percolation rates. The goal is to effectively transform the conventional cover in the enhanced test section into a water balance or ET cover.

Revegetation: Transformation of conventional covers into water balance covers may rely on sustainable vegetation and evapotranspiration. We designed the revegetation study on the test pad to evaluate the effects of soil-ripping practices, plant species mixes, planting methods, and irrigation on plant germination, species composition, diversity, and abundance. The study is comparing combinations of soil manipulation treatments, four species mixes, two planting methods, and ambient precipitation versus precipitation plus irrigation. Planting methods include broadcast seeding and broadcast seeding paired with transplanting seedlings of dominant species. Seeding, transplanting, and installation of the irrigation system were completed in FY 2015. All plots received an organic fertilizer and mycorrhizal fungi inoculum. We irrigated one-half of the plots to wet the seedbed for the first growing season. In FY 2016, we used transect sampling to monitor for germination rates, survival of seedlings and transplants, and plant species composition and abundance. Two shrub species had the highest survival and growth rates: fourwing saltbush (*Atriplex canescens*) and rabbitbrush (*Ericameria nauseosa*).

***Out-Year Work*:**

- Replace outdated percolation and runoff monitoring instrumentation in the lysimeter test sections
- Publish a paper on as-built cover engineering properties and changes in the water balance, including percolation
- Install Phase II of the revegetation study on the GJDS disposal cell cover
- Use the lysimeter test sections to monitor and compare the water balance (including percolation) of the GJDS disposal cell cover, both as-built and as-modified to function as a water balance cover
- Draft a proposal to evaluate different water balance models using the lysimeter data

5.6 Enhanced Natural Attenuation

Introduction: LM is responsible for ongoing remediation of residual contamination in soil and shallow groundwater at several UMTRCA sites. Enhanced Natural Attenuation studies seek to understand and then enhance hydrological, ecological, and microbiological processes in the surface and near-surface environment that remove, transform, isolate, or slow the dispersion of contaminants. Studies focus on (1) phytoremediation of soil and shallow groundwater, (2) microbial attenuation of soil contaminants, (3) ET to control soil leaching and dispersion of groundwater contamination, and (4) remote-sensing tools to monitor phytoremediation and ET on a landscape scale. All five studies include collaboration and cost sharing with other researchers and agencies and educational outreach with a focus on stakeholder communities.

The five Enhanced Natural Attenuation studies include:

- Tuba City, Arizona, Evapotranspiration
- Shiprock, New Mexico, Phytoremediation: Hydraulic Control
- Monument Valley, Arizona, Subpile Soil Phytoremediation
- Monument Valley, Arizona, Land-Farm Phytoremediation
- USGS UAS Evapotranspiration

Relevance: These studies address needs identified in the AS&T Five-Year Plan (DOE 2012) and support implementation of the LM Strategic Plan (DOE 2016c). The Five-Year Plan identified phytoremediation, phytomonitoring, and remote sensing as important future funding areas and recommended studies that "continue to refine phytotechnologies, survey needs for applications at other LM sites, and explore new collaborations." The studies are applications of new, potentially more sustainable, and cost-effective technologies for residual soil and shallow groundwater contamination at arid and semiarid LM sites. Studies at the Monument Valley, Shiprock, and Tuba City sites represent successively broader applications and refinements of the science published by predecessors of AS&T.

5.6.1 Study 1: Tuba City Evapotranspiration

Overview: The products of this study—landscape-scale estimates of ET—were input to the revised groundwater flow model for the Tuba City site. The types of vegetation and the influences of ET on groundwater hydrology vary within the model domain. Some plant species, classified as phreatophytes, survive by extracting groundwater. ET within these plant communities can result in a net discharge of groundwater if ET exceeds precipitation. Other upland desert plants survive on meteoric water, potentially limiting groundwater recharge if ET is equivalent to precipitation. For all plant communities within the model domain, excessive livestock grazing or other disturbances can tip the balance to a net groundwater recharge.

This study was designed to address five objectives:

1. Characterize and delineate different vegetation types or zones within the groundwater model domain, focusing on the separation of plant communities including phreatophytes that survive by tapping groundwater and upland plant communities that are dependent on precipitation.
2. Refine a remote-sensing method, developed to estimate ET at the Monument Valley site, for application at the Tuba City site.
3. Estimate recent seasonal and annual ET for all vegetation zones, separating phreatophytic and upland plant communities within the Tuba City groundwater model domain.
4. For selected vegetation zones, estimate ET that might be achieved given a scenario of limited livestock grazing.
5. Analyze the uncertainty of ET estimates for each vegetation zone and for the entire groundwater model domain.

Prior Activities: AS&T scientists and collaborators characterized and mapped plant communities within the groundwater model domain and refined and applied an ET algorithm.

We characterized and mapped vegetation zones by field-identifying plant species within the groundwater model domain, estimating changes in the abundance of dominant species along a north-south transect through the domain, defining separate plant associations, and delineating boundaries between plant associations on a satellite image. We used a modified relevé method to estimate species abundance in selected stands and then grouped and classified stands as plant associations. We used a simplified gradient analysis to illustrate how the abundance of dominant species varied along the north-south transect and to define separate plant associations. We then produced a map of discrete vegetation/ET zones by interpreting and field-checking boundaries between plant associations on a QuickBird satellite image.

ET rates were estimated using a remote-sensing algorithm originally developed for groundwater-dependent riparian plants in the southwestern United States, as modified and validated for desert plants at the Monument Valley site. The algorithm is based on the Enhanced Vegetation Index (EVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on the Terra satellite, acquired at approximately daily satellite overpass intervals. We used the USGS MOD13 product, which is a composite image over 16-day periods. Our ET algorithm was developed by empirically relating MODIS EVI with meteorological data and ET measured at eddy covariance and Bowen ratio moisture flux towers at 13 riparian phreatophyte sites in Arizona and New Mexico. The algorithm was then modified for desert plants based on 2 years of sap flux measurement at the Monument Valley site. For the Tuba City analyses, MODIS EVI pixels corresponding to shape files for each vegetation/ET zone were obtained from February 2000 to December 2012. LAI was determined from MODIS EVI imagery using an algorithm we developed at the Monument Valley site. We used a relationship between LAI and EVI to calibrate ET estimates for vegetation zones at the Tuba City site. We analyzed changes in ET in response to grazing and climate by estimating ET for years of heavy grazing and light grazing, and for wet and dry years.

FY 2016 Activities: AS&T scientists and collaborators wrote a final report for LM, submitted an abstract for presentation at the Waste Management 2017 conference, and published a journal article:

DOE (U.S. Department of Energy), 2016. *Evapotranspiration Dynamics and Effects on Groundwater Recharge and Discharge at the Tuba City, Arizona, Disposal Site*, LMS/TUB/S13751, ESL-RPT-2016-02, Office of Legacy Management, February.

Bush, R., E. Glenn, C. Jarchow, W. Waugh, A. Lasse, and T. Bartlett, DRAFT. "Effects of Rangeland Evapotranspiration on Groundwater Recharge, Discharge, and Flow at the Tuba City, Arizona, Disposal Site," Submitted to Waste Management 2017.

Glenn, E.P., C.J. Jarchow, and W.J. Waugh, 2016. "Evapotranspiration dynamics and effects on groundwater recharge and discharge at an arid waste disposal site," *Journal of Arid Environments* 133:1–9.

The 2016 *Journal of Arid Environments* abstract follows:

Deserts have been used for waste disposal due to presumed low groundwater recharge. The US Department of Energy is evaluating groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. They developed a groundwater flow model to determine how fast contaminants were moving towards a downgradient stream, Moenkopi Wash, used to irrigate crops. We used remote sensing algorithms and precipitation (PPT) data to estimate ET and the ET/PPT ratios within the 3513 ha groundwater model domain (GMD) from 2000 to 2012. ET and PPT were nearly balanced (125 mm yr^{-1} and 130 mm yr^{-1}, respectively). However, seasonal and interannual variability in ET and PPT were out of phase. Spatial variability in vegetation differentiated areas where ET was less than PPT (potential recharge areas) from those where ET exceeded PPT (potential discharge areas) within the GMD. ET estimates predicted that 0.2 million cubic meters per year of groundwater contributed to surface flows in Moenkopi Wash, supported by measurements of streamflow at the upstream and downstream boundaries of the GMD. Even small differences between ET and PPT can influence groundwater flow, hence land use practices that enhance discharge through ET can be part of an overall remediation strategy.

5.6.2 Study 2: Shiprock Phytoremediation: Hydraulic Control

Overview: The goal of the Shiprock disposal site phytoremediation pilot study is to establish vegetation that can transpire shallow groundwater and thereby help control dispersion of groundwater contamination. Phytoremediation and hydraulic control occur naturally at the Shiprock site. We designed the pilot study to evaluate the feasibility of enhancing natural phytohydraulic control by planting native phreatophytic shrubs. The pilot study includes two locations: (1) a terrace between the disposal cell and an escarpment north of the disposal cell where a uranium plume enters the floodplain and (2) the radon-barrier borrow pit south of the disposal cell where nitrate levels are elevated in alluvial sediments.

The Shiprock pilot study objectives address three topics:

1. **Revegetation:** Establish native phreatophytic shrubs by transplanting seedlings started in a greenhouse and then irrigating transplants until roots have accessed plume groundwater.
2. **Hydraulic Control:** Enhance plant transpiration with the goal of slowing groundwater flow and contaminant transport in seeps at the base of the escarpment, in floodplain groundwater, and in the nitrate plume west of the disposal site.
3. **Risk Evaluation:** Once plant roots have accessed groundwater, evaluate exposure pathways associated with plant uptake of uranium and other contaminants.

Prior Activities: LM scientists and collaborators (Table 19) designed a factorial field experiment (Table 20) to test three hypotheses related to hydraulic control at the Shiprock site:

- Transplanted native phreatophytes will grow and survive when irrigated.
- Transplants will root into and transpire groundwater and then survive without irrigation.
- Contaminants taken up into plant tissues will be at concentrations that are below risk thresholds.

Table 19. Collaborators on the Shiprock Phytoremediation Study

Perry Charley, Marnie Carroll, and students Diné College Shiprock, New Mexico	David Moore Environmental Research Laboratory University of Arizona
Edward Glenn, PhD Environmental Research Laboratory University of Arizona	Michael O'Neill, PhD Farmington Agricultural Science Center New Mexico State University
Margaret Mayer, Barbara Klein, and students Diné College Tsaile, Arizona	William Waugh, PhD Environmental Sciences Laboratory Navarro Research and Engineering, Inc.

Table 20. Treatment Structure of the Shiprock Phytohydraulic Control Field Experiment

Factor (Independent Variable)	Level
Plume location	a. Uranium (terrace) b. Nitrate (borrow pit)
Depth to groundwater	a. 4.5–6.0 meters b. 6.0–7.5 meters
Irrigation	a. Irrigated 2007–2013 Irrigated 2007–2010, not irrigated 2011−2013
Native plant species (phreatophyte)	Black greasewood (*Sarcobatus vermiculatus*, SAVE) Fourwing saltbush (*Atriplex canescens*, ATCA)

Two plots are on the terrace east of the disposal cell and the overlying shallow uranium-contaminated groundwater moving toward the San Juan River floodplain, and two plots are within the radon-barrier borrow pit west of the disposal cell and the overlying shallow nitrate plume. In each location (terrace and borrow pit), depth to groundwater is between 4.5 and 6.0 m for one plot and between 6.0 and 7.5 m for the other plot. Transplants of local phreatophytes were randomly planted in each plot, and plots were split for the two irrigation treatments. An important follow-on hypothesis (not tested by the current pilot studies) is that transpiration rates from large-scale plantings of native phreatophytes will be high enough to significantly slow or stop groundwater plume dispersion.

Obligatory and facultative phreatophytes occur naturally on the terrace and in the radon-barrier borrow pit. We transplanted fourwing saltbush and black greasewood randomly along drip irrigation lines within the plots at each location. We irrigated all plants from 2006 to 2010 using San Juan River water hauled to tanks and then ceased irrigation in half of each plot in 2011. Diné College students measured plant mortality and growth annually from 2007 to 2012 and calculated changes in plant canopy area for each plant. Students also sampled stems and leaves for a subset of plants in all four plots in 2013. Concentrations were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) at the Arizona Laboratory for Emerging Contaminants following an EPA protocol. We used δD and $\delta^{18}O$ values to infer water sources for plant, soils, and shallow groundwater. Soils and plants were sampled on July 11, 2013. Groundwater was sampled in 2006, 2007, and 2013. We analyzed water isotopes for a combination of samples from the 2006, 2007, and 2013 data. San Juan River water data were from 2007.

Work to date was funded by the Shiprock site with some in-kind funding for faculty and graduate students at the University of Arizona and for faculty and intern students at Diné College.

FY 2016 Activities: All fieldwork for the Shiprock pilot study is complete. In FY 2016, AS&T scientists and collaborators completed data analyses and drafted a DOE report, which along with a summary and recommendations follows.

> DOE (U.S. Department of Energy), Draft. *Growing Desert Phreatophytes for Hydraulic Control of Groundwater at the Shiprock, New Mexico, Disposal Site: Interim Pilot Study Report*, LMS/SHP/S14558, ESL-RPT-2016-04, Office of Legacy Management.

1. *Native desert phreatophytes were successfully established*. Irrigated fourwing saltbush and black greasewood transplants from native seed accessions grew to maturity in test plots both in the borrow pit and on the river terrace. The higher mortality of greasewood than of saltbush transplants may be attributable to reproduction physiology. Transplants grew largest on the river terrace where groundwater was reportedly 6.0–7.5 m deep. Saltbush were larger than greasewood in 2012. Monitoring will resume to determine if greasewood catches up as observed in phytoremediation plantings at the Monument Valley site.

2. *Roots of healthy, mature plants were removing precipitation, irrigation water, and groundwater.* We discontinued irrigation on part of each test plot in 2011, evaluated water isotope ratios to test hypotheses about plant water sources in 2013, and continued observing the health of phreatophytes until 2016. Analyses of plant water sources indicated that (1) irrigated plants were indeed primarily using irrigation water, (2) the healthiest unirrigated plants grew on the river terrace and were primarily using shallow groundwater, and (3) less healthy plants in river terrace and borrow pit plots were primarily using a combination of rainwater and residual irrigation water that may have mounded under the plots. Observations of overall good plant health in 2016 provided additional evidence that many of these desert phreatophytes were surviving by tapping shallow groundwater.

3. *Uptake of contaminants by transplants did not increase exposure risk for animals.* Growing phreatophytes in contaminated groundwater can create exposure through plant uptake of contaminants. We compared contaminant concentrations in current-year stem and leaf tissue

of plants in test plots with plants in reference areas and with MTLs published by the National Research Council for elements in animal diets. Test plot plants were not increasing exposure risk to grazing animals. Uranium levels were statistically higher in test plot plants than in reference area plants, but they were about 4 orders of magnitude below an MTL and 1–3 orders of magnitude below uranium levels in typical livestock diets and supplements. All plant strontium levels were more than 2 orders of magnitude below the MTL. Selenium levels in test plot plants were within the MTL range but not significantly different than levels in reference area plants.

4. *A large phreatophyte planting could potentially remove a significant volume of groundwater from the terrace.* We calculated potential groundwater discharge or recharge as ET − PPT. Preliminary ET estimates, based on fractional plant cover in test plots and an algorithm developed at the Monument Valley site, were extrapolated to the areas of hypothetical large plantings on the river terrace and in the borrow pit. For the river terrace area, ET ranged from 258 to 352 mm/yr and groundwater discharge from 7603 to 16,707 cubic meters per year (m^3/yr), or between 3.8 and 8.4 gallons per minute (gal/min). For the borrow pit area, ET ranged from 91 to 115 mm/yr and groundwater recharge from 3583 and 4913 m^3/yr, or between 1.8 and 2.4 gal/min. A joint study planned with USGS in 2016–2017 (Study 5) would refine the ET algorithm for Shiprock by combining ground measurements and multispectral data from both high-resolution unmanned aircraft systems and low-resolution satellite imagery.

5.6.3 Study 3: Monument Valley Subpile Soil Phytoremediation

Overview: LM conducted a suite of pilot studies designed to evaluate, on a landscape scale, proposed passive and active remedies for ammonium, nitrate, and sulfate in the alluvial aquifer and in a source area at the Monument Valley site. The pilot studies focused on passive remedies as alternatives to active pump-and-treat technologies. We evaluated natural and enhanced phytoremediation using native desert plants, and natural and enhanced microbial denitrification, all as potential remedies for both the shallow portions of the alluvial aquifer and for soil remaining where a uranium mill tailings pile had been removed—that is, the subpile soils, which are a continuing source of groundwater contamination.

The enhanced phytoremediation pilot study for subpile soils involved delineating, planting, and irrigating the entire denuded area where ammonium and nitrate concentrations were shown to be elevated within the original tailings pile footprint. Plantings of native fourwing saltbush shrubs matured within 5 years; native black greasewood transplants took longer. Monitoring of soil water content and percolation flux, and results of a soil salt balance study, provided evidence that ET from the mature planting was preventing leaching of ammonium, nitrate, and sulfate into the alluvial aquifer—ET had cut off the subpile soil as a source of groundwater contamination. The planting also extracted and metabolized nitrogen and sulfur from subpile soils, but not enough to account for a rapid drop in total soil nitrogen as monitored through soil sampling and analysis.

Prior Activities: We tested a hypothesis that microbial denitrification was causing the rapid drop in total nitrogen (N) and that denitrification could be accelerated. The enhanced denitrification pilot study involved deficit irrigation of the subpile planting—irrigating less than the amount of water removed by evapotranspiration—and supplying a carbon source in the irrigation stream. The pilot studies demonstrated, using a combination of (1) direct assays of denitrification in the subpile soils and (2) analysis of nitrogen-15 enrichment in soils undergoing nitrate loss, that irrigation-induced microbial denitrification was responsible for about a 50% drop in total subpile soil nitrogen between 2000 and 2007. From 2007 to 2012, the year irrigation ceased, we measured no additional drop in total nitrogen. In 2012, we began empirically testing the hypothesis that, without irrigation, subpile soil nitrogen levels would resume dropping. We speculated that (1) a drier soil would enhance nitrification and (2) an increase in soil carbon, as a consequence of saltbush plant mortality and decaying roots, would enhance microbial denitrification.

FY 2016 Activities: This study is complete. AS&T scientists and collaborators published a journal article in February 2016.

> Glenn, E.P., F. Jordan, and W.J. Waugh, 2016. "Phytoremediation of a nitrogen-contaminated desert soil by native shrubs and microbial processes," *Land Degradation and Development*, DOI: 10.1002/ldr.2502.

The published abstract follows:

> We combined phytoremediation and soil microbial nitrification and denitrification cycles to reduce nitrate and ammonium levels at a former uranium mill site near Monument Valley, Arizona. Ammonia used in uranium extraction was present throughout the soil profile. Sulfate, applied as sulfuric acid to solubilize uranium, was also present in the soil. These contaminants were leaching from a denuded area where a tailings pile had been removed and were migrating away from the site in groundwater. We planted the source area with two deep-rooted native shrubs, *Atriplex cansescens* and *Sarcobatus vermiculatus*, and irrigated transplants for 11 years at 20% the rate of potential evapotranspiration to stimulate growth, then discontinued irrigation for 4 years. Over 15 years, total nitrogen levels dropped 82%, from 347 to 64 mg kg^{-1}. Analysis of δ15N supported our hypothesis that coupled microbial nitrification and denitrification processes were responsible for the loss of N. Soil sulfate levels changed little; however, evapotranspiration reduced sulfate leaching into the aquifer. For arid sites where traditional pump-and-treat methods are problematic, the Monument Valley data suggest that alternatives that incorporate native plants and rely on vadose zone biogeochemistry and hydrology could be a sustainable remediation for nitrogen contaminated soil.

5.6.4 Study 4: Monument Valley Land-Farm Phytoremediation

Overview: LM proposed land farming as an alternative to the traditional pump-and-treat approach for nitrate and ammonia in the Monument Valley alluvial aquifer. The land-farm pilot study involved irrigating crops of native shrubs with nitrogen-contaminated groundwater pumped from the alluvial aquifer. Land-farm phytoremediation was studied to provide a contingency if monitoring shows that natural or enhanced attenuation remedies are not reducing aquifer nitrogen levels fast enough or otherwise prove to be inadequate.

The land-farm pilot study was designed to address three general objectives:

- Reduce nitrate and ammonia levels in the alluvial aquifer by pumping and irrigating a native shrub crop, converting nitrate and ammonia into useful plant biomass
- Reduce sulfate levels in the alluvial aquifer by pumping plume water, irrigating the land farm, and sequestering groundwater sulfate as calcium sulfate in the soil profile, analogous to natural gypsiferous soils in the area
- Improve rangeland condition and produce safe forage for livestock or a crop such as native plant seed for use in rangeland revegetation or mine land reclamation

Prior Activities: The pilot study was designed as a factorial field experiment to answer the following questions (i.e., questions LM and Navajo Nation scientists would need to answer before proceeding with a large-scale land farm):

- Which native crop uses nitrate most efficiently?
- What is an optimum irrigation rate to remove as much nitrogen and sulfur as possible while limiting deep percolation and leaching of contaminants back into the aquifer?
- What is the optimum nitrate concentration in irrigation water?
- Will sulfate and nitrate accumulate in the soil and in what forms?
- How productive are the crops?
- Are crops irrigated with plume water safe for livestock?

The treatment structure for our land-farm pilot study consisted of two main factors: (1) nitrate concentration in irrigation water and (2) crops in the cropping system. Four nitrate treatment levels were derived from the results of preliminary greenhouse studies: 250 milligrams per liter (mg/L), a level not likely toxic to crop plants or to livestock feeding on the crop; 500 mg/L, a level not likely toxic to crops but possibly toxic to livestock; 750 mg/L, a level possibly toxic to crops; and a clean water control. We selected two native shrubs as crop plants: fourwing saltbush and black greasewood. We transplanted seedlings grown from locally collected seed on a 2 m grid spacing. A randomized split-block design structure developed for the study consisted of a 50 × 100 m area divided into four blocks. Four plots in each block received the four different nitrate levels. Each plot was split at random and planted, half with fourwing saltbush and the other half with black greasewood, for a total of 32 equal-sized split-plots receiving four replications of 8 different treatment combinations (nitrate level × crop).

Irrigation, soil nitrogen sampling, soil moisture monitoring, risk assessments, and an evaluation of beneficial uses are complete. We designed the irrigation system to deliver water from two wells: a clean water well completed in the De Chelly aquifer and a well completed in nitrate-contaminated water in relatively high nitrate-contaminated alluvial groundwater. Plant canopy cover and leaf area index were estimated using QuickBird data that were calibrated and validated against ground monitoring data. We used LAI from Licor 2000 meter readings as a ground calibration and then estimated landscape-scale LAI from QuickBird normalized difference vegetation index data. We estimated percent canopy cover by classifying pixels as either bare soil or vegetation using a program in ERDAS software and compared these values to cover estimated from a visual inspection of images using a point-intercept method. We sampled for soil nitrogen at the beginning of the study and then again 5 years later, and we monitored volumetric soil water content monthly during the growing season using a neutron hydroprobe.

We conducted greenhouse, modeling, and field studies to evaluate the uptake of soil constituents and potential toxic effects for land-farm plants and for animals that might consume those plants. The toxicity studies focused on nitrogen and sulfur but also included uranium and other regulated groundwater contaminants of concern (COCs). We were concerned primarily with the accumulation of nitrate, sulfate, hydrocyanic acid, strontium, uranium, and other constituents within the plants and how the accumulation of these constituents could affect the quality of forage for livestock. The COCs, nitrate and ammonium, are also the dominant sources of nitrogen in desert soil, an essential element for plant growth. Therefore, nitrate and ammonium can be viewed both as contamination with respect to groundwater quality and as a resource with respect to plant nutrition and growth. The land-farm study evaluated options for exploiting nitrogen contamination to fertilize native plants for possible beneficial land reuse as seed and forage crops.

FY 2016 Activities: All of the field work for this study is complete. The work to date was funded by the Monument Valley site and in-kind contribution through various grants at the University of Arizona, Vanderbilt University, and the DOE Consortium for Risk Evaluation with Stakeholder Participation (CRESP). AS&T is funding the publication of a paper.

5.6.5 Study 5: USGS UAS Evapotranspiration Assessment

Overview: This project, a collaboration with USGS and UA, will use UASs to acquire high-resolution spectral data needed to estimate spatial and temporal variability in ET in floodplain ecosystems for input to groundwater flow evaluations. We plan to combine UAS imagery, Landsat and MODIS imagery, ground measurements of LAI, and an empirical ET algorithm to estimate ET in tamarisk-dominated riparian ecosystems adjacent to the Shiprock, New Mexico, Disposal and Moab, Utah, Processing sites. Data will be scaled from ground measurement to UAS and satellite imagery to refine the empirical ET algorithm and then to estimate seasonal and annual variation in ET for the different riparian zones at the two sites and in adjacent reference areas.

Prior Activities: This project started in 2015. AS&T and USGS scientists attended the Unmanned Aircraft Systems Technologies Workshop at the USGS National Center in Reston, Virginia, on May 19–21, 2015, and collaborated on the following proposal in response to a USGS call: “Effects of Changes in Tamarisk Evapotranspiration on Groundwater at a Southwestern Uranium Mill Tailings Site.” USGS gave the proposal a high score and selected it for funding.

FY 2016 Activities: AS&T, USGS, and UA scientists wrote a TTP for the study, selected study sites, and drafted a field work plan. The TTP describes six tasks:

1. *Delineate plant associations*. Discrete riparian vegetation zones will be mapped by field-identifying species with in the UAS flight area, defining distinct plant associations, and delineating plant association boundaries on a satellite image.
2. *Measure leaf area index.* LAI will be estimated for dominant riparian plant species using a LI-COR LAI-2000 instrument, and independently using a combination of allometric stem measurements and leaf harvesting. Algorithms will then be developed relating easy-to-

obtain LI-COR LAI-2000 readings to difficult-to-obtain leaf-harvesting estimates, and the LAI-2000 data will then be scaled over the entire flight area.

3. *Acquire UAS and satellite imagery.* High-resolution imagery obtained using a USGS UAS with a five-band multispectral camera will be used to map Normalized Difference Vegetation Index (NDVI) and EVI vegetation indices. These UAS products will be correlated in turn with NDVI and EVI based on low-resolution Landsat and MODIS satellite imagery acquired as close as possible to the time of the UAS flight.
4. *Scale ground to remote UAS and satellite data.* LAI, fractional cover, and ET can be scaled from ground estimates to high-resolution UAS, and then to Landsat and MODIS imagery. LAI will be determined on sample plants on the day of the UAS flight for each species as described above. Fractional cover will be determined by the proportion of bare soil and vegetation visible in the UAS imagery. UAS images will be converted to NDVI and EVI and then intercalibrated across UAS, Landsat, and MODIS images by regression. LAI and ET will be calculated from ground meteorological data to determine potential ET and algorithms already developed relating actual ET to ETo and the vegetation index data.

5.7 Educational Collaboration

Secretary of Energy Ernest Moniz reaffirmed a DOE commitment to tribal partnerships in 2015, with an emphasis on science, technology, engineering, and mathematics (STEM) education for Native American youth. Secretary Moniz and tribal leaders agree that STEM education is "a means of building hope for the future, building resilient economies for tribal governments, and building strong native nations for future generations." Secretary Moniz is "committed to broadening the dialogue with tribal leaders, building and strengthening more partnerships, and exploring more opportunities and solutions with tribes across the nation."

We created the Educational Collaboration focus area to strengthen and build LM's long-standing commitment to environmental science education. Our goals are to strengthen existing partnerships with tribal colleges and Native American graduate students and to explore opportunities for new partnerships. For many years, almost all AS&T Surface Studies have been built on a foundation of collaboration and cost-sharing with university researchers and their students, as well as on dissemination of knowledge through class presentations, seminars, and peer-reviewed publications. The TTP outlined the continuation of this practice of collaboration and cost-sharing:

1. Continue the existing partnership with the Navajo Nation's Diné College, including seminars and classroom instruction within the Environmental Sciences program.
2. Continue collaboration with the University of Arizona. Maintain an adjunct faculty appointment at UA and serve on graduate committees for Native American students.
3. Expand the program to foster and coordinate new educational initiatives and partnerships.

5.7.1 Initiative 1: Diné College Collaboration

Overview: This initiative is a continuation of our long-standing partnership with Diné College and it supports DOE's commitment to tribal partnerships with an emphasis on STEM education for Native American youth. This partnership is a two-way exchange of ideas. We share ideas about scientific methods, and Diné College shares ideas about the cultural acceptability of scientific approaches. Our partnership in 2016 had two focus areas:

1. Accept invitations to teach classes and seminars in the Environmental Sciences program at Diné College, with emphasis on the scientific method and enhanced natural attenuation research at LM sites on Navajo land.
2. Explore new opportunities for students in Diné College's Environmental Sciences program to participate in field studies at LM sites on Navajo land.

Prior Activities: Diné College is both a stakeholder and a partner in our efforts to develop and implement sustainable and culturally acceptable remedies for soil and groundwater contamination at uranium mill tailings sites on Navajo land. This partnership serves as an example of how Native American students and their way of life can be incorporated into remediation and research projects to better understand how to restore Mother Earth.

Through an educational philosophy grounded in the Navajo traditional living system, which places human life in harmony with the natural world, Diné College has helped guide researchers beyond traditional engineering approaches to seek more sustainable remedies for soil and groundwater contamination at the Monument Valley processing site and the Shiprock disposal site. Students and researchers are asking, allegorically, "What is Mother Earth already doing to heal a land injured by uranium mill tailings, and what can we do to help her?" This guidance has led researchers to investigate applications of natural and enhanced attenuation remedies, such as phytoremediation and bioremediation, involving native plants and microorganisms. College faculty, student interns, and local residents have contributed to several aspects of pilot studies including site characterization, sampling designs, installation and maintenance of plantings and irrigation systems, monitoring, and data interpretation.

Our partnership with Diné College has received recognition as a successful grassroots effort; it is the product of personal initiatives by all parties rather than a top-down program. Many Diné College students and university graduate student partners have received recognition at tribal college STEM conferences and other national technical forums. The partnership also received recognition from EPA, CRESP, and the National Academy of Sciences (NAS).

***EPA*:** In 2011, EPA invited us to give a presentation at a national tribal colleges and universities workshop titled "Building EPA/TCU Partnerships."

***CRESP*:** CRESP researchers invited us to contribute a chapter on our educational partnership in a book published in 2011:

> Waugh, W.J., E.P. Glenn, P.H. Charley, B. Maxwell, and M.K. O'Neill, 2011. "Helping Mother Earth Heal: Diné College and Enhanced Natural Attenuation Research at U.S. Department of Energy Uranium Processing Sites on Navajo Land," In: Burger, J. (ed.) *Stakeholders and Scientists: Achieving Implementable Solutions to Energy and Environmental Issues*, Springer, New York.

NAS**:** The AS&T educational partnership with Diné College was featured in an NAS documentary film, "Weaving STEM Education and Culture: The Faces, Places, and Projects of the Tribal Colleges and Universities Program." The documentary highlighted the high-quality STEM instructional and outreach programs within the National Science Foundation's Tribal Colleges and Universities Program.

FY 2016 Activities: Teaching at the Tsaile campus of Diné College during fall 2015 and spring 2016 semesters involved lecture classes, lab classes, seminars, and a field trip:

Lecture: "Using Plants to Clean Up Uranium Mill Tailings Contamination at Monument Valley, Arizona" (November 11, 2015).

Lab: "Environmental Statistics: Land Farm Phytoremediation at Monument Valley" (November 11, 2015).

Seminar: "Helping Mother Earth Heal: Ecological Remedies for Uranium Mill Sites" (November 18, 2015).

Lecture: "Climate Change: Design and Long-Term Performance of Engineered Covers for Uranium Mill Tailings" (March 15, 2016).

Lecture and Lab: "Using Plants to Clean Up Uranium Mill Tailings Contamination at Monument Valley, Arizona" (March 17, 2016).

Field Trip: Tour of Monument Valley phytoremediation pilot studies and student participation in soil sampling (March 18, 2016).

5.7.2 Initiative 2: Long-Term Effectiveness of Revegetation at Tuba City

Overview: AS&T created a partnership with the University of Arizona to help fund Native American graduate student research projects that support LM goals, objectives, and compliance actions. Quentin Benally, an MS student at UA, is investigating the long-term value of LM revegetation efforts and Navajo Nation grazing management practices at the Tuba City site. Mr. Benally's project supports LM's ecosystem management commitments. Dr. Karletta Chief, an Associate Professor in the Department of Soil, Water and Environmental Science at UA, and an extension specialist for Native American communities, advises Mr. Benally. An AS&T scientist serves on Mr. Benally's graduate committee.

Background: LTS&M of UMTRCA sites includes monitoring the revegetation of land disturbed during surface remediation. Revegetation at LM sites is generally based on principles and guidance developed over many years for mine land reclamation, roadside revegetation, rangeland management, and ecological restoration. Revegetation science focuses on restoration of the ecological integrity and productivity of disturbed land. Revegetation typically involves the manipulation and management of the physical, chemical, and biological properties of soils and seedbed preparation, planting, and maintenance of vegetation. At UMTRCA sites, revegetation often includes erosion control, weed management, habitat restoration, and livestock forage production.

Long-term revegetation success can be dependent on many factors, including the severity of ecological disturbance, initial soil properties, quality of revegetation efforts, climatic variability, and ongoing land management. Short-term evaluations have indicated that revegetation can be a challenging tradeoff between cost and probability of success. Low-cost practices are generally less successful, especially at arid and semiarid sites. Well-planned and higher-cost methods often improve short-term success. However, studies of the long-term value of revegetation practices are rare. Long-term quantitative monitoring and the application of knowledge from past projects to new ones are lacking. Understanding the long-term effectiveness of past revegetation efforts will lead to improved plans, implementation, and maintenance of future revegetation efforts. At the Tuba City site, LM has a unique opportunity to evaluate, in tandem, the long-term effectiveness of DOE revegetation practices and the health of Navajo rangeland.

Prior Activities: Mr. Benally started his study in FY 2014, and continued with field and laboratory work during FY 2015 and FY 2016. Mr. Benally and collaborators drafted a work plan, field-characterized vegetation, remotely estimated ET, evaluated soil fertility, and characterized soil morphology. An article was written for the LM *Quarterly Update*.

Nearly 30 years ago, DOE stripped the vegetation and soil from a large parcel east of the current Tuba City disposal site to remove windblown contamination originating from the mill tailings pile. DOE then hauled in replacement soil; treated the area with a mixture of mulch and fertilizer; seeded the area with a mixture of native shrubs, grasses, and forbs; and fenced the area to protect it from livestock grazing. In concert with the revegetation study, Mr. Benally is evaluating the effects of changes in grazing practices on vegetation health. Results will support Navajo Nation efforts to improve rangeland management. A large island of native rangeland protected from grazing serves as an ecological benchmark to gauge the health of both the stripped and revegetated area and the historically overgrazed rangeland.

Mr. Benally designed his study to answer the following land stewardship questions that are important to his tribe and to LM:

- Did DOE achieve their revegetation goals—has the stripped land healed?
- How well did short-term evaluations predict long-term revegetation success?
- Did revegetation limit the spread of harmful weeds?
- Is the rangeland recovering after decades of overgrazing?

The composition and health of vegetation in three zones—revegetated, grazed, and protected—measured both on the ground and with remote sensing, will tell us if the ecological condition of revegetated and overgrazed areas has improved. We used a line transect method to estimate percent cover of species. We also estimated LAI and ET for the three areas using an empirical algorithm linking MODIS EVI satellite data, our stem flow data for desert plants at Monument Valley, and published atmospheric flux tower data for several southwestern riparian sites. We also described soil morphology in test pits and sampled soil fertility (physical, chemical, and microbiological variables) to determine if ecological conditions in the three areas are attributable to differences in soil properties.

5.7.3 Initiative 3: Adaptation of Disposal Cell Covers to Climate Change

Overview: This is another initiative AS&T scientists proposed through our partnership with Dr. Karletta Chief, University of Arizona. The initiative involves collaborating with Native American graduate students on research projects that support the LM mission. Goals of this initiative are to help LM comply with Executive Order 13693, *Planning for Federal Sustainability in the Next Decade*, and with DOE's Climate Change Adaptation Plan. The initiative also supports the Environmental Management System Climate Change Adaptation team. Our overall objective is to project the long-term performance and adaptability of LM disposal cell covers to climate change and related changes in cover ecology and soil morphology. AS&T is collaborating on this study with Carrie Joseph, a PhD candidate at UA. Ms. Joseph was funded primarily through an Alfred P. Sloan Foundation Indigenous Graduate Partnership.

Background: All federal agencies have been tasked with determining how changes in climate would impact their missions. This effort began in 2009 with Executive Order 13514. In 2013, the President issued Executive Order 13653, *Preparing the United States for the Impacts of Climate Change,* and DOE issued a Climate Change Adaptation Plan as part of the Strategic Sustainability Performance Plan.

Executive Order 13653 sets the federal policy framework and calls for agencies to manage federal lands and waters for climate preparedness and resiliency, share data and develop decision support tools, integrate climate change considerations into risk management, and establish collaboration between agencies as well as with state, local, and tribal efforts. These efforts go beyond climate change mitigation, which generally focuses on reducing greenhouse gas emissions. Climate change adaptation initiatives help reduce the vulnerability of natural and human systems to actual or expected climate change effects. Adaptation includes improving our ability to cope with or avoid harmful impacts and taking advantage of beneficial impacts now and in the future.

The DOE Climate Change Adaptation Plan identifies four specific agency goals. The first two goals address gaining better understanding of climate change science and the potential risks and opportunities. The second two goals focus on addressing risks and opportunities and integrating efforts into existing programs and documents. This AS&T initiative supports LM efforts to satisfy these goals by evaluating how climate can influence the design and maintenance of LM disposal cell covers. For disposal cell covers to be sustainable—to continue to satisfy UMTRCA radon flux and groundwater protection requirements for 200–1000 years—covers must accommodate (i.e., adapt to) inevitable long-term changes in the climate, soils, and ecology of the site.

Prior Activities: AS&T scientists developed a conceptual approach for investigating how climate might influence the long-term performance of LM disposal cells. Ms. Joseph began developing a research plan for her contributions to the project.

The conceptual approach was framed to address goals and objectives of the DOE Climate Change Adaptation Plan. The approach has six parts:

1. **Climate Change Directives:** Review orders and directives that address climate change and determine their applicability to the long-term performance of disposal cells.
2. **Climate Scenarios:** Identify climate change scenarios for a range of disposal sites based on paleoclimatological data, meteorological records, and climate change projection models.
3. **Conceptual Evaluation—Future Vulnerability and Risk:** Evaluate potential impacts of climate change on the performance of disposal cell covers and assess risks.
4. **Conceptual Evaluation—Adaptability and Building Resilience:** Identify if and how covers were designed to adapt to climate change, how ongoing natural processes might actually increase cover resilience, and in what ways DOE could enhance resilience.
5. **Tools for Projecting Long-Term Performance:** Assess models and other tools for projecting the long-term performance of covers and identify key input parameters.
6. **Natural Analogs:** Develop an approach for selecting and investigating natural analogs of the long-term impacts of climate change on the soils and ecology of disposal cell covers.

Ms. Joseph identified three study areas for her graduate work:

Study Area 1: Future climate scenarios for uranium mill tailings sites near Native American communities in the southwest.

Study Area 2: Ecological responses to short-term and long-term trends in climate with emphasis on changes in vegetation growing on and near mill tailings disposal cells.

Study Area 3: Local perceptions of long-term risks to human health and the environment posed by uranium mill tailings disposal sites near southwestern Native American communities and opportunities for improving two-way communication and information exchange in the decision-making process.

5.7.4 Initiative 4: Educational Collaboration Program Plan

LM requested a program plan to identify opportunities for expanding higher education partnerships.

FY 2016 Activities: LM approved a program plan called "Grow Higher Education Collaborations," which was included in Version 1.0 of the TTP in October 2015. In FY 2016, under this program plan, AS&T scientists (1) supported the LM internship program with Diné College, (2) initiated collaboration on University of Arizona's environmental educational modules for tribal colleges, (3) identified potential AS&T projects tied to LM Goal 1 (protect human health and the environment) that match graduate student research requirements, and (4) continued to cultivate new educational partnerships with tribal and local colleges and universities linked to other stakeholder communities.

The program plan includes a table listing LM sites and local stakeholder colleges and universities. We also developed a program matrix that identified LTS&M issues related to the performance of disposal cells, current and potential AS&T projects designed to address those issues, specific technical questions associated with each LTS&M issue, and AS&T studies that could be designed as graduate student research projects.

As an example, the program plan identified Colorado Mesa University (CMU) as a stakeholder university in Grand Junction. As part of an LM effort to cultivate an educational partnership with CMU, in FY 2016, an AS&T scientist presented an invited seminar at the CMU public seminar series, Natural Resources of the West: The Role of Social and Natural Sciences in Resource Management. An AS&T scientist also served as a guest instructor in an Environmental Sciences class.

Waugh, W.J., 2015. "Ecology of Engineered Covers for Uranium Mill Tailings," Natural Resources of the West Seminar Series, Colorado Mesa University, Grand Junction, Colorado, November 16.

Waugh, W.J., 2015. "Using Plants to Clean Up Uranium Mill Tailings Contamination on Navajo Nation Land," ENVS 475: Experimental Design and Statistical Analysis in Environmental Science, Colorado Mesa University, Grand Junction, Colorado, December 2.

5.8 Gold King Mine Spill Impact to UMTRCA Sites

Overview: On August 5, 2015, a former gold mine in the San Juan Mountains near Silverton, Colorado, released an estimated 3 million gallons of contaminated water to the nearby Cement Creek. The creek runs into the Animas River, then to the San Juan River in New Mexico. LM manages two sites in the watershed at Durango, Colorado, and Shiprock, New Mexico, that could potentially be impacted. The purpose of this study is to determine what, if any, impacts may result at these two sites. The study primarily consists of additional sampling and analysis of water from surface locations and selected wells at each site, followed by analysis of the data gathered by LM and others compared to historic data. In addition to typical COCs, we will also analyze for arsenic, cadmium, copper, mercury, and lead, as these have all been detected by analytical work from other agencies as a result of the spill.

Prior Activities: None.

FY 2016 Activities: During FY 2016 we sampled surface water locations and near-river wells at the Durango, Colorado, processing site and the Shiprock, New Mexico, disposal site for contaminants related to the Gold King Mine spill. These data, in conjunction with data collected by others including USGS and the Colorado Department of Health, will be compared to historic data to determine if the Gold King Mine spill impacted and continues to impact surface and groundwater quality at the UMTRCA Durango, Colorado, and Shiprock, New Mexico, sites. We are currently evaluating the data and will publish a summary report at the end of 2016.

5.9 Unmanned Aircraft System Technology Evaluation

Overview: The overall objective of the Unmanned Aircraft System Technology Evaluation Project is to evaluate whether using UAS technologies for LTS&M inspection and spatial data collection results in meaningful improvements in activity efficiency (time and cost), operational safety, data quality, data visualization, and stakeholder communications. The study is a collaborative effort between USGS and LM with USGS providing the UAS, collecting relevant information, and processing the data. LM's role is to provide sites and to evaluate the data. Questions the study was designed to answer include:

- How does the use of UAS technology to support the technical needs of a given LTS&M activity impact that activity's cost?
- Does using UAS technology to support a given LTS&M activity improve efficiency (e.g., reduce the time required to complete this activity)?
- What human health and safety improvements are realized by using UAS technology to support a given LTS&M activity?
- What new useful and necessary data types will arise from using UAS technologies to support LTS&M actions?
- How will the quality of data that are typically acquired for a given LTS&M activity improve by using appropriate UAS technologies?
- Do the visualization tools arising from the use of UAS technologies improve our ability to document site conditions?
- Do the visualization products arising from the use of UAS technologies improve stakeholder communications?
- Should LM own and fly its own UAS for data collection purposes?

Prior Activities: None.

FY 2016 Activities: In FY 2016, we developed the TTP for the study and a field work plan for the Grand Junction disposal cell. Data to be collected, processed, and analyzed will include aerial photographs and multispectral images to document baseline waste volumes and topographic and vegetative conditions. The UAS data collection effort will be repeated, and the new data will be compared to the baseline conditions to evaluate changing site conditions. In addition, we also attended a UAS LiDAR demonstration.

6.0 FY 2016 Ancillary Work Plans

The AS&T program includes a portfolio of short-term studies, implemented through AWPs, requested by a LM site manager or one or more LMS subject matter experts. This work is approved and performed on an as-requested basis. Examples include supporting DOE interoffice collaborations across multiple LM sites, supporting approved technical studies, performing short-term investigations, and developing white papers. The following sections summarize FY 2016 AWP studies.

6.1 Uranium In Situ Recovery

Overview: Reactive transport modeling is being used as a tool for prediction of downgradient uranium fate and transport at uranium in situ recovery (ISR) sites. The goal of this study is for LM to stay current with uranium ISR developments. This need comes from the concern that uranium ISR is likely to occur on properties next to current and future LM sites. As such, LM needs to stay current with potential locations of uranium ISR developments and the potential for the transport of contaminants (including uranium) away from nearby ISR facilities. This study was originally initiated in 2010 by EPA Region 8 and USGS in Denver in response to the proposed Dewey Burdock ISR site near Edgemont, South Dakota. Previous work includes two USGS Open-File Reports and multiple presentations on the unique conditions at the site. EPA is working on the permitting process for this site and needs to develop appropriate requirements to protect downgradient aquifers. The methods being developed at this site include the estimation of uranium sorption parameters and the use of those parameters in reactive transport modeling. The parameter estimation and modeling efforts focus on the natural attenuation processes for uranium in downgradient bedrock. Developing a consistent methodology will assist EPA and other stakeholders in evaluating aquifer protection at the Dewey Burdock site and will be applicable at other uranium ISR sites, including some LM sites. In addition, this study provides general data analysis and modeling techniques that will be applicable to any site with uranium fate and transport issues in groundwater.

Prior Activities: We prepared and submitted two manuscripts that were accepted for publication in the journal *Mine Water and the Environment*. The two manuscript titles are "Sorption testing and generalized composite surface complexation models for determining uranium sorption parameters at a proposed in-situ recovery site" and "Predictive reactive transport modeling at a proposed uranium in situ recovery site with a general data collection guide." In addition, we prepared a poster entitled "Approaches for Downgradient Reactive Transport Modeling at Uranium In-Situ Recovery Sites" with a companion proceedings article for the "MODFLOW and MORE 2015: Modeling a Complex World" conference in Golden, Colorado (May 31–June 3, 2015).

FY 2016 Activities: The two manuscripts listed above in prior activities were finalized and published online (Johnson et al. 2016a; Johnson and Tutu 2016). The manuscripts will appear in print in *Mine Water and the Environment* in an upcoming issue.

We prepared an abstract (Johnson et al. 2016f) for an invited talk, "Water-quality issues related to uranium in situ recovery sites" for the Geological Society of America 2016 Annual Conference (Denver, Colorado) in an in situ technologies technical session. Dr. Raymond H. Johnson presented this talk at the conference on September 28, 2016. This presentation is the final activity of the uranium in situ recovery AWP.

6.2 Evaporite Sampling Phase I

Overview: In the desert southwest, any water that contains high amounts of dissolved solids that evaporates will form efflorescent crusts or evaporites that contain a variety of precipitated minerals. These evaporites become concentrated sources of anything that was dissolved in the original water. This concentration mechanism becomes especially important at LM sites with groundwater seepage discharge points. The resulting evaporite deposits can then become longer-term storage and exposure points for any COCs that may have been in the groundwater. This mechanism has the potential to hinder natural flushing strategies and may have implications for plume persistence.

The goal of this study is to provide initial steps in understanding where, how, and why evaporite deposits form at LM sites. This evaporite study involved a document review of LM sites, the use of satellite imagery, and interviews with LM and LMS employees with historical site knowledge.

Information was reviewed in order to assemble a list of LM sites with potential evaporite deposits for consideration in possible hypotheses on how evaporite samples may influence future water quality and flushing strategies. These results will be used to develop a more detailed technical study for future evaporite sampling across the assembled list of LM sites, with a focus on plume persistence.

In addition, evaporite samples from the Riverton, Wyoming, site have been provided to the SLAC research group. They will assist in providing mineralogical information on data on the uranium oxidation state. At the time of this report, these data are not yet available.

Prior Activities: In FY 2015 a draft "Evaporite Study Phase I" white paper was completed and reviewed. This white paper summarized LM sites with evaporite deposits and provided a literature review with appropriate references. This white paper was edited and converted to a full LMS report in FY 2016.

FY 2016 Activities: The white paper listed above was converted to a full LMS report *Uranium-Bearing Evaporite Mineralization Influencing Plume Persistence: Literature Review and DOE-LM Site Surveys* (DOE 2016a). The completion of this report closes out this AWP. Proposed future work on evaporites is included in the Persistent Secondary Contaminant Sources TTP.

6.3 Well Redevelopment Evaluation

Overview: Monitoring well redevelopment, the surging or high-volume pumping of a well to loosen and remove accumulated sediment and biological build-up from a well, is considered an element of monitoring well maintenance that is implemented periodically during the lifetime of the well to mitigate its gradual deterioration. Well redevelopment has been conducted fairly routinely at a few LM sites in the western United States, but at most other sites in this region it is not a routine practice. A catalyst for this project was a concern that there was a need for strict criteria for a programwide approach to well redevelopment at LM sites. There was also an implicit question as to whether well redevelopment was a necessary practice that was being overlooked at some sites. The primary objective of this study was to determine if there are significant differences in laboratory analytical results between pre- and post-redevelopment groundwater samples.

Prior Activities: Initial tasks for this AWP were completed by LMS Environmental Monitoring Operations staff in FY 2014 and FY 2015. These tasks entailed (1) documenting the overall approach to, and criteria for, redevelopment of wells at LM sites; and (2) compiling an inventory of previous redevelopment events. This inventory, which documented nearly 500 previous well redevelopment events at 16 LM sites, served as the basis for activities undertaken by AS&T in FY 2016.

FY 2016 Activities: In FY 2016, we first searched the literature for impacts of well redevelopment on sample analytical results. Although literature discussions parallel the prevailing industry-wide assumption that well redevelopment is necessary to increase production or to extend the life of a well, no data in the literature indicate that redevelopment affects chemical signatures in monitoring wells. We then undertook a detailed evaluation of the well redevelopment inventory in concert with an evaluation of corresponding groundwater contamination trends from the LMS database. We also evaluated differences between pre- and post-redevelopment field measurements and sample analytical results. Evaluation of both short- and long-term changes in groundwater chemistry relative to preceding and subsequent well redevelopment events yielded no evidence that redevelopment has any quantifiable or predictable effect on groundwater sample quality. Groundwater concentrations of uranium, the primary contaminant of concern at most LM UMTRCA sites, generally remained unchanged pre- and post-well-redevelopment.

These results are documented in the report titled *Evaluation of Pre- and Post-Redevelopment Groundwater Chemical Analyses from LM Monitoring Wells*. We also presented these findings at the September 20, 2016, AS&T Semiannual Update meeting in Grand Junction.

6.4 Nevada Offsites (NVOS) ArcGIS Two-Dimensional (2D) Transport Modeling Assessment

Overview: The ArcGIS program has the ability to calculate relatively simple advective transport in two dimensions using raster files of an aquifer's head, saturated thickness, porosity, and transmissivity. This is not a substitute for numerical modeling, though it can act as a screening tool to make quantitative predictions of advective transport for sites with sufficient data sets.

Prior Activities: Discussions with Sandia National Laboratories to receive data for the Gnome-Coach, New Mexico, site. The Gnome-Coach site geology is conducive to 2D conceptualization, and the site is at the edge of the numerical model developed by Sandia, allowing a comparison of 2D transport modeling with three-dimensional (3D) numerical model results.

FY 2016 Activities: Data from the Gnome-Coach, New Mexico site has been received from Sandia National Laboratories and is being processed for testing of the ArcGIS transport modeling. ArcGIS requires a porosity raster, and the data set provided specific storage. A porosity raster is being estimated from the specific storage data set.

6.5 NVOS 3D Visualization Project

Overview: The 3D visualization project is being used to improve the understanding of site subsurface conditions by interactively viewing various data sets such as subsurface features, well locations, concentrations, water levels, model results, and institutional controls in their relative positions. It is initially being used for the Nevada Offsites and the Weldon Spring site to develop conceptual models, evaluate monitoring networks, present numerical model results, and communicate recommendations to stakeholders.

Prior Activities: In August 2015, 3D visualization was used to present numerical model results of the Gasbuggy, New Mexico, Site to stakeholders and to make future monitoring recommendations. The visualization allowed a large amount of information to be shared quickly and facilitated agreement on future monitoring recommendations.

A 3D visualization tool was used to evaluate the monitoring network of the Shoal, Nevada, Site and to position new monitoring wells that were installed in 2014.

FY 2016 Activities: 3D visualization was used as part of an August 2016 presentation to EPA and state regulators evaluating the monitored natural attenuation remedy for the Weldon Spring, Missouri, site.

The 3D visualization of the Rulison site was presented to DOE and Navarro Research and Engineering, Inc. (Navarro), management in a June 2016 brown-bag lunch presentation.

The 3D visualization was used as part of a presentation to communicate conceptual model development and the enhancement of the monitoring network at the Shoal site to regulators in late August 2016.

6.6 Tracer Testing Workshop

Overview: Various LM sites have multiple challenges in quantifying and predicting groundwater flow and contaminant transport. Groundwater tracer testing is being considered to address some of these challenges. Dr. Paul Reimus (Los Alamos National Laboratory) is an expert in implementing and applying groundwater tracer tests to unique contaminant transport problems. Work with Dr. Reimus was initiated in FY 2016 to pursue tracer test possibilities with the hope of testing implementation in FY 2017. End uses for groundwater tracer testing include (1) distinguishing between alternative conceptual models of flow and transport, (2) providing interrogation of key transport processes (i.e., sorption or dual domain), (3) supporting model parameter inputs for predictions of contaminant travel times and distances, and (4) evaluating remedial options. Traditional types of tracer testing include single well borehole dilution and push-pull testing and multiple well tests under a forced or natural gradient. At LM sites with possible uranium-rich evaporites in the unsaturated zone, these traditional tests may be adapted to include a focused flood irrigation in a limited area at the surface.

Prior Activities: None

FY 2016 Activities: Dr. Paul Reimus came to the Grand Junction office August 2–4, 2016. On August 2, Dr. Reimus gave a presentation on various groundwater tracer testing methods that might be useful at LM sites. This presentation was given to an audience that included interested LM and LMS employees. Attendees had the chance to discuss tracer testing ideas with Dr. Reimus after the presentation and throughout the rest of the day. Dr. Reimus toured the Grand Junction office site and the Rifle site on August 3 along with a tour of the Grand Junction disposal site on August 4. Those visits provided Dr. Reimus with an opportunity to see these LM sites in person, along with having additional site-focused technical discussions with LM and LMS employees.

6.7 LM and Subsurface Insights Modeling Collaboration

Overview: Roelof Versteeg of Subsurface Insights in May 2016 was awarded a grant by the DOE Office of Science to further develop real-time modeling capabilities. LM, through ongoing collaborations at the Rifle, Colorado, site, was approached by Subsurface Insights to share existing site data to test and demonstrate PAF (Predictive Assimilation Framework) capabilities. PAF has the capability to evaluate continuous time series, geochemical sampling, and electrical geophysical monitoring data. PAF can process and display this data and use the data to automatically update groundwater flow and transport models using parameter estimation calibration techniques.

Prior Activities: None.

FY 2016 Activities: We are assisting Subsurface Insights by providing regular automated downloads of SOARS data from multiple LM sites to be used as input to the PAF algorithm.

7.0 Environmental Sciences Laboratory

Overview: Funding from the AS&T subtask order is used to maintain the Environmental Sciences Laboratory at the LM office at Grand Junction. The ESL operates a fixed-base laboratory and a mobile laboratory with capabilities to conduct geochemical and ecological studies. Funding requirements include:

- Maintaining service contracts for equipment
- Maintaining and repairing equipment
- Developing new laboratory procedures
- Procuring new equipment and consumable items
- Updating laboratory manuals, including the *Environmental Sciences Laboratory Procedures Manual* (LMS/PRO/S04343) and the *Environmental Sciences Laboratory Chemical Hygiene Plan* (LMS/PLN/S04615)
- Managing waste disposal issues
- Managing facility issues, housekeeping, and cleaning
- Maintaining a chemical inventory, including a separation and segregation system, Safety Data Sheets, and certificates of analysis
- Inspecting and testing emergency showers, eyewash stations, the automated external defibrillator, and first-aid kits on a regular basis
- Maintaining backups of electronic instrument files
- Conducting inspections and tours
- Calibrating flow meters and other field equipment
- Training

The ESL continues to be an integral part of the LM program. Because of the large emphasis on groundwater studies inherent in the work conducted in LM, the laboratory is often needed by a wide range of technical staff.

FY 2016 Activities: We completed all laboratory maintenance and calibration tasks. The laboratory operated trouble-free. Training modules were reviewed and updated. A baseline Industrial Hygiene Evaluation was performed by the Navarro industrial hygienist. We completed a comprehensive review of the ESL Chemical Hygiene Plan. We added new procedures to the ESL Procedures Manual (to be formalized when the manual is reissued November 2016) and completed three laboratory inspections. All chemical containers were inspected for integrity. A new spill kit was procured that includes supplies to clean chemical as well as mercury spills. All accumulated hazardous materials and wastes were transported to the Mesa County Hazardous Waste Disposal Facility. All accumulated purge water from the Gnome-Coach, New Mexico site (dating from 2009 to present) was evaporated. The remaining evaporites were scanned by Safety and Health and stored in the locked Control Area cabinet.

A new ion chromatography system was procured and installed. The service agreements for the TOC, ICP, and LSC instruments were renewed. A new sieve shaker, Wylie mill, automated alkalinity titrator, and hand-held spectrophotometers were procured. Three Chemchek KPA-11 uranium analyzers were sent to the manufacturer for tune up and repair. Preventive maintenance was conducted on the laboratory compressor and vacuum pump. Flooring was replaced throughout the ESL. The fenced area to the north and west of Building 32 was expanded, leveled, and resurfaced with milled asphalt. New sea-land containers were procured, placed, and leveled as additional storage space for the ESL and the Environmental Sampling group. Sea-land containers were added to the expanded area for storage for the Uranium Leasing Program and the Environmental Sciences Group. The Safety and Health storage shed was relocated to the expanded area. A new three-sided building was constructed for the storage of all-terrain vehicles and trailers.

Multiple sampling events (and subsequent analyses) were conducted in support of Variation in Groundwater Aquifers (Section 5.1). In addition, we provided laboratory and procurement support to Scientific Focus Area subtask and SLAC subsurface investigations. Column studies were performed on Riverton, Wyoming, floodplain soils. Samples were submitted to the ESL for analyses from the Old Rifle, Rocky Flats, Durango, and Grand Junction sites in Colorado; the L-Bar and Shiprock, New Mexico, sites; the Bear Creek and Riverton, Wyoming, sites; the Monticello, Utah, sites; the Shoal, Nevada site; and the Monument Valley and Tuba City, Arizona, sites.

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Appendix A

Communication Model for Applied Studies & Technology (AS&T) Program

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LMS/ESL/S13220

Communication Model for Applied Studies & Technology (AS&T) Program

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Table

Abbreviations

AS&T	Applied Studies and Technology
AWP	Ancillary Work Plan
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOE	U.S. Department of Energy
FUSRAP	Formally Utilized Sites Remedial Action Program
ITRC	Interstate Technology and Regulatory Council
LM	Office of Legacy Management
LM-1	LM Office of Legacy Management (Program Director)
LM-10	LM Office of Business Services
LM-20	LM Office of Site Operations
LM-20.1	LM UMTRCA/NVOS Team
LM-20.2	LM RCRA/CERCLA/FUSRAP Team
LM-20.3	LM Asset Management Team
LMS	Legacy Management Support
NVOS	Nevada Offsites
RCRA	Resource Conservation and Recovery Act
SME	subject matter expert
TTP	Technical Task Plan
UMTRCA	Uranium Mill Tailings Radiation Control Act

1.0 Introduction

The purpose of this Communication Model is to outline how the U.S. Department of Energy (DOE) Office of Legacy Management (LM) and the Legacy Management Support (LMS) contractor Applied Studies and Technology (AS&T) Program management team provides relevant, useful, and timely information to LM management and operations staff and other stakeholders.

The Communication Model provides a framework to manage and coordinate the wide variety of communications that support the AS&T Program. The Communication Model covers who will receive the communications, how the communications will be delivered, what information will be communicated, who communicates, and the frequency of the communications.

This Communication Model compliments the AS&T Program work management process guidance.

2.0 Program Communication Objectives

Effective communication of program successes and progress is necessary to ensure the usefulness of AS&T Program outcomes. Clearly defining the expectations of communications and the delivery method of the communication will improve accessibility of beneficial information resulting from AS&T work.

Main communication objectives for the AS&T Program include:

- Identify Program effectiveness (metrics and anecdotal information of significant and/or interesting study successes)
- Solicit input into study selection and scope of work
- Report on study progress
- Implement LM operational improvements using AS&T Program outcomes
- Encourage LM Program-wide participation and ideas
- Foster interest and sharing of AS&T Program progress and outcomes with:
    - the DOE scientific community
    - appropriate regulators
    - scientific peer groups
    - site-specific Stakeholder communities

3.0 AS&T Communications – Audiences, Messages and Methods

Table 1 summarizes the AS&T communication model identifying the various audiences for our communications, the purpose and messages communicated to our different audiences and delivery methods for these messages.

The LM AS&T program manager provides guidance for implementing the AS&T communications model and works with LM study leads/LMS principal investigators, LM/LMS site managers and LMS Public Affairs to outline responsibility for developing and delivering specific communication products and services including:

- Technical Task Plans and Ancillary Work Plans
- Planning and review meetings
- Reports and journal articles
- Scientific/technical workshops
- Stakeholder meetings and workshops
- Conference participation
- Site-specific meetings and workshops

4.0 Description of Communication Delivery Methods

This section summarizes the contents of the communication delivery methods tabulated in Section 3.0.

4.1 AS&T Annual Report

The AS&T Annual Report provides a summary of progress on all active AS&T studies. It is typically 30–50 pages in length.

The report includes an Executive Summary and a Program Effectiveness section that reports selected study outcomes with respect to the following topics:

- Supporting the LM Strategic Plan
- LTS&M cost implications
- Improvement to human health and environmental safety
- Improved understanding of LTS&M operations
- Advances in technology and scientific understanding and impacts to site(s) or program specific compliance requirements
- Maximizing the usefulness of existing data assets and improving conveyance of technical information
- Benefits of scientific collaborations and cost sharing
- Educational collaboration
- Stakeholder impacts

4.2 Semiannual AS&T Program Updates

This is a PowerPoint (or equivalent) presentation by the LMS AS&T principal investigators to LM executive management and site managers summarizing the progress of active Technical Task Plans (TTPs), Ancillary Work Plans (AWPs), and the Environmental Science Laboratory.

Table 1. AS&T Communication Matrix

Audience	Purpose/Messages	Delivery Method/Frequency
LM Executive Management[a]	• Identify AS&T program effectiveness (metrics and anecdotal information of significant and/or interesting program achievements) — Alignment with LM strategic plan — Impacts on LM program costs — Impacts on compliance requirements — Impacts on human health and environmental safety — Impacts on operational efficiencies — Advances in scientific understanding that support LM decision making — Scientific collaborations and cost sharing — Educational collaborations — Stakeholder impacts	• AS&T Prospectus (under development) • AS&T Annual Report • Semi-annual AS&T Program Updates • Program Effectiveness Alerts (developed as they are achieved) • Articles in LM Quarterly Program Update newsletter • AS&T SharePoint site (updated regularly)
LM/LMS Site Management[b]	• Solicit input into study selection and scope of work — Identification and prioritization of scientific and LTS&M operational needs — Study proposal reviews and recommendations — Study progress reviews — Input into decisions on: (1) study continuation ("Go" decision); (2) changes in study scope of work; or (3) study termination ("Kill" decision) — inform environmental strategies or future remedial approaches	• Participation in AS&T workshop • Technical Task Plans (TTPs) and Ancillary Work Plans (AWPs) (prepared and revised as directed) • AS&T Annual report • Semi-annual AS&T Program Updates • Articles in LM Quarterly Program Update newsletter • AS&T progress summaries • Technical presentations/workshops (as scheduled) • AS&T SharePoint site (updated regularly)
LM/LMS Site Operations[c]	• Reporting on progress of studies — Impacts of new understanding on site operations and compliance — Integration of study findings/outcomes into site operations	• Study presentations (as scheduled) • Targeted LM/LMS site manager briefings (as scheduled) • Input to annual execution year plan • Input to site planning (as scheduled)
DOE Scientific Community[d]	• Share gains in scientific understanding and knowledge about surface and subsurface systems • Present collaboration opportunities to advance understanding of surface and subsurface systems and environmental remedy responses. • Present LM data available to support and advance collaborative or mutual and unilateral environmental studies • Present new knowledge about climate change impacts on surface and subsurface systems	• Active participation in DOE science and technology workshops and working groups (as scheduled; as invited)
Regulators[e]	• Share progress and outcomes of studies that have the potential to impact compliance	• Site-specific meetings, reports or workshops (as directed by the LM site manager)
Scientific Peer Groups[f]	• Share — Gains in scientific understanding and knowledge about surface and subsurface impacts on environmental remedies — Improved understanding of long-term changes to engineered controls — Understanding the impacts of climate change on environmental remedies	• Participation in scientific conferences/workshops (as scheduled) • Publish peer-reviewed scientific/technical journal articles (as scheduled)
Stakeholder Groups[g]	• Share — Improvements in site characterization approaches and remedy evaluation — Status and expected behavior of existing environmental remedies	• Site-specific meetings and workshops (as scheduled) • Active participation in ITRC meetings and ITRC working groups (as scheduled) • Participation in industry conferences (as scheduled)

[a] LM-1 director; LM-10 director; LM-20 director; LM-20.1 team leader; LM-20.2 team leader; LM-20.3 team leader
[b] LM-20.1 UMTRCA/NVOS team; LM-20.2 RCRA/CERCLA/FUSRAP team; LM-20.3 Asset Management team
[c] LM/LMS task assignment managers, site managers and technical/operations staff
[d] DOE Office of Environmental Management technology development; DOE Office of Science
[e] State regulators; Tribal regulators; U.S. Environmental Protection Agency; U.S. Nuclear Regulatory Commission
[f] Examples: Interstate Technology and Regulatory Council (ITRC); American Geophysical Union (AGU); International Atomic Energy Agency (IAEA)
[g] Examples: Navajo Nation; La Plata, CO County Commission; Rocky Flats Citizen's Advisory Board; Fernald Citizen's Advisory Board

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4.3 AS&T Workshop

This is a workshop organized by the LM and LMS AS&T Program manager to identify, screen, and recommend new studies to add to the AS&T portfolio of work on an as needed basis. Participants in this workshop include LM and LMS site managers and technical subject matter experts (SMEs).

4.4 AS&T Technical Task Plans (TTPs)

TTPs document scope of work for multiyear studies where the deliverable is expected to enhance LM's strategic capabilities by way of new knowledge, enhanced technical capability, improvements to current LM/LMS operations, or new or improved technology applications. TTPs are a maximum of 20 pages. The general format for TTPs is provided in the latest version of the LM Internal Use document *Applied Studies and Technology (AS&T) Program Guidance to Identify, Select and Monitor Applied Studies.* Active TTPs are available on the AS&T SharePoint site (https://projects.lm.doe.gov/AST/SitePages/Home.aspx).

4.5 Ancillary Work Plans (AWPs)

AWPs document investigations requested by a LM site manager and one or more LMS SMEs. Examples include supporting DOE interoffice collaborations, supporting active TTPs, performing short-term investigations, and developing white papers. AWPs are a maximum of 2 pages. The general format for an AWP request is provided in the latest version of the LM Internal Use document *Applied Studies and Technology (AS&T) Program Guidance to Identify, Select and Monitor Applied Studies*. Active AWPs are available on the AS&T SharePoint site (https://projects.lm.doe.gov/AST/SitePages/Home.aspx).

4.6 LM Quarterly Program Update

LMS AS&T principal investigators regularly contribute articles about ongoing AS&T work to the LM Quarterly Program Update newsletter.

4.7 Peer-Reviewed Journal Articles and Workshop/Conference Presentations

AS&T principal investigator and investigation team members regularly submit technical articles documenting advances in scientific understanding for consideration in peer-reviewed technical journals and professional conferences or workshops. Typically, two to five of these articles are published or presented each year.

4.8 Program Effectiveness Alerts

LMS AS&T principal investigators develop "Fact Sheet"-style one-page summaries of significant AS&T Program successes. These alerts are developed on an as-achieved basis and are provided to the LM/LMS AS&T program managers and LM study lead via email.

4.9 AS&T Program SharePoint Site

LMS maintains an AS&T SharePoint site. This site is the main internal communications hub for the Program and includes:

- Program overview
- Work management processes
- Active TTPs and AWPs
- Responsibility Assignment matrix (RAM) and Responsible, Approver, Consulted, Informed (RACI) matrix
- Annual workshops
- Study focus area descriptions
- Environmental Sciences Laboratory (ESL) overview
- Data-mining application descriptions
- ESL/AS&T reports
- Program weekly report archive

Contact the LM or LMS AS&T Program manager to gain access to the AS&T SharePoint site.

4.10 AS&T Weekly Report

The LM AS&T Program manager compiles a weekly summary that includes AS&T actions and progress related to (1) Management and planning and (2) active TTPs and AWPs. In addition, the weekly summary includes a look-ahead to upcoming work. Each weekly summary is sent by email to the LM-20.1 Environment Team, the LM-20.2 Environment Team, and selected LMS SMEs and technical staff.