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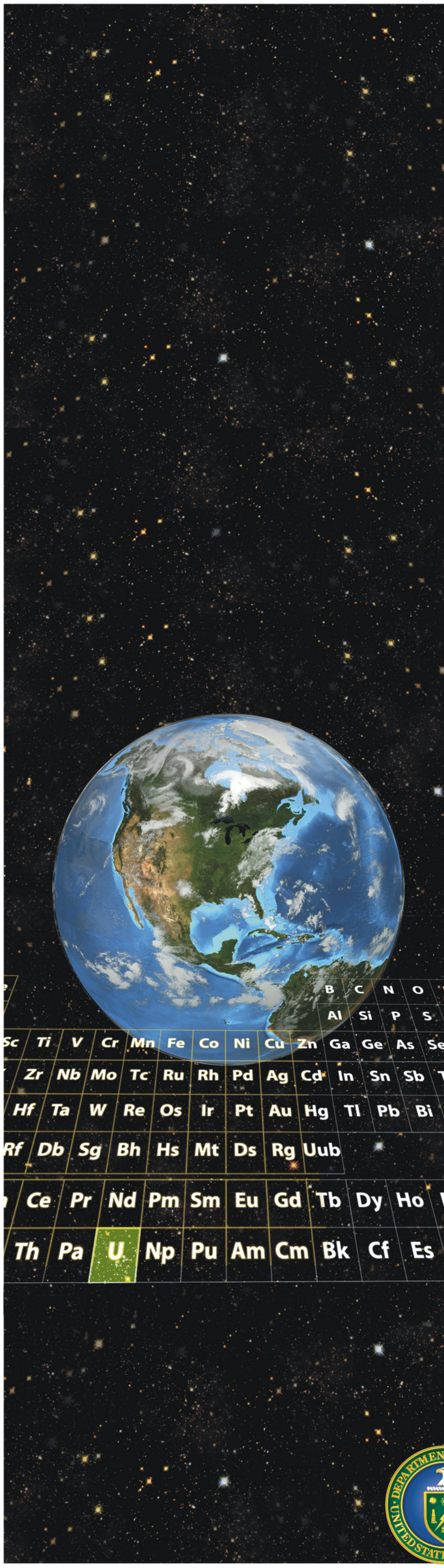
Environmental Sciences Laboratory



Applied Studies and Technology

Fiscal Year 2017 Annual Report

January 2018

U.S. DEPARTMENT OF ENERGY | Legacy Management

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Figure

Tables

Abbreviations

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AC	activated carbon
AS&T	Applied Studies and Technology
ATCA	*Atriplex canescens*
CMU	Colorado Mesa University
CO_2	carbon dioxide
COC	contaminant of concern
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
DMAV	data mining, analysis, and visualization
DOE	U.S. Department of Energy
DOI	digital object identifier
ECAP	Enhanced Cover Assessment Project
EDD	electronic data deliverable
ENA	enhanced natural attenuation
EPA	U.S. Environmental Protection Agency
EQuIS	Environmental Quality Information System
ESA	Ecological Society of America
ESL	Environmental Sciences Laboratory
ET	evapotranspiration
EVI	Enhanced Vegetation Index
ft	feet
FY	fiscal year
GEMS	Geospatial Environmental Mapping System
GJDS	Grand Junction Disposal Site
GKM	Gold King Mine
GMD	groundwater model domain
HDPE	high-density polyethylene
HPLC	high performance liquid chromatograph
IAEA	International Atomic Energy Agency
IDL	Interactive Data Language
IP	internet protocol
IT	informational technology
LAI	leaf area index
lidar	light detection and ranging

LM	Office of Legacy Management
LMS	Legacy Management Support
LTCP	long-term cover performance
LTS&M	long-term surveillance and maintenance
LTSP	long-term surveillance plan
m	meters
mg/L	milligrams per liter
ml	milliliters
mm	millimeters
mm/year	millimeters per year
MODIS	Moderate Resolution Imaging Spectroradiometer
MTL	maximum tolerance level
N	nitrogen
NAS	National Academy of Sciences
NRC	U.S. Nuclear Regulatory Commission
NRZ	naturally reduced zones
NVOS	Nevada Offsites
OLF	Original Landfill
PAF	predictive assimilation framework
^{210}Pb	lead-210
PeSCS	persistent secondary contaminant sources
PPT	precipitation
^{222}Rn	radon-222
SAVE	*Sarcobatus vermiculatus*
SC	specific conductance
SEEPro	Site Environmental Evaluation for Projects
SFA	Scientific Focus Area
SOARS	System Operation and Analysis at Remote Sites
SQL	structured query language
STEM	science, technology, engineering, and mathematics
UA	University of Arizona
UAS	unmanned aircraft system
UMTRCA	Uranium Mill Tailings Radiation Control Act
USGS	U.S. Geological Survey

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 postclosure responsibilities and to ensure the continued protection of human health and the environment. Given the long half-lives of some radionuclides, some 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 toward fulfilling its mission.

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) effectively documents and communicates AS&T study results and conclusions; (3) promotes the application of applicable AS&T study outcomes to improve the effectiveness of LM operations; and (4) integrates AS&T into LM-wide optimization and improvement initiatives.

The AS&T program includes a portfolio of long-term studies for which the deliverables are new knowledge, enhanced technical capability, advancement of current LM operations, and new or improved technology applications. These studies are the primary focus for the AS&T program. In fiscal year (FY) 2017, AS&T conducted technical studies of (1) variation in groundwater aquifers; (2) plume persistence; (3) persistent secondary contaminant sources; (4) System Operation and Analysis at Remote Sites (SOARS); (5) data mining, geochemical analysis, and project visualization; (6) long-term cover performance; (7) enhanced natural attenuation; (8) educational collaboration; (9) Gold King Mine release impact on Uranium Mill Tailings Radiation Control Act sites; and (10) unmanned aircraft system technology evaluation.

The AS&T program also includes a portfolio of short-term investigations. These short-term investigations are approved and performed as requested. Examples include supporting DOE interoffice collaborations across multiple LM sites, supporting approved technical studies, performing short-term investigations, and developing white papers. In FY 2017, AS&T ancillary studies included (1) Nevada Offsites (NVOS) ArcGIS Two-Dimensional Transport Modeling Assessment; (2) NVOS Three-Dimensional Visualization Project; (3) LM and Subsurface Insights Modeling Collaboration; (4) Literature Review of Uranium Sequestration Through Polyphosphate Injection; and (5) Title II Groundwater Flow and Contaminant Transport Model Evaluation Guidance.

The program made significant progress on all technical and ancillary studies, which are summarized here. Three examples of AS&T contributions to the LM mission are described below.

Persistent Secondary Contaminant Sources: This study was initiated in FY 2017 and is a continuation of the Plume Persistence Study that was completed in FY 2017. In FY 2017, AS&T continued collaborations and cost sharing for this study with the SLAC National Accelerator Laboratory, which Stanford University operates on behalf of DOE. These collaborations have 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 study, initiated in FY 2016, 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. In FY 2017, the research team presented results of its research and conducted field studies at one additional LM site. A fourth field investigation is scheduled for the beginning of FY 2018.

Educational Collaborations: The AS&T Educational Collaboration initiative builds on LM's long-standing 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 2017, as with prior fiscal years, this initiative was advanced through partnerships with Diné College and the University of Arizona (UA) and through planning for new educational partnerships. In FY 2017, AS&T scientists initiated a new partnership with Colorado Mesa University (CMU), gave seminars in CMU classes during the 2017 spring semester, recruited students to become interns, and teamed with faculty and graduate students on several projects.

As part of AS&T's partnership with UA, LM supports Native American graduate student research projects that support LM goals. In FY 2017, Ms. Carrie Joseph was accepted in the PhD program at UA. She drafted a research prospectus and served as an invited speaker at LM meetings with tribes. Her research is underway. Mr. Quentin Benally completed his research data analysis in October 2016, submitted his thesis in November 2016, passed his thesis defense in December 2016, and graduated from UA in May 2017 with a master's degree in Environmental Science.

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 conferences on science, technology, engineering, and mathematics and at 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, journal publications, and conference presentations in nationally and internationally recognized forums.

1.0 Introduction

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) *2016–2025 Strategic Plan* (LM Strategic Plan) (DOE 2016e) presents LM's goals and objectives. The objectives of Goal 1 (to protect human health and the environment) are to comply with environmental laws and regulations, reduce postclosure-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 2016e). Applied Studies and Technologies (AS&T) is a core component of LM's efforts to fulfill this goal by incorporating improvements in scientific understanding and technology applications with management strategies to decrease long-term costs. AS&T program objectives developed to achieve this goal are presented in Section 2.0 of this *Fiscal Year 2017 Annual Report*. This report also documents the studies AS&T is conducting to fulfill these objectives and to continually 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. Section 3.0 of this annual report highlights AS&T's effectiveness and achievements.

AS&T work consists of two categories of study. Long-term studies enhance LM's strategic capabilities by way of new knowledge or understanding, enhanced technical capability, optimizing current LM operations, and advancing technology applications. Short-term investigations are considered on an ad hoc basis and can include supporting DOE interoffice collaborations across multiple LM sites, supporting active long-term work, performing short-term investigations, and developing white papers.

In fiscal year (FY) 2017, AS&T work included 10 long-term studies and five short-term investigations. The long-term studies focused 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 (LTCP) studies, (5) enhanced natural attenuation (ENA) studies, (6) educational collaboration initiatives, (7) environmental monitoring, and (8) data collection. Section 4.0 of this annual report summarizes FY 2017 long-term studies. The short-term investigations range from uranium sequestration to developing a systematic framework for evaluating Title II site groundwater flow and contaminant transport models. Section 5.0 of this annual report summarizes the FY 2017 short-term investigations.

In addition to these study areas, AS&T manages the Environmental Sciences Laboratory (ESL). The ESL features a geochemical laboratory, an ecology laboratory, a petrography facility, and an instrument calibration facility (Section 6.0).

AS&T work was performed at (or for) numerous sites in FY 2017. Table 1 provides a list of the sites discussed in this report, the abbreviated site names used in this report and the regulatory driver (statues or programs) for each site. Figure 1 presents the locations of the sites listed in Table 1.

Table 1. FY 2017 Referenced DOE Sites

Site Name and State	Site Abbreviation	Regulatory Driver
Bluewater, New Mexico, Disposal Site	Bluewater site	UMTRCA Title II
Central Nevada Test Area, Nevada	CNTA	Nevada Offsite
Crested Butte, Colorado, Site	Crested Butte site	none
Durango, Colorado, Disposal Site	Durango disposal site	UMTRCA Title I
Durango, Colorado, Processing Site	Durango processing site	UMTRCA Title I
Falls City, Texas, Disposal Site	Falls City site	UMTRCA Title I
Fernald Preserve, Ohio, Site	Fernald site	CERCLA
Gasbuggy, New Mexico, Site	Gasbuggy site	Nevada Offsite
Gnome-Coach, New Mexico, Site	Gnome-Coach site	Nevada Offsite
Grand Junction, Colorado, Disposal Site	GJDS	UMTRCA Title I
Grand Junction, Colorado, Site	Grand Junction site	DOE Defense Decontamination and Decommissioning Program
Green River, Utah, Disposal Site	Green River site	UMTRCA Title I
Lakeview, Oregon, Disposal Site	Lakeview site	UMTRCA Title I
L-Bar, New Mexico, Disposal Site	L-Bar site	UMTRCA Title II
Mexican Hat, Utah, Disposal Site	Mexican Hat site	UMTRCA Title I
Moab, Utah, Processing Site	Moab site	Uranium Mill Tailings Remedial Action (UMTRA)
Monticello, Utah, Disposal and Processing Sites	Monticello site	CERCLA/RCRA
Monument Valley, Arizona, Processing Site	Monument Valley site	UMTRCA Title I
Mound, Ohio, Site	Mound site	CERCLA/RCRA
New Rifle, Colorado, Processing Site	New Rifle site	UMTRCA Title I
Old Rifle, Colorado, Processing Site	Old Rifle site	UMTRCA Title I
Rifle, Colorado, Disposal Site	Rifle disposal site	UMTRCA Title I
Riverton, Wyoming, Processing Site	Riverton site	UMTRCA Title I
Rocky Flats, Colorado, Site	Rocky Flats site	CERCLA/RCRA
Rulison, Colorado, Site	Rulison site	Nevada Offsite
Sherwood, Washington, Disposal Site	Sherwood site	UMTRCA Title II
Shiprock, New Mexico, Disposal Site	Shiprock site	UMTRCA Title I
Shirley Basin South, Wyoming, Disposal Site	Shirley Basin site	UMTRCA Title II
Shoal, Nevada, Site	Shoal site	Nevada Offsite
Tuba City, Arizona, Disposal Site	Tuba City site	UMTRCA Title I
Weldon Spring, Missouri, Site	Weldon Spring site	CERCLA

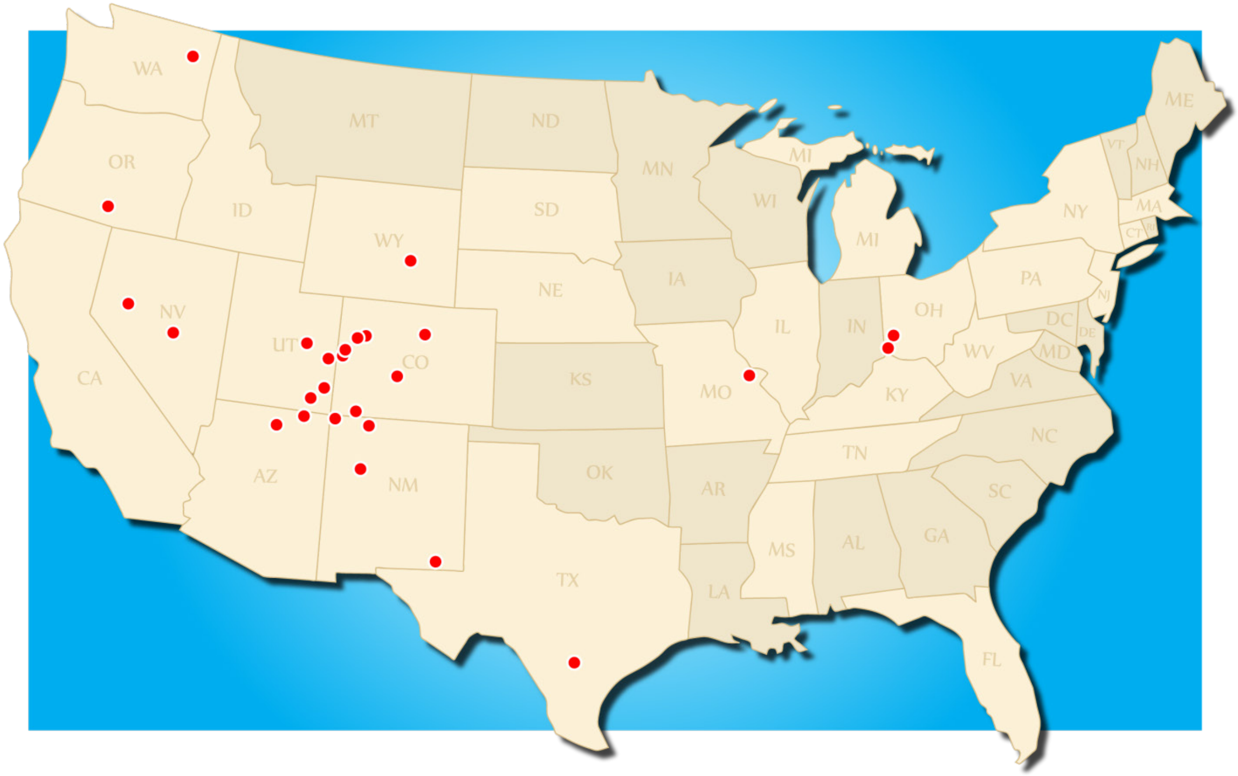

Figure 1. FY 2017 Referenced DOE Sites

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 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 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 about 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 use the results
- Use AS&T projects to create and promote opportunities, discourse, and achievements in environmental science education

In FY 2017, AS&T studies have resulted in the advancement of many LM objectives (DOE 2016e), including the following:

1. Reduce postclosure-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 LM's 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 2017 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, 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 AS&T's understanding of uranium behavior in the subsurface and AS&T's 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 use and build on the results (3, 4, 6, 7)
- Educational collaboration to promote science, technology, engineering, and mathematics (STEM) education and opportunities and strengthen existing partnerships with tribal colleges and Native American students (4, 6, 7, 8)

3.0 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.

3.1 Overview of Long-Term Studies and Short-Term Investigations

In FY 2017, AS&T worked on 10 long-term studies and five short-term investigations, as presented in Table 2. This table 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 this report where more detail is provided. Details regarding long-term study and short-term investigation activities can be found in Sections 4.0 and 5.0, respectively.

Table 2. FY 2017 Active Long-Term Studies and Short-Term Investigations

Title	Status	Location in Annual Report
Long-Term Studies		
Variation in Groundwater Aquifers	Ongoing in FY 2018	Section 4.1
Plume Persistence	Completed in FY 2017	Section 4.2
Persistent Secondary Contaminant Sources	Ongoing in FY 2018	Section 4.3
SOARS: System Operation and Analysis at Remote Sites	Ongoing in FY 2018	Section 4.4
Data Mining, Geochemical Analysis, and Project Visualization	Ongoing in FY 2018	Section 4.5
Long-Term Cover Performance	Ongoing in FY 2018	Section 4.6
Enhanced Natural Attenuation	Ongoing in FY 2018	Section 4.7
Educational Collaboration	Ongoing in FY 2018	Section 4.8
Gold King Mine Release Impact to Uranium Mill Tailings Radiation Control Act (UMTRCA) Sites	Completed in FY 2017	Section 4.9
Unmanned Aircraft System Technology Evaluation	Ongoing in FY 2018	Section 4.10
Short-Term Investigations		
Nevada Offsites (NVOS) ArcGIS Two-Dimensional (2D) Transport Modeling Assessment	Completed in FY 2017	Section 5.1
NVOS 3D Visualization Project	Completed in FY 2017	Section 5.2
LM and Subsurface Insights Modeling Collaboration	Ongoing in FY 2018	Section 5.3
Literature Review of Uranium Sequestration Through Polyphosphate Injection	Ongoing in FY 2018	Section 5.4
Title II Groundwater Flow and Contaminant Transport Model Evaluation Guidance	Ongoing in FY 2018	Section 5.5

3.2 Effectiveness and Achievements

The following sections summarize AS&T past and present (FY 2017) program effectiveness and achievements.

3.2.1 Long-Term Cover Performance Studies

LM is currently responsible for the LTS&M of over 90 sites, some of which will never be released for unrestricted use (DOE 2016e). 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 LM's understanding of long-term processes that affect disposal cell performance with the goal of improving performance, sustainability, and cost effectiveness. These studies are described in the following paragraphs.

Initiated in the 1990s, these studies address gaps in the scientific understanding of how disposal cell covers are changing over long periods and what changes might be 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 U.S. Nuclear Regulatory Commission (NRC) regulators to move the regulatory framework toward 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 multiyear 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 disposal cell covers at the Fall City site and Bluewater site. In FY 2017, the research team analyzed FY 2016 data, published and presented the research, drafted test pit restoration reports for FY 2016 sites, and prepared for field sampling of disposal cell covers at the Shirley Basin site and the Lakeview site.

- **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 (UA) 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 2017, the student 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 in Monticello, Utah. The current study developed instrumentation and methods for large-scale monitoring of the Monticello site disposal cell cover system. Results show nearly zero percolation through the water balance cover over a 17-year period. The study has garnered national and international (IAEA) recognition for innovation, and it has become a technical basis for water balance cover designs at other DOE, state, and municipal disposal sites. In FY 2017, aging instrumentation was replaced, cover performance monitoring continued, and the study was selected for a presentation to the LM director. 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 GJDS in FY 2007. In FY 2017, a comparison of the performance of conventional and new instrumentation was installed at a field test facility.

3.2.2 SOARS: System Operation and Analysis at Remote Sites

Because many LM sites are in remote locations, making routine field visits costly, AS&T established System Operation and Analysis at Remote Sites (SOARS) to remotely collect and transmit data in real time to LM servers. SOARS supports LM's objectives to reduce postclosure-related health risks in a cost-effective manner, improve the long-term sustainability of environmental remedies, and make information more accessible.

SOARS is operational at 21 LM sites in eight states (Table 3). Cumulatively, SOARS maintains 118 dataloggers coupled to approximately 900 sensors of varying types. Understanding weather patterns and extremes is an important component of LTS&M. To facilitate data acquisition, SOARS maintains weather stations at 16 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. In addition, SOARS makes it possible to control values and pumping rates remotely from LM office locations. It is expected that the SOARS footprint will continue to expand with technology development and as more sites transition to LM and additional needs for this system are identified.

The utility of SOARS instrumentation and data was highlighted in FY 2017 as part of the AS&T Gold King Mine Release Impact to UMTRCA Sites project (Section 4.9). SOARS systems collect real-time surface and groundwater elevation data at both sites included in this study. The SOARS data allowed us to evaluate the groundwater–surface water interactions during the period of interest, which would otherwise not have been possible. Additionally, a new data mining, analysis, and visualization (DMAV) program (Section 4.5) was developed to calculate a water balance for the Shiprock site and the Monticello site evaporation ponds based on SOARS data.

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 systems 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 2017, the savings and efficiencies associated with SOARS continued to reduce LM program costs.

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

Table 3. Sites with SOARS Instrumentation

Site Name	Number of Dataloggers	Weather Station
Bluewater site	11	Yes
GJDS	3	Yes
CNTA	1	No
Crested Butte site	3	Yes
Durango disposal site	1	Yes
Fernald site	1	No
Grand Junction site	4	Yes
Green River site	2	No
Lakeview site	6	Yes
L-Bar site	2	Yes
Monticello site	7	Yes
Mexican Hat site	1	Yes
Monument Valley site	5	Yes
Mound site	1	No
New Rifle site	9	Yes
Old Rifle site	6	Yes
Rifle disposal site	5	Yes
Rocky Flats site	10	Yes
Shiprock site	30	Yes
Tuba City site	5	No
Weldon Spring site	5	Yes

3.2.3 Persistent Secondary Contaminant Sources

This multiyear study, initiated in FY 2017, is a continuation of the work performed as part of the Plume Persistence Study. It is focused on improved scientific understanding of the existence and influence of persistent secondary contaminant sources on groundwater quality. 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 secondary contaminant sources that may not have been previously recognized. These secondary sources can have an influence on the effectiveness of selected environmental remedies. 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 2017, AS&T has continued valuable collaborations and cost sharing associated with this study with the SLAC National Accelerator Laboratory. These collaborations continued to enhance data collection and refined interpretations of subsurface processes that control contaminant migration.

3.2.4 Variation in Groundwater Aquifers Study

This multiyear study, initiated in FY 2014, focused on advancing scientific understanding of mechanisms responsible for large vertical chemical concentration variations in groundwater that could impact plume migration rate estimations as well as interpretations of historical contaminant trends, both of which could affect interpretation of remedy efficacy. Study results indicate that several LM sites have considerable vertical stratification of dissolved constituents 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 chemical concentration trends, vertical stratification impacts need to be considered in both sampling methodology and data interpretation.

There was an encouraging outcome of this study at the Shiprock site, where data support using specific conductance (SC), an easily obtained measure of salinity, as a low-cost surrogate for monitoring concentrations of uranium and sulfate, the primary site contaminants, in groundwater. Using SOARS instrumentation (Section 4.4), this parameter can also be continuously monitored using downhole sensors. The sampling regime at the Shiprock site makes it the most extensive and costly of the UMTRCA sites currently managed by LM (DOE 2013). This study supports LM's objective to understand and improve the long-term sustainability of environmental remedies in a cost-effective manner (DOE 2016e). Outcomes from this study may also affect future groundwater monitoring well design, groundwater monitoring protocols, and the interpretation of groundwater sample analytical data (Section 4.1).

3.2.5 Enhanced Natural Attenuation

ENA 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 ENA studies include (1) evapotranspiration (ET) to control soil leaching and dispersion of groundwater plumes at the Tuba City site; (2) phytoremediation to support the hydraulic control of shallow groundwater at the Shiprock site; (3) microbial attenuation of soil contaminants at the Monument Valley site; (4) land-farming techniques to remediate groundwater contaminants at the Monument Valley site; and (5) the use of UAS imagery to monitor phytoremediation and ET on a landscape scale at the Shiprock site and the Moab site. A summary of these projects is presented below.

- **Tuba City Evapotranspiration**
  This study, initiated in FY 2015 in collaboration with the U.S. Geological Survey (USGS) and partners from academia, refined a remote-sensing method for landscape-scale estimates of ET, which can greatly influence both groundwater recharge and discharge in desert environments. In FY 2017, collaborators presented the results of the study at two applied science conferences. This study is complete.

- **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 site. Students and faculty from University of Arizona (UA) and Diné College, a Navajo-owned community college, supported field sampling activities and data analysis. In FY 2017, collaborators completed a final DOE report for the project and presented the research at an international science conference. This study is complete.
- **Monument Valley Subpile Soil Phytoremediation**
  This study is also a collaboration with students and faculty from UA 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 site. This study produced evidence that a combination of native transplants and microorganisms had isolated, through ET, and removed, through denitrification, most of the soil contamination; the pilot study was the remedy. In FY 2017, results were incorporated in a draft Groundwater Compliance Action Plan for the Monument Valley site, and collaborators input ET data from Monument Valley site in a groundwater flow model and presented the modeling study at an applied science conference. This study is complete.
- **Monument Valley Land-Farm Phytoremediation of Groundwater**
  This multiyear study produced an option for groundwater remediation at the Monument Valley site. It 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. In FY 2017, collaborators drafted a paper for publication on land-farm phytoremediation.
- **USGS UAS Evapotranspiration Study**
  This study, a collaboration with USGS and UA, is using 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. The study combines UAS imagery, Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, ground measurements of leaf area index (LAI), and an empirical ET algorithm to estimate ET in tamarisk-dominated riparian ecosystems adjacent to the Shiprock and Moab sites. In FY 2017, collaborators calculated and mapped ET using UAS multispectral data, used the ET algorithm to evaluate temporal changes in plant populations on water use, presented research at technical conferences, and had a paper accepted for publication in a technical journal.

3.2.6 Educational Collaboration

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 LM's long-standing 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 hands-on field experiences for environmental science students at Diné College. In FY 2017, an AS&T scientist presented seminars and taught classes on ecological remedies for uranium mill tailings, taught labs on environmental sampling designs and statistics and led students on field trips and soil sampling activities, and helped faculty organize and conduct a summer field biology class that included LM sites.
- **University of Arizona Partnership**
  This partnership was created in FY 2013 with a UA 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 2017, a student completed his thesis on the long-term success of revegetation practices at the Tuba City site and then graduated. Another student passed her written and oral comprehensive exams, was accepted into the PhD program, and submitted a research prospectus on the long-term management of UMTRCA sites near Native American communities.
- **Grow Higher Education Collaboration**
  In FY 2016, LM developed a program plan to grow and expand higher education collaborations with a continued emphasis on STEM education at colleges and universities near stakeholder communities. In FY 2017, AS&T scientists gave invited presentations at Colorado Mesa University (CMU), initiated a geochemistry partnership with CMU, mentored a CMU intern, and collaborated with faculty and graduate students at three other universities.

Table 4 provides a FY 2017 summary of Education Collaboration activities (see Section 4.8 for details).

Table 4. FY 2017 Educational Outreach Summary

College/University	AS&T Activity
Diné College	Seminars, class instruction, field trips, and field sampling activities during fall, spring, and summer sessions
University of Arizona, Tucson, Arizona	Master thesis advisor and PhD committee member
University of Wisconsin–Madison	Collaborated with faculty and graduate students
University of Virginia	Collaborated with faculty and a postdoctoral student
University of California–Berkeley	Collaborated with a graduate student
Colorado Mesa University, Grand Junction, Colorado	Guest instructors in Geology and Environmental Science classes; summer intern mentor

3.3 Conferences and Workshops

To acquire and disseminate information related to LM issues, study collaborators participate in conferences and workshops as attendees and presenters. FY 2017 participation is summarized in Table 5.

Table 5. FY 2017 Conferences and Workshops

Conference or Workshop	Location	Date	Title	Conference Item	AS&T Activity	Location in Annual Report
Third Annual Conference on Hydropedology	Beijing, China (university collaborator)	10/16/2016	Patterns of Decadal Soil Change on Technogenic Soil Systems Employed for Radioactive Waste Containment	Presentation	Long-Term Cover Performance	Section 4.6
American Geophysical Union 2016	San Francisco, California	12/15/2016	Potential for Water Savings by Defoliation of Saltcedar (*Tamarix* spp.) by Saltcedar Beetles (*Diorhabda carinulata*) in the Upper Colorado River Basin	Poster	Enhanced Natural Attenuation	Section 4.7
American Geophysical Union 2016	San Francisco, California	12/16/2016	Methods for Measuring Effects of Changes in Tamarisk Evapotranspiration on Groundwater at Southwestern Uranium Mill Tailings Sites	Poster	Enhanced Natural Attenuation	Section 4.7
Waste Management 2017	Phoenix, Arizona	3/7/2017	Radon Fluxes from Two Earthen Barriers over Uranium Mill Tailings After Two Decades of Service	Proceedings article and presentation	Long-Term Cover Performance	Section 4.6
Waste Management 2017	Phoenix, Arizona	3/8/2017	Effects of Rangeland Evapotranspiration on Groundwater Recharge, Discharge, and Flow at the Tuba City, Arizona, Disposal Site	Proceedings article and presentation	Enhanced Natural Attenuation	Section 4.7
American Geophysical Union 2016	San Francisco, California (SLAC collaborator)	12/16/2016	Biogeochemical Constraints on Uranium Cycling in Redox Active Floodplain Sediments	Presentation	Persistent Secondary Sources	Section 4.3
American Geophysical Union 2016	San Francisco, California USA (SLAC collaborator)	12/16/2016	Hydrologic and Temporal Influences of Evaporite Minerals on the Vertical Distribution, Storage, and Mobility of Uranium	Presentation	Persistent Secondary Sources	Section 4.3
Waste Management 2017	Phoenix, Arizona	3/9/2017	Use of Groundwater Flow, Solute Transport, and Geochemical Modeling to Evaluate Long-Term Nitrate Plume Concentrations Following Phreatophyte Source Control	Proceedings article and presentation	Enhanced Natural Attenuation	Section 4.7
MODFLOW and More 2017	Golden, Colorado	5/21/2017	Estimating Evapotranspiration and Recharge Rates Using a Remote Sensing Algorithm	Poster	Enhanced Natural Attenuation	Section 4.7
SUITMA 9	Moscow, Russia (university collaborator)	5/22/2017	The Spatial Extent of Evolved Soil Architecture Along a Bioturbation Sequence on an Engineered Cover for Uranium Mill Tailings Containment in New Mexico, USA	Presentation	Long-Term Cover Performance	Section 4.6

Table 5. FY 2017 Conferences and Workshops (continued)

Conference or Workshop	Location	Date	Title	Conference Item	AS&T Activity	Location in Annual Report
Ecological Society of America 2017	Portland, Oregon	8/8/2017	Effects of Changes in Tamarisk Evapotranspiration on Groundwater at Southwestern Uranium Mill Tailings Sites	Presentation	Enhanced Natural Attenuation	Section 4.7
Ecological Society of America 2017	Portland, Oregon	8/10/2017	Growing Desert Phreatophytes to Control Flow of Contaminated Groundwater at a Uranium Mill Site	Poster	Enhanced Natural Attenuation	Section 4.7
2017 Goldschmidt Geochemistry Conference	Paris, France (SLAC collaborator)	8/15/2017	Redox, Hydrological, and Molecular Controls over Uranium Mobility in Redox-Variable Aquifers	Keynote presentation	Persistent Secondary Sources	Section 4.3
Waste Management 2017	Phoenix, Arizona	3/8/2017	Long-Term Stewardship at a Former Uranium Mill Tailings Site in Riverton, Wyoming	Proceedings article and presentation	Persistent Secondary Sources	Section 4.3

3.4 Collaborations

AS&T collaborated with a number of universities, government agencies, and national laboratories during FY 2017 (Table 6). Collaboration takes multiple forms, including intellectual teaming, cost sharing, and LM providing site access for research purposes.

Table 6. Collaborating Partners

Collaborative Entity	AS&T Activity	Location in Annual Report
SLAC National Accelerator Laboratory	Plume Persistence Persistent Secondary Contaminant Sources	Section 4.2 Section 4.3
University of Virginia	Long-Term Cover Performance	Section 4.6
University of Wisconsin–Madison	Long-Term Cover Performance	Section 4.6
University of California–Berkeley	Long-Term Cover Performance	Section 4.6
University of Arizona	Enhanced Natural Attenuation Educational Collaboration	Section 4.7; Section 4.8
U.S. Nuclear Regulatory Commission	Long-Term Cover Performance	Section 4.6
Desert Research Institute	Long-Term Cover Performance	Section 4.6
U.S. Geological Survey	Enhanced Natural Attenuation Unmanned Aircraft System Technology Evaluation Persistent Secondary Contaminant Sources	Section 4.7 Section 4.10 Section 4.3
Office of Science and Technology Policy	SOARS	Section 4.4
Lawrence Berkeley National Laboratory	SOARS	Section 4.4

3.5 AS&T Reports

In FY 2017, AS&T prepared five project summary reports (Table 7).

Table 7. FY 2017 Long-Term Study and Short-Term Investigation Summary Reports

Report	AS&T Activity	Location in Annual Report
Growing Desert Phreatophytes for Hydraulic Control of Groundwater at the Shiprock, New Mexico, Disposal Site	Enhanced Natural Attenuation	Section 4.7
Assessment of Potential Gold King Mine Release Impacts to Durango, Colorado, and Shiprock, New Mexico, LM UMTRCA Sites	Gold King Mine Spill Impact to UMTRCA Site	Section 4.9
Plume Persistence Final Project Report	Plume Persistence	Section 4.2
Technical Memorandum: Nevada Offsites (NVOS) ArcGIS Two-Dimensional (2D) Transport Modeling Assessment	Nevada Offsites (NVOS) ArcGIS Two-Dimensional (2D) Transport Modeling Assessment	Section 5.1
Technical Memorandum: NVOS 3D Visualization	NVOS 3D Visualization Project	Section 5.2

3.6 Technical Educational Exchanges

AS&T conducts technical exchanges to communicate study findings and evaluation techniques to managers, scientists, and engineers. In FY 2017, AS&T presented six technical educational exchange presentations to LM and LMS staff, including those presented at the AS&T Semiannual Update (Table 8).

Table 8. Technical Educational Exchanges

Educational Exchange Topic	Presentation Title	Date
Data mining and visualization	Data Mining and Visualization Demonstration	July 25, 2017
Shiprock phytoremediation	Growing Desert Phreatophytes for Hydraulic Control of Groundwater at the Shiprock, New Mexico, Disposal Site	February 21, 2017
Gold King Mine release impacts to LM Uranium Mill Tailings Radiation Control Act Sites	Evaluation of Potential Gold King Mine Release Impacts to LM Uranium Mill Tailings Radiation Control Act Sites	March 21, 2017
SOARS overview	SOARS	March 21, 2017
Persistent secondary sources	Zooming in for a Microscopic View of Uranium Plume Persistence	September 7, 2017
Long-term cover performance	Got It Covered? Will Soil Formation Increase Radon Flux on Disposal Cells?	September 7, 2017

3.7 International Atomic Energy Agency

An AS&T scientist served as a consultant and Environmental Remediation Group leader for an IAEA consultancy meeting on a technology review for decommissioning and environmental remediation at IAEA Headquarters in Vienna, Austria, November 21–25, 2016. The objective of the meeting was to provide IAEA with guidance on how to capture and make globally available updated information on the most relevant and effective technologies and techniques used in decommissioning and environmental remediation and to begin creating a “Wiki style” database of relevant information.

3.8 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 6.0). In FY 2017, the ESL made significant contributions to AS&T studies. ESL 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; Riverton site; Durango disposal site; Monticello site; and the Tuba City site.

4.0 FY 2017 Long-Term Studies

In FY 2017, 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, groundwater monitoring, UAS data collection, and education collaborations. Long-term study details and results are presented in the following sections.

4.1 Variation in Groundwater Aquifers

Overview: This study, also called the Variation Project, focuses on evaluating variation in concentrations of dissolved constituents in groundwater monitoring wells. The catalyst for this project was the observation in 2012–2013 that concentrations of dissolved ions, as indicated by SC, and contaminant concentrations varied with depth in groundwater monitoring wells at several former LM uranium-ore processing sites. In some cases, the range in SC, uranium, and other contaminants observed over a decade or more in a well could be reproduced in a single afternoon simply by sampling the well at different depths. Based on these observations, we undertook a multiyear investigation to determine the extent of dissolved ion and chemical variation that occurs in monitoring wells at sites managed under the UMTRCA program.

Prior Activities: This study comprised two phases. Phase I was conducted to assess the overall prevalence of vertical stratification in LM site monitoring wells based on measurements of SC, a measure of salinity, alone. Between July 2013 and October 2014, SC and temperature profiles were obtained at 0.5-foot (ft) intervals in 400 monitoring wells at 15 LM sites in the western U.S. At all sites profiled, underlying groundwater contains elevated levels of milling-related constituents, primarily uranium and sulfate. This profiling effort culminated in the submittal of the 2015 AS&T report titled *Variation in Groundwater Aquifers: Results of 2013–2014 Phase I Field Investigations* (DOE 2015). An overview of the study was included in the third quarter (July–September 2015) LM Program Update.[2]

Most of the wells profiled (about 70%) had little variation in the SC profiles—that is, SC measurements were fairly consistent within the monitoring well water column. This was not the case, however, at two LM sites located on river floodplains—the Durango processing site and the floodplain portion of the Shiprock site. At these sites, dissolved ion concentrations (as indicated by SC) increased with depth, at times markedly, and in many cases within the screened interval of the monitoring wells. Based on historical monitoring data, there were also some indications that this stratification in SC might correlate with site contaminants or other parameters. For these reasons, these two floodplain sites were selected for further evaluation in Phase II.

Phase II of the project focused on investigating whether the measured vertical variation in SC applies to site contaminants—in particular, uranium—and, if so, to what extent SC correlates with those parameters. Between August and November 2015, SC and chemical vertical profiles were obtained at 24 wells at the Durango processing site and 36 wells on the Shiprock site floodplain. At each well, following initial SC profiling, groundwater samples were collected

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

at 1 ft vertical intervals and analyzed for uranium, major ions (including sulfate), nitrate, organic carbon, iron, and pH. Vertical profiles of radon-222 (^{222}Rn), a direct indicator of groundwater residence time in the monitoring well, were also obtained in a subset of the wells. Samples were analyzed at the ESL. 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 site and Durango processing site in spring and summer 2016.

FY 2017 Activities: The central activity in FY 2017 consisted of the analysis and interpretation of field data collected in Phase II. AS&T's DMAV database and corresponding applications (Section 4.5) were instrumental to this effort. To frame the results of this analysis, we attempted to answer three primary questions. First, do measured values of SC in a wellbore covary with uranium or other milling-related site contaminant concentrations? Second, if the answer to the first question is yes, can SC be used as a low-cost indicator of uranium or other UMTRCA site contaminant concentrations? Finally, how might the observed intrawell variations of contaminant concentrations potentially impact LM's interpretation of remedy progress at floodplain sites?

Results: One of the major findings of the Phase I study was that the chemical concentrations in a given well, particularly at floodplain sites, can vary significantly depending on the depth at which samples are collected, even within the screened interval of the well. Based on the Phase II field results, this was true for uranium, sulfate, and other constituents at both the Durango processing and Shiprock sites. This finding is important for several reasons.

A major goal at many LM sites is to estimate future groundwater contaminant concentrations, spatial distributions, and restoration time frames. These predictions are based in part on groundwater monitoring data—samples collected routinely (often annually or semiannually) in monitoring wells, usually at single, often unspecified, depths. Until this project was initiated in 2013, there was an assumption at many LM sites that the water quality within the water column within or below the screened interval was homogenous. Although samples might typically be collected from midscreen well depths, it was relatively common to sample at depths that varied from this convention—for example, within the lower screen or sump portion of the well. If, as we found in this study, dissolved ion and contaminant concentrations vary with depth in the monitoring well, this could affect interpretations of temporal trends, especially when using low-flow sampling techniques.

A second goal of this study was to determine the degree of correlation between SC and site contaminants, if any. Based on the Phase II results, there is no apparent correlation between SC and uranium, the focus of LM's monitoring efforts at most UMTRCA sites. Although concentrations of dissolved ions and uranium did vary in many of the wells profiled, no consistent pattern was observed. In fact, in many of the Durango processing site wells, uranium decreased with depth, in contrast to the increasing trend observed for SC. Overall, chemical profiles in Durango processing site wells were irregular and varied from well to well. This might be due to the complex geology at the site, which is underlain by five distinct geological formations. Many of the wells profiled were screened across two geologic units.

This was not the case at the Shiprock site. In many of the wells profiled, in particular those with the highest degrees of variation measured in Phase I, there is a strong linear relationship between SC and uranium concentrations, as well as other analytes. These findings support using SC, an easily obtained measure of salinity, as a low-cost surrogate for monitoring uranium and sulfate, the primary site contaminants in wells where this correlation has been established. Another observation is that vertical profiles of ^{222}Rn in monitoring wells is useful in discerning zones with high groundwater influx and zones that are relatively stagnant, and as such it could help optimize screen placement when new monitoring wells are installed. The draft *Variation in Groundwater Aquifers: Results of Phase II Field Investigations and Final Summary Report* will be finalized in FY 2018.

4.2 Plume Persistence

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 long-term study for the plume persistence study in 2013.

The main study questions are as follows:

1. How and where does uranium reside on the aquifer solids (i.e., uranium form and distribution)?
2. What are the uranium amounts and release rates from naturally aged aquifer solids?
3. What are the uranium release mechanisms?
4. How do the effects of questions 1–3 influence groundwater remediation strategies?

Prior Activities: Geoprobe coring was conducted at 22 locations in 2012 over the uranium plume at the Grand Junction site to determine the location and amounts of mill-related contaminants (mainly uranium). Core samples were collected at 1 ft depth intervals for a total of 366 samples. AS&T conducted batch tests on the core samples to determine the mass of uranium removed by four different extracting media. The different extractants were intended to release uranium that is bound in different forms. The results of these extractions were used in conjunction with data from petrography and column testing to evaluate the mineralogical residences of the uranium. The results provided information to help determine how tightly the uranium is bound to the aquifer solids.

Fission-track radiography is a procedure to determine where uranium resides in a soil or rock sample compared to grain mineralogy. Thin sections are covered with a mica sheet and irradiated in a USGS research reactor. The decay of the uranium etches the mica, which can be seen using a microscope. Fission-track radiography was performed on polished thin sections. This technique provides a unique means to identify the mineralogical associations of uranium. Fission-track analyses indicated that uranium resides in mineral coatings on grain surfaces. Fission tracks were 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.

Column test data were simulated using one-dimensional (1D) numerical models that incorporate multispecies chemical equilibrium and rate-limited desorption. 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.

FY 2017 Activities: This study was completed in FY 2017. The results are documented in the project report *Plume Persistence Final Project Report* (DOE 2017a). A summary of the report findings is presented below.

Answering the study questions involved the use of selective chemical extractions (uranium amounts and where the uranium resides with depth), fission-track radiography with thin-section petrography (how and where does uranium reside on the microscopic scale), X-ray diffraction (uranium association with mineralogy), column testing (uranium release rates), and reactive transport modeling (uranium release mechanisms and influence on groundwater remediation strategies).

The selective extraction data indicate an increasingly effective removal of uranium with increasing aggressiveness of the leaching and digesting solution technique from carbonate leach to 5% nitric acid leach, to microwave digestion, to total digestion. It is likely that the 5% nitric acid leach removes the majority of uranium sorbed to mineral surfaces; however, definitive association of the uranium associated with each selective extraction versus the mineralogy could not be interpreted. The selective extraction data identified higher uranium concentration zones at the site that have secondary uranium deposited due to the uranium mill processes (1) above the water table (most common), (2) below the water table in limited areas and likely associated with gypsum, and (3) near and below the water table in association with organic carbon.

Fission-track radiography results indicate that uranium in the solid-phase samples is associated with (1) heavy mineral grains (i.e., monazites), (2) organic carbon, and (3) mineral coatings and cements that function as intragranular material, likely composed of iron oxyhydroxides or clays, or both.

Column test data showed an initial spike of uranium concentrations with the peak value related to the overall uranium content of the sample. After the peak concentration, uranium continues to be released, providing strong evidence for possible field scale plume persistence issues. Stopping the flow during the column tests indicated nonequilibrium conditions for uranium release within the columns, but the column flow velocities were much faster than field velocities. Most of the column tests only analyzed uranium in the column effluent water, but a larger column test was conducted to perform additional geochemical analyses. The larger column test results indicated gypsum was dissolved based on the increase of calcium and sulfate concentrations in the column effluent water. The presence of gypsum was confirmed by the X-ray diffraction data. The data from this column were used for reactive transport modeling and an evaluation of geochemical processes.

Reactive transport modeling of the column test results evaluated a variety of geochemical processes to assess which processes were most important. Sorption and dual porosity were the most important processes for calibrating modeled uranium data to measured column data. However, modeled sulfate and calcium concentrations were too low without the addition of gypsum. The modeling efforts showed a low sensitivity for dispersivity and some minor improvement with the addition of cation exchange. However, dispersivity may be an important parameter to include at the field scale.

Upscaling from the column tests to typical groundwater flow velocities was tested with the final calibrated reactive transport model. At the slower groundwater velocities similar to those in the field, the dual porosity (nonequilibrium) influences seen in the column test with higher velocity did not exist. Flow velocities are an important consideration when evaluating plume persistence under natural flow gradients and comparing possible remediation strategies. The use of groundwater tracer tests at the field scale was recommended for getting the best parameter estimates for reactive transport modeling, which can then provide a tool for testing possible remediation approaches before full implementation and provide significant cost savings.

4.3 Persistent Secondary Contaminant Sources

Overview: The Persistent Secondary Contaminant Sources (PeSCS) long-term study is a continuation of the work performed as part of the Plume Persistence long-term study (Section 4.2). PeSCS was initiated in FY 2017; its objectives are to better understand the existence and influence of PeSCS on groundwater quality. While uranium mill tailings are a primary uranium source for groundwater contamination, several LM sites have elevated uranium concentrations decades after the mill tailings have been removed. These plume persistence issues are likely related to PeSCS that can delay natural flushing beyond a target period (such as the 100-year time frame) and may require a change in LM site conceptual models, associated predictive numerical models, and accepted groundwater compliance strategies.

Four main PeSCS are the focus of the PeSCS long-term study. They include:

- Surficial and subsurface precipitation of contaminant-bearing evaporites
- Naturally reduced zones (NRZs) that have elevated uranium concentrations
- Sorbed contaminants that can delay natural flushing and active remediation
- Dual-domain processes at multiple scales that can delay natural flushing and active remediation

The objective of the PeSCS long-term study is to expand upon previous work to achieve the following:

- Gain a better understanding of where and why secondary contaminant sources occur
- Develop estimates of secondary contaminant release rates through data and modeling
- Use these release rate estimates to evaluate natural flushing rates and possible alternate concentration limit exceedances
- Build a set of modeling techniques that can help evaluate these release rates at multiple LM sites
- Use these modeling techniques to evaluate remedial alternatives

The main project questions are as follows:

- How and where do contaminants (focusing on uranium) reside in the subsurface and on the aquifer solids?
- What are the contaminant amounts and release rates?
- What are the contaminant release mechanisms?
- How do the processes related to these three questions influence groundwater quality?

Prior Activities: Prior work on this topic was completed under the completed Plume Persistence long-term study, which is summarized in DOE 2017a. This prior work established techniques that are now being used as part of the PeSCS long-term study and helped to identify the four main secondary contaminant sources listed in the Overview Section (Section 5.2.1).

FY 2017 Activities: The PeSCS long-term study is divided into five tasks as presented in the following sections.

Literature Review

A detailed literature review was initiated in summer 2017 to summarize existing reports at LM sites that document plume persistence and secondary contaminant source issues. In addition, this literature review will compare LM sites with other legacy uranium mill sites provided in the literature, along with organic contaminant sites that have plume persistence issues. A full LMS series report on the literature review results is planned for FY 2018.

Fieldwork

The Grand Junction site and Riverton site are the current focus of field studies. At both sites, detailed coring has already provided data on locations and depths with higher uranium concentrations in the solid phase. At the Riverton site, these coring locations were instrumented with multilevel groundwater wells in fall 2015. Since their installation, sampling has been ongoing. These wells were sampled immediately after flood events in May 2016 and June 2017, which provided valuable data on uranium release rates. Samples were collected by the USGS personnel in the Riverton office and were sent to the ESL for analyses. Thorough data analyses and geochemical modeling of the Riverton site multilevel well data have been initiated in FY 2017, but the majority of that work should take place in FY 2018.

At the Grand Junction site, solid phase analyses were collected as part of the Plume Persistence long-term study. These data were used to identify three locations for groundwater tracer testing, which will be completed in collaboration with Dr. Paul Reimus from the Los Alamos National Laboratory. Dr. Reimus has expertise in doing groundwater tracer testing and gave an internal presentation in February 2017 to introduce the planned techniques. Each location has different solid-phase geochemistry with higher uranium concentrations including: (1) evaporites in the unsaturated zone, (2) an NRZ with higher organic content, and (3) a zone below the water table with gypsum. Groundwater tracer testing will inject Gunnison River water mixed with multiple tracers as outlined in a detailed work plan (DOE 2017b). Initial well installations have been completed, and tracer injection will occur in FY 2018. During and after the tracer injections, tracer movement and geochemical analyses will be used to assess the direction and rate of movement for groundwater flow, along with the fate and transport of uranium. The field data will be compared with laboratory data discussed below to determine any uranium mobility differences due to scale. All of these data will be used to better determine the secondary uranium sources along with potential release rates and mobility. These data will provide important input parameters for future uranium fate and transport modeling efforts.

In leading up to the full-scale tracer testing, a single borehole injection with lithium bromide was completed in March 2017. The natural movement of this conservative tracer was traced using a direct-push sampling method that allowed for groundwater sampling at multiple depths several feet away from the borehole. This method demonstrated that the direct-push approach can be useful for collecting groundwater samples to track tracer movement. For the full-scale tracer testing, initial data will be collected from monitoring wells, but longer-term tracer and contaminant movement can be tracked using the direct-push approach. This direct-push technology was completed to demonstrate the use of a drilling stem that can collect water samples and detect changes in electrical conductivity with depth (due to solid phase or water phase changes). Analyses of this single borehole injection are ongoing and will be published as a master's thesis in FY 2018.

The Riverton site is also scheduled for groundwater tracer testing in late in FY 2018 with an associated work plan to be completed several months beforehand. Discussions on detailed work plans and initial permitting efforts are underway. Tracer testing at the Riverton site will likely focus on uranium transport from evaporites in the near surface silt layer. Past flooding appears to cause a spike in uranium concentrations in the underlying sand and gravel aquifer due to evaporite dissolution. This mechanism can be confirmed by a flood irrigation tracer test using river water and conservative tracers to track subsequent groundwater flow and uranium mobility.

Laboratory Work

With detailed solid phase testing at the Riverton site in fall 2015, splits of the core samples were saved for later analyses. These cores have been tested by repacking them into a column and testing the resulting effluent with a variety of influent solutions. The Riverton site column testing can provide insight into uranium release rates, concentrations, and mechanisms. This testing procedure is also applicable at multiple LM sites. The Riverton site column testing was completed in FY 2017, with a final report planned for FY 2018 that will include detailed interpretations and geochemical modeling results. These results will be useful in designing the planned field-scale tracer testing at Riverton site.

In support of the upcoming tracer tests, a new high performance liquid chromatograph (HPLC) was purchased and set up in the ESL. This HPLC will be used to analyze upcoming tracer test samples for multiple new analytes. Software installation and development of analytical procedures were completed in FY 2017.

Fission-track radiography (Section 4.2) is being conducted on Riverton site samples to assist in identifying secondary contaminant sources. Initial interpretations have been completed in FY 2017 with much of the work being completed by a CMU intern. Work planned for FY 2018 includes additional analyses using a scanning electron microscope to better identify the makeup of grain coatings. Technical articles on these techniques and interpretations are planned for FY 2018.

Modeling

The majority of work on the modeling task will be initiated in FY 2018 for both the Grand Junction and Riverton sites as groundwater tracer testing data are collected. Initial geochemical modeling has been completed for the Riverton site column tests and multilevel well data.

Reporting and Outreach

This task is intended to provide PeSCS results to a wide audience. In FY 2017, this was accomplished through conference presentations and outreach to CMU. Outreach to CMU included lecturing at an applied geochemistry course in spring 2017 and a lecture on the Riverton site on March 28, 2017. These lectures were part of the Educational Collaboration initiative (Section 4.8) and ongoing meetings are planned for continued student interaction in FY 2018. The presentation given in March 2017 was highlighted in the LM Program Update for the second quarter of 2017. In addition, interactions with CMU helped lead to the hiring of an intern to assist with thin-section and fission-track radiography work. The PeSCS work has benefitted from mineralogic interpretations from CMU professors, and the CMU students have benefitted from interactions with scientists working on the PeSCS project.

The following is a list of presentations, proceedings articles, and abstracts that were given or submitted in FY 2017 with current status and the related task:

- Dam, W.L., A. Gil, R.H. Johnson, S. Campbell, J.R. Bargar, and M. Picel, "Long-Term Stewardship at a Former Uranium Mill Tailings Site in Riverton, Wyoming"

  Presentation and proceedings article given for the 2017 Waste Management Conference, Phoenix, Arizona, March 6–9 (Task 2; this work included multilevel sampling data and interpretations from Riverton)

- Rice, R. and M. Schulmeister, "Development of a New, Direct-Push-Based, Geophysical and Geochemical Approach for Groundwater Tracer Tests"

  Abstract accepted to the National Groundwater Association 2017 Groundwater Summit, Nashville, Tennessee, December 4–7 (Task 2)

- Johnson, R.H., P.W. Reimus, A. Tigar, S. Morris, K. Tafoya, W. Dam, W. Frazier, R. Bush, and S. Campbell, "Multiple Tracer Testing Approaches for Improved Groundwater Flow and Reactive Transport Modeling Input Parameters"

  Abstract accepted to the National Groundwater Association 2017 Groundwater Summit, Nashville, Tennessee, December 4–7 (Task 2)

- Johnson, R.H., A. Tigar, S. Morris, S. Campbell, K. Tafoya, R. Bush, and W. Frazier, "Column Tests and Multilevel Well Geochemistry to Explain Contaminant Plume Persistence Issues Downgradient of a Former Uranium Mill Site"

  Abstract submitted to the 11th International Conference on Acid Rock Drainage and the 2018 International Mine Water Association Annual Conference, Pretoria, South Africa, September 10–14, 2018 (Tasks 2 and 3)

- Johnson, R.H., P.W. Reimus, R. Bush, and W. Frazier, "Understanding Uranium Plume Persistence Processes at a Former Uranium Mill Tailings Area Through the Use of Laboratory and Field Methods"

  Abstract submitted to the Conference on Remediation of Chlorinated and Recalcitrant Compounds, sponsored by Battelle, April 8–12, 2018, Palm Springs, California (Tasks 2 and 3)

- Ranalli, A., R.H. Johnson, and R. Bush, "Uranium Plume Persistence at U.S. Department of Energy UMTRCA Sites"

  Abstract submitted to the Conference on Remediation of Chlorinated and Recalcitrant Compounds, sponsored by Battelle, April 8–12, 2018, Palm Springs, California (Task 1)

In addition, a presentation titled "Zooming in for a Microscopic View of Uranium Plume Persistence" was given at the September 7, 2017, AS&T semiannual update meeting. This talk highlighted interpretations of secondary contaminant sources at the Riverton site based on solid-phase analyses, multilevel groundwater data over 2 years, and new fission-track radiography interpretations.

SLAC Collaboration

The current focus of SLAC research is on uranium cycling associated with an NRZ at the Riverton site. This work has focused on detailed analysis of soil core and pore water in and above an identified NRZ that also has a multilevel well nearby. SLAC research has provided companion data on uranium concentrations in evaporites above the NRZ and uranium sorbed to organics within the NRZ that couples directly with PeSCS work. This includes the identification of uranium concentrations in the solid phase and pore waters before and after the May 2016 and June 2017 flooding events. Sequential extraction work by an SLAC researcher (Roycroft 2017) helped determine the solubility of uranium in the evaporites and discovered that uranium was redeposited in the unsaturated silt layer above the NRZ within 2 months. These data will be used directly in the PeSCS work to assist in evaluating uranium release rates, groundwater uranium concentrations, and remaining secondary source concentrations before and after flooding events. Pore water and solid phase sampling by SLAC is ongoing at the Riverton site. The results of the collaboration with SLAC researchers is documented in Task 5 above (Dam et al. 2015) and in the following list of publications and presentations with LM and LMS scientists as coauthors.

Publications:

- Noël, V., K. Boye, S.E. Bone, K. Maher, J.S. Lezama-Pacheco, E.L. Cardarelli, W.L. Dam, R.H. Johnson, and J.R. Bargar, 2017. "Redox Constraints on U Mobility in the Floodplains of Upper Colorado River Basin," *Environmental Science & Technology* (in review).

Invited talk:

- Bargar, J.R., V.N. Noël, S. Bone, S. Roycroft, K.H. Williams, W. Dam, and R. Johnson, 2017. "Redox, Hydrological, and Molecular Controls over Uranium Mobility in Redox-Variable Aquifers," presented at the Goldschmidt Geochemistry Conference, Paris, France, August 15 (keynote).

Presentations:

- Boye, K., V. Noël, C. Bobb, E.L. Cardarelli, W.L. Dam, R.H. Johnson, R. Kukkadapu, M. Tfaily, L. Pasa-Tolic, S. Fendorf, C.A. Francis, K. Maher, and J. Bargar, 2017. SLAC Science Focus Area: "Hydrologically Driven Process Coupling Between Biogeochemical Cycles and Solute Transport in Transiently Saturated Sediments at the Riverton Site (Wyoming)," presented at the 2017 Environmental System Science Principal Investigators Meeting, Potomac, Maryland, April 26 (poster).
- Noël, V., K. Boye, J. R. Bargar, K. Maher, S.E. Bone, E. Cardarelli, W.L. Dam, and R.H. Johnson, 2016. "Biogeochemical Constraints on Uranium Cycling in Redox Active Floodplain Sediments," presented at the American Geophysical Union Fall Meeting, San Francisco, California, December 14 (oral).
- Roycroft, S.J., V. Noël, K. Boye, C. Besancon, K.L. Weaver, R.H. Johnson, W.L. Dam, S.E. Fendorf, and J. R. Bargar, 2016. "Hydrologic and Temporal Influences of Evaporite Minerals on the Vertical Distribution, Storage, and Mobility of Uranium," presented at the American Geophysical Union Fall Meeting, San Francisco, December 14 (oral).

SLAC researchers have published extensively on their findings at the Riverton site. While some of these publications satisfy basic research needs for the SLAC funding agencies, processes that control uranium mobility provide important information for PeSCS work on uranium release rates and concentrations at Riverton and other LM sites. The following highlights a few of those publications and an invited talk:

Journal publications:

- Bone, S.E., J.J. Dynes, J. Cliff, and J.R. Bargar, 2017. "Uranium(IV) Adsorption by Natural Organic Matter in Sediments," *Proceedings of the National Academy of Sciences of the United States of America*: 114(4):711–716, digital object identifier (DOI): 10.1073/pnas.1611918114.
- Boye, K., V. Noël, M. Tfaily, E.L. Cardarelli, S.E. Bone, K.H. Williams, J.R. Bargar, and S. Fendorf, 2017. "Vulnerability of Thermodynamically Constrained Carbon Within Floodplain Sediments," *Nature Geoscience*, 10:415–419.
- Dublet, G., J.S. Lezama-Pacheco, J.R. Bargar, S. Fendorf, N. Kumar, G.V. Lowry, and G.E. Brown, 2017. "Partitioning of Uranyl Between Ferrihydrite and Humic Substances at Acidic and Circumneutral pH," *Geochimica Et Cosmochimica Acta* (in press), https://doi.org/10.1016/j.gca.2017.07.013.
- Noël, V., K. Boye, R.K. Kukkadapu, S.E. Bone, J.S. Lezama-Pacheco, E.L. Cardarelli, N. Janot, S. Fendorf, K.H. Williams, and J.R. Bargar, 2017. "Understanding Controls on Redox Processes in Floodplain Sediments of the Upper Colorado River Basin," *Science of the Total Environment*, 603–604:663–675.

Invited talk:

- Bargar, J.R., S.E. Bone, J. Cliff, J. Dynes, N. Janot, and V. Noël, 2017. "Molecular Controls over Uranium Mobility in Complex Redox-Active Sediment Systems," presented at the 253rd American Chemical Society National Meeting, San Francisco, California, April 3.

4.4 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 datasets.

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:

- Improved ability to manage the sites, including improved understanding of site characteristics, identifying and diagnosing problems, and making timely repairs or adjustments
- Reduced health and safety risk
- Cost reductions
- Temporally continuous data and real-time data availability
- Expedited corrective actions
- Reduced fuel consumption and greenhouse gas emission reduction

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.

Traditionally, water levels and other field measurements are obtained every quarter or every year during groundwater monitoring events at LM sites. These discrete events only provide a "snapshot" in time of water levels or other groundwater parameters. Many SOARS monitoring instruments take measurements at intervals of 30 minutes or less, allowing scientists to observe transient groundwater responses to external stresses such as rain events, floods, or groundwater pumping. These transient data provide significant insight into aquifer hydraulics and can be used to refine site groundwater flow models and site conceptual models.

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, 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 92 solar panels. Data are downloaded daily through 23 internet protocol (IP) cell modems and four landline IP connections. Onsite communication with the modems is accomplished using 111 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 2017 Activities: AS&T operated SOARS continuously through FY 2017 with relatively few issues. Web access to the SOARS system was functional more than 98% of the time. Dataloggers and radio links functioned well. AS&T 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. AS&T 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 4.5). Regularly scheduled and alarm-driven calibration checks were conducted on field instruments at many sites. Most instruments continued to maintain their calibrations and functioned properly. Instruments were regularly lab tested and calibrated before installation or reinstallation at field sites. AS&T replaced outdated or nonfunctional equipment during maintenance trips. New technology is continually researched so SOARS stays current as technology improves; this includes wireless instrumentation and sensors, multiparameter sensors, and improved communication techniques. Before any new technology is deployed by SOARS at LM sites, it undergoes laboratory testing to confirm functionality and the manufacturer's specifications. Software for data collection and datalogger operating systems was kept up to date with the latest versions. Support for site activities and operations are a top priority, and these were always given immediate attention to maintain the flow of quality data.

A continuing emphasis in FY 2017 was on maintaining the quality of SOARS data that are accessed by the DMAV programs (Section 4.5). DMAV programs are also used to identify, erroneous SOARS data that are subsequently entered into a corrections database. The corrections database is detailed in Section 4.5. Erroneous data can result from field issues such as power interruptions, equipment malfunctions or inadvertent disturbance to the instruments by field personnel. When anomalies are identified in incoming data and subsequently verified as erroneous, these data are documented in the corrections database. Currently, the corrections database has more than 21,000 entries. AS&T's continuing effort to maintain the corrections database results in high-quality data that can be used with confidence to evaluate site conditions. Before the advent of DMAV programs, erroneous site data were manually removed or corrected, which was time-consuming. DMAV 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. Continued cooperation with Cyber Security will ensure a secure and robust system across all instrumented sites.

A new station was installed at the Mexican Hat site to monitor erosional features on the disposal cell cover side slope with a webcam and meteorological sensors. Precipitation is the most important measurement at Mexican Hat, as intense rainfall events may be the catalyst for development of the erosional features. As a result, a new Doppler radar based sensor was installed along with a traditional tipping bucket precipitation gauge to evaluate new technology, reduce maintenance requirements, and potentially increase measurement accuracy.

Larger solar panels and batteries were installed at many sites to provide increased power for newly installed heated tipping buckets. These sites and the SOARS program will benefit from these new instruments as they do not require propylene glycol (antifreeze) in the winter to operate, which reduces travel requirements for maintenance, increases measurement accuracy, and eliminates a potential contaminant at the sites.

A new meteorological station, upgraded SOARS stations, and wireless transducers were installed at the Tuba City site. The Tuba City site has three pumping wells that are monitored by pressure transducers and ultrasonic flow meters to provide scientists with remote access to real-time water level and flow measurements through the SOARS system and give them the ability to control the pumps remotely. The wireless transducers are installed in 12 monitoring wells.

Four new SOARS stations were installed to acquire soil profile data at the Crested Butte site, which is part of the LM Scientific Focus Area (SFA) program. These sensors measure pore water matric potential, volumetric moisture content, temperature, and bulk soil electrical conductivity. These data are communicated back to the router station. The Rocky Mountain Biological Laboratory also received assistance with maintaining its meteorological stations, and the Small Business Innovation Research program received assistance with field hardware and testing of an experimental snow water equivalent plate continued.

Improvements were made to the Monticello site SOARS systems to provide improved accuracy of Pond 4 water level measurements by installing a new stilling well in the northeast corner of the pond and adding conductivity, temperature, and depth sensors. Three new manual download transducers were installed in wells adjacent to Montezuma Creek. Panasonic Toughpads were purchased, tested, set up, and distributed to the Monticello site team to allow remote access to the groundwater transfer building system SOARS data and remote operation of the system.

An overview of the SOARS program was presented at the March 21, 2017, AS&T semiannual update meeting.

4.5 Data Mining, Geochemical Analysis, and Project Visualization

Overview: The motivation for developing DMAV computer applications was the need to rapidly visualize large amounts of data from multiple databases. Databases currently used by LM and LMS project personnel include Site Environmental Evaluation for Projects (SEEPro), Environmental Quality Information System (EQuIS), SOARS, Supplemental, SOARS Calibration Access, and data from field dataloggers. Data also come from offsite repositories such as the USGS Water Services and the National Uranium Resource Evaluation 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 using datasets 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.

Interpretations of subsurface data often are based on small subsets of data. Using a larger dataset provides additional constraints that can improve interpretations. The human mind is better able to process and interpret large datasets if the data are crafted into suitable visualizations. Statistical approaches can also be used to help make sense of large datasets. Although many computer programs that can produce visualizations and perform statistical data operations are available commercially, 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:

- It is a relatively easy language that was designed for scientific programming.
- It is used by scientists worldwide.
- It has a long history (it was first developed in the mid-1980s).
- Many useful functions and procedures are available with IDL.
- It is well suited to visualizations.
- It has a data-mining module.
- It interfaces with other common programming languages.
- It is 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 4.4). The SOARS data include (1) downhole data (e.g., water levels, specific conductance, 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 are 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 long-term study (Section 4.1). 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 (corrections database). 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 4.4). The raw data are always maintained so that refined data can be readily compared to the original. This corrections database is regularly maintained. Without these corrections, the SOARS data are difficult to interpret because of “noise” that can compromise data quality. Corrections should be made immediately following any field or datalogging 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: Eighteen DMAV apps were completed and were partially beta tested. Calibration data were mined from the SOARS Calibration Access database and the SEEPro database. All apps had menu-driven, user-friendly interfaces. Apps were put on Citrix so they can be accessed by personnel through the internet. 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. Maintenance of networks and Citrix needed for DMAV apps continued in FY 2016. Beta testing and bug fixes continued.

FY 2017 Activities: In FY 2017, 10 new apps were written and partially beta tested: (1) ESL electronic data deliverable (EDD), (2) ESL Load, (3) ESL Search, (4) ESL Supplemental, (5) Map Utility, (6) Reports Shiprock Treatment System, (7) Search By Database, (8) Search EQuIS, (9) SOARS Fast Contours, and (10) Update Files. A few former apps were discontinued or replaced. There are currently 30 apps in the DMAV app store (Table 9). These apps use network connections to the databases and are retrieving the most currently available data. Maintenance of networks and Citrix that was needed for DMAV apps continued in FY 2017. Beta testing and bug fixes continued. A major effort this fiscal year was to migrate apps to a new generation of app programming. The new generation includes two major improvements: (1) an additional set of structured query language (SQL) queries now access EQuIS in addition to SEEPro and (2) utilization of a new framework that strives to encapsulate all queries in a set of object-oriented IDL classes.

Table 9. DMAV Apps

Program Name	Snapshot
Baseline Comparisons	Compares chemical results for 2 years to assess cleanup rates
ESL EDD	Makes electronic data deliverables (EDDs) from ESL data
ESL Load	Loads data from laboratory spreadsheets into the ESL database
ESL Search	Provides a table of data mined from the ESL database
ESL Supplemental	Populates the Supplemental Database with data from the ESL
Histograms	Histograms
Map Utility	Makes quick plots and provides coordinates of GIS shape files
Profiles Spatial	Makes contour and bubble plots of 3D data
Profiles Stickball	Makes stickball plots of 3D data
Profiles Vertical	Makes XY plots of 3D data
Profiles Statistics	Makes box plots and statistical tables of well profile data
Reports Energy	Reports energy consumption for LM facilities
Reports Monticello Treatment System	Analyzes the Monticello pump-and-treat system with features including water balance of the evaporation pond
Reports Pumping	Makes real-time reports of pumping rates and masses of contaminants removed at LM pump-and-treat systems
Reports Rainfall	Makes real-time reports of rainfall at LM facilities
Reports Shiprock Treatment System	Analyzes the Shiprock site pump-and-treat system with features including water balance of the evaporation pond
Reports Wind	Makes rose diagrams of SOARS wind data

Table 9. DMAV Apps (continued)

Program Name	Snapshot
Search By Database	Compares data in the SEEPro and EQuIS databases
Search EQuIS	Provides a table of results from the EQuIS database
Search Master	Provides a table of results from the SEEPro, EQuIS, SOARS, Supplemental and other databases
SOARS Contours	Provides contour visualizations of SOARS groundwater elevation, specific conductance, and temperature data
SOARS Fast Contours	Provides contour plots of data in real time (5-minute intervals) for assessing the progress of system pump tests (currently limited to Monticello)
SOARS Maintenance	Makes timeline plots of SOARS data; used extensively for quality assurance and input to a “Corrections” database
Spatial Chemistry	Makes contour and bubble plots of groundwater chemical data
Timelines	Time plots using data from SEEPro, EQuIS, SOARS, and the Supplemental Database
Update Files	Set of programs used to populate the data warehouse (used only by system administrators)
Uranium Isotopes	Makes plots of activity ratios (uranium-234 to uranium-238) versus uranium concentration and compares with standard mixing curves
Water Isotopes	Makes plots of $\delta^{18}O$ versus δD and compares to meteoric water curves
Well Construction	Depicts multiple well constructions hung by elevation
XY Plot	Correlates two parameters on XY plots

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

New Apps

Several apps were written to support a database for the ESL, which has been analyzing samples for many years and keeping the results in Excel spreadsheets. Some electronic files from earlier years are lost or misplaced. Although records are available for all data that have been collected in the ESL, it is scattered and difficult to search. Also, the detail that goes into the data spreadsheets varies. For these reasons, it seemed useful to develop an easily searchable database that contains all of the ESL data. A mySQL database was developed to store the data, and four apps were developed. The ESL Load app reads laboratory spreadsheets and imports the contents to the ESL database. Some restructuring of the spreadsheets is normally required before using this app. A lexicon is used to ease the burden of restructuring. The lexicon interprets various uses of terms so that database entry personnel are not required to modify to a set of common terms. For example, temperature may be entered in the spreadsheets as “Temp,” “temperature,” “TMP,” and so on. The ESL EDD app extracts data from the ESL database and imports it to an EDD that can be sent directly to the SEEPro and EQuIS data entry personnel. It can be tailored to meet any electronic data format that is required. The ESL Supplemental app extracts data from the ESL database and imports it to AS&T’s Supplemental Database. By this means, ESL data can be directly used and displayed by other DMAV apps.

The Map Utility app provides a user-friendly platform to perform a variety of functions to help interface apps with spatial data. User-prepared spreadsheets are read in, and the following can be quickly accomplished: converting from state plane to latitude and longitude coordinates and vice versa, creating state plane shape files from latitude and longitude coordinates (useful for creating shape files from Google Earth data), and displaying shape files. The app is adaptable: As additional needs arise, new functionality can easily be implemented.

Three apps were developed that export data from the various databases and provide it on screen. As with all apps, the data can also be exported to a file that can be opened by other programs such as Excel. The Search EQuIS app simply searches the EQuIS database. It is meant to be used on an interim basis while the EQuIS front end is being developed by informational technology (IT) personnel. It provides an easy and nearly instantaneous way to view a user-defined set of data from EQuIS. The Search By Database app extracts a set of user-defined data from both the EQuIS and SEEPro databases so they can be compared. During the transition from SEEPro to EQuIS, some data are only in SEEPro, while other data are only in EQuIS. This app provides a quick means of determining which database holds a specific set of data. The Search Master app was improved during this performance period. Searches are made by one of the following "data types": groundwater, surface water, treatment systems, water levels, datalogger data (non-SOARS), computed values, PHREEQC values, solids chemistry, weather data, energy usage, river gage, and soil moisture. These data are extracted from all of the databases and the DMAV data warehouse.

The Shiprock Treatment System app provides data from the Shiprock site pump-and-treat system. A user can view water level data from the 52 wells that are monitored by SOARS. Monthly flow rate data from the 19 pumping locations are available. Cumulative flows for any combination of wells can be plotted. Water balance data for the evaporation pond are available in the following forms: water volume in the pond, water depth and elevation in the pond, and evaporation rate calculated in three ways (using the Penman theoretical equation, using measured pan evaporation rates, using the difference between the inflows plus rainfall and the pond volume changes). All visualizations include critical points such as the elevation at which the pond will overflow. Another graph provides timeline estimates of when overflow will occur.

The SOARS Fast Contour app was designed to monitor fluctuation of water table elevations during pumping tests conducted at the Monticello site pump-and-treat system during summer 2017. A user-defined set of dates and times are contoured. Data are updated at 5-minute intervals so the system is being viewed in near-real time. An option is available that uses differences from a baseline established before pumping started in lieu of absolute elevations. This option produces color contour visualizations that clearly define the pumping locations. Another option allows the user to omit specific wells. By omitting the pumping wells, details of the non-pumped areas are more visible. Flow vectors are also available and help to define the groundwater flow network.

The Update Files app provides the system administrator with a user-friendly interface to run the 38 programs that populate the DMAV data warehouse. Some of the database mining tasks involve numerous computations and are too computer intensive to run in real time. In these situations, AS&T uses the Update Files app to run the programs and populate the data warehouse during off hours. The other DMAV apps can efficiently pull data from the data warehouse rather than having to run them in real time. Some examples of data that are handled by the Update Files app follow:

- Uranium data are entered in the databases in their chemical forms and as isotopic components. Users often wish to display the uranium data as a common type. To accomplish this, one of the Update Files programs extracts all of the uranium data regardless of type, makes the necessary conversions, and imports the calculated results to a data warehouse table.

- Compilation of multilevel sampler data from SEEPro, EQuIS, and Supplemental databases. Multilevel sampler data are identified in the database as having the same site code, different location codes, the same (or nearly the same) coordinates, screens at different depths, and sampling for the same analyte from at least two depths on the same (or nearly the same) date and time. Extracting the data using these criteria is time-consuming and provides a good example of the use of data warehousing.
- Data from USGS river gaging stations are downloaded in real time by the DMAV apps. However, to avoid excessive URL connection and download times, the data are archived in the data warehouse. Thus, apps only need to import the most recent data, limiting the internet connection time to the USGS website.

Migration of Apps to EQuIS Compatibility

Many of the DMAV apps were written before the migration from SEEPro to EQuIS. Thus these apps required migration to be compatible with EQuIS. This migration mainly involves coupling Microsoft SQL queries with the existing Oracle SQL queries. Most of the migration was completed in FY 2017. Only four apps remain to be migrated. The migration involves not only adding the addition of SQL queries but also major restructuring of each app to a new system architecture. The main feature of this new architecture involves encapsulation of the database queries in specialized IDL classes. Previously, most of the queries were embedded in each individual app. The new classes contain more universal queries that can be used with all apps. Triplet queries are needed each time a query is accessed: an Oracle query to mine SEEPro, a Microsoft SQL server query to mine EQuIS, and a mySQL query to mine the Supplemental database or the data warehouse. Other queries are also needed to mine SOARS data and the SOARS calibrations. The new structure will enhance AS&T's ability to debug and add new features to the apps.

New Features to Apps

Many new features were added to the apps during this fiscal year. Many of these came at the request of users. Some selected examples follow:

- A "crosshairs" was added to the SOARS Maintenance app. Using the mouse, a crosshairs can be placed on a specific data point on the graphic to read the X and Y values of that point.
- Previously, the PHREEQC modules were run using all major ions but did not include nitrate. Unlike most groundwater data, nitrate is a major contributor to ionic strength in some of the samples from the Shiprock site. Because ionic strength (calculated by PHREEQC) was being used as a surrogate to specific conductance for the Variation Project, nitrate was added to PHREEQC calculations run by the apps.
- User-defined "Project Names" and "Groups" were added to some apps. Project Names are used to encapsulate a set of samples to be acted on by the apps. For example, the "AMB01 201608"' project has all the data that were sampled for the Variation Project from Ambrosia Lake for a sampling event in August 2016. Groups are used to specify sets of locations for a site. For example, the group "Fault Wells" for the Bluewater site refers to a set of wells that are near the faults as characterized by the site lead. Both Project Names and Groups have been extremely valuable by enabling rapid visualizations of associated data.

Supplemental Database
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., Garvin 2012; Robertson et al. 2016), including the Integrated Field Research Challenge work at the Old Rifle site, often produce data that are useful to LM projects but are not commonly entered into the SEEPro or 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 included (1) chemical data from the Variation Project Phase II, (2) miscellaneous data from the ESL, and (3) additional Riverton site multilevel samples.

Communication
A demonstration of the DMAV apps was given at the LM office at Westminster, Colorado, in July 2017. Numerous one-on-one and small group tutorials were provided to various users.

4.6 Long-Term Cover Performance

Introduction: LM is responsible for postclosure stewardship of 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 2016e).

LTCP consists of five 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
- Study 5: Aeolian Deposition on Covers

LTCP 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, biological uptake, 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 1000 years to the extent reasonably achievable" (Title 40 *Code of Federal Regulations* Section 192 [40 CFR 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 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. Taproots 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 may begin with freeze-thaw and desiccation cracking, retention of borrow soil structure during construction, and biointrusion. Postconstruction 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 ET, 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 ET 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.

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

Overview: This study will improve LM's understanding of the effects of natural ecological and soil-forming processes on cover engineering properties. Previous research demonstrated how soil-forming processes create structure or 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, there is 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, and microbial feedbacks evolve in cover systems and the 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 analog 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. Both large-scale and conventional-scale radon flux chambers were used. 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. The research team is 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 10). 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. The research team 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 fieldwork at the first test site.

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 the research team used previously to measure effects of pedogenic processes on soil hydraulic properties. The following two methods for measuring radon were compared: (1) an activated carbon (AC) sorbent and (2) a solid-state electronic radon detector (also called a RAD7 unit). Researchers modeled radon diffusion to determine the appropriate sorption and detection period and chamber size to ensure the accuracy of radon flux measurements. A 1D 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.

Table 10. Research Team for the AS&T Study Area—Effects of Soil-Forming Processes on Cover Engineering Properties

AS&T Study Area Research Team	
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[c] School of Engineering and Applied Science University of Virginia	Aaron Tigar, research assistant Applied Studies and Technology Navarro Research and Engineering, Inc.
David Dander[a] Project Services Navarro Research and Engineering, Inc.	Kuo Tian, PhD[b] Civil and Environmental Engineering University of Virginia
Mark Fuhrman, PhD[b] Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission	Xiadong Wang[b] Geological Engineering University of Wisconsin–Madison
William Likos, PhD[b] Geological Engineering University of Wisconsin–Madison	William Waugh, PhD[a] Applied Studies and Technology Navarro Research and Engineering, Inc.
Alex Michaud, graduate student[b] Geological Engineering University of Wisconsin–Madison	Morgan Williams, PhD candidate[a] Department of Geography University of California–Berkeley

Notes:
[a] Funding through LM
[b] Funding through Office of Nuclear Regulatory Research, NRC
[c] Funding through Consortium for Risk Assessment with Stakeholder Participation, DOE

In FY 2016, the research team (1) calibrated radon flux sensors, (2) developed a laboratory diffusion apparatus, (3) developed fieldwork control plans for the Falls City and Bluewater sites, and (4) completed field sampling for radon flux, soil engineering properties, and soil morphology for ranges of conditions on disposal cells at Falls City and Bluewater sites.

AC canisters and continuous electronic radon flux detectors (RAD7) were compared in the laboratory. Laboratory tests were 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. The AC measurements were consistently less than the RAD7 measurements. The AC canisters measured 42.0% lower radon concentrations than the RAD7 system.

Work control project teams completed fieldwork plans for Falls City and Bluewater sites. Work plans documented the work sequence, test site restoration tasks, potential dose to fieldworkers, job safety analyses, training requirements, dosimetry, cultural resource evaluation, waste management, and other safety and environmental management requirements.

Field activities at the Falls City and Bluewater sites included soil sampling and installation of instrumentation to measure radon flux on top of the radon barrier at six (Falls City site) and nine (Bluewater site) test pit locations. Most tests pits were paired, with one of the pair isolating a surface feature (e.g. deep-rooted plants) and the other a close-by control (e.g., no vegetation), with both in an area with relatively high as-built radon flux values. Flux chambers with four different cross-sectional areas were installed to assess potential scaling effects associated with soil structure. 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 and at least two thin-walled Shelby tube samples of the radon-barrier material for laboratory analyses of key soil engineering properties. Continuous (stacked) block samples of radon-barrier material were taken at test pit locations characterized by a relatively thick barrier to assess depth-dependent changes in soil properties.

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 and nutrient cycling. Analog test pits were excavated at the edge of radon-barrier borrow areas. The morphology of analog soil profiles can provide clues about how soil-forming processes might continue to change the cover in the long term (hundreds to thousands of years). In situ soil morphology was characterized in a total of 16 cover cell pits and four analog soil pits at the two sites. Bulk soil samples and core samples were collected and analyzed to allow for a spatially resolved understanding of rates and qualities of soil change, including the distribution of carbon, nitrogen, soil biota, physical architecture, and mobile solutes.

FY 2017 Activities: In FY 2017, the research team (1) selected two additional UMTRCA study sites, (2) drafted work plans for the new sites, (3) continued laboratory soil engineering and morphology analyses of FY 2016 samples (Falls City and Bluewater sites), (4) drafted test pit restoration reports for FY 2016 sites, (5) completed field work at the Shirley Basin site, and (6) presented, published, or drafted papers on results from FY 2016 field studies. A summary of the preliminary study findings was also presented at the September 7, 2017, AS&T semiannual update meeting.

Site Selection

For FY 2017, the research team selected sites with cover designs that were similar to the FY 2016 sites, but in contrasting climates. In FY 2016 a thick cover in a warm and humid climate at Falls City site was compared with a thin cover in a warm and dry climate at the Bluewater site. For FY 2017, the research team selected the Shirley Basin site, a cold and dry site with a cover design that is almost identical to Falls City site, and the Lakeview site, a cold and semiarid site with a cover that is similar to Bluewater site's. As in FY 2016, LMS organized work control project teams and drafted fieldwork plans for Shirley Basin site and Lakeview site. And as before, the work plans document the work sequence, test site restoration tasks, potential dose to fieldworkers, job safety analyses, training requirements, dosimetry, cultural resource evaluation, waste management, and other safety and environmental management requirements.

Test Pit Restoration

Reconstruction of covers in test pits at each study site is a critical final field activity at these sites. In FY 2017, LMS drafted test pit restoration reports for Falls City site and Bluewater site that document the restoration and follow-up inspections of test pits excavated on and off the cover during the study. AS&T excavated test pits at six locations on the Falls City site cover and nine locations on the Bluewater site cover. The nominal surface area impacted by the test pit excavations was less than 16 square yards on the cover and 1 square yard on the radon barrier.

The acceptability of test pit restoration with respect to meeting the original engineering design specifications was confirmed by measurements of lift depths, soil moisture contents, compaction densities, and radon fluxes before, during, and after restoration. The long-term acceptability of test pit restoration will be monitored during annual site inspections.

The radon barrier (and growth medium layer at the Falls City site) was restored primarily using excavated soil. AS&T brought in additional borrow soil as needed to replace samples removed for laboratory analyses. Cover layers were replaced in 6–8 inch, moisture-conditioned, compacted lifts. Verification testing confirmed that the radon barrier compaction satisfied a 95% of maximum dry density requirement. Lift moisture contents were adequate to achieve the compaction requirement. Radon flux values on top of the restored radon barrier surface were generally an order of magnitude less than preexcavation values, two orders of magnitude less than as-built conditions, and three orders of magnitude less than the UMTRCA standard. AS&T replaced protective layers overlying the radon barrier (bedding and rock riprap or topsoil and vegetation) with stockpiled materials from the excavation. Personnel then compacted, recontoured, and reseeded the surface.

Soil Engineering

Radon Flux Measurements at Bluewater: In FY 2017, data from in situ radon flux measurements taken at the Bluewater site in 2016 were analyzed. The research team compared radon fluxes using data from both the AC canister method and the RAD7 method. The average ratio of fluxes using AC canisters vs RAD7 detectors was 0.50, which was similar to comparisons in the laboratory. The team learned that larger exposure times and smaller flux chamber volumes both cause this ratio to decrease. It also compared flux measurements from chambers of four different cross-sectional areas to assess potential scaling effects. No significant trends were observed. Finally, the geometric mean of radon fluxes calculated at the Bluewater site was below the regulatory maximum of 0.74 becquerel/square meter-second.

Geotechnical Analysis of Bluewater Soil Samples: In FY 2017, the research team determined the saturated hydraulic conductivity for 18 large-diameter block samples (intact, undisturbed soil monoliths) obtained from the Bluewater site radon barrier in FY 2016. The geometric mean for all samples was 3.6×10^{-4} square centimeters. The team also measured radon flux for a subset of block samples to determine if the radon barrier was a significant source of radon. Radon was indeed emanating from the radon barrier material, though values were insignificant. Trimmings of the block samples were used to determine grain size distribution, plasticity, and specific gravity of the radon barrier soil. Radon barrier soil extruded in 50 millimeter (mm) increments from the thin-walled Shelby tubes also were used to develop depth profiles of water content, dry unit weight, and saturation. As expected, the radon barrier was drier in test pits with vegetation and ant borrows. Additionally, soil samples from specific depths were obtained from multiple Shelby tubes for lead-210 (^{210}Pb) analysis, as ^{210}Pb content in radon barrier samples may be a good indicator of long-term radon flux.

Development of Laboratory Diffusion Apparatus: The research team modified a radon diffusion coefficient testing apparatus, developed in FY 2016, to accept thin-walled Shelby tube (75 mm diameter) radon barrier samples. Preliminary tests of Shelby tube samples indicate that radon diffusion coefficients for clay samples compacted to known densities and degrees of saturation in the lab were in good agreement with published values and values calculated using empirical correlations. In FY 2018, the research team plans to use this modified apparatus to measure diffusion coefficients for radon barrier samples from the Shirley Basin and Lakeview sites.

Soil Morphology

Development of Conceptual Models: A comprehensive understanding of soil-forming processes was initiated across the entire UMTRCA portfolio through a review of annual site inspection reports. NUREG/CR-4504 (NRC 1986) was used to develop a matrix of keywords and key processes that correspond to soil change (with minor additions given current scientific understanding of the subject). During FY 2017, the research team reviewed annual inspection reports (or the included photographic evidence) with the incidence of these keywords annotated accordingly. With this, the team was able to track the site-to-site occurrence of observed change actors over time and understand shared trends across the portfolio as a function of time, design, climate, and management. This work is intended to ensure that ongoing site selection is representative of the portfolio and to give the research group the opportunity to extrapolate findings from detailed fieldwork to sites that share a common pedogenesis and ecological succession trajectory. The entire set of inspection reports, for all sites, has been digitized and will be reviewed in FY 2018.

Laboratory Activities: The full set of soil samples collected at the Bluewater and Falls City sites in FY 2016 was analyzed for chemical, biological, and physical soil properties. Data are being consolidated into master sheets for easy dissemination to the research group, DOE, and NRC. The team also developed a wet aggregate stability method that is suitable for high clay soils common to radon barriers. The method will allow the research group to link the observed development of soil structure with measurements of the physiochemical stabilization of emergent soil architecture. These links have implications to ongoing soil development and site performance. Tests of soil aggregates from all sites are currently in process.

Shirley Basin Site Fieldwork

The research group conducted a detailed field study September 16–30, 2017, at the Shirley Basin site. Six test pits were excavated. Field engineering activities included soil sampling and installation of instrumentation to measure radon flux. Radon flux was measured at each test pit using flux chambers, electronic RAD7 devices, and AC 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. Replicate measurements were obtained with each chamber to evaluate measurement repeatability within a subset of test pits. The research team also measured radon flux at the approximate contact between the top surface of the tailings and the radon barrier. Soil sampling at the test pits included two stacked, large-diameter block samples of radon barrier material and at least two thin-walled Shelby tube samples of the radon barrier material. In FY 2018, the team will analyze the block and tube samples in the laboratory to determine water retention characteristic curves, saturated hydraulic conductivity, radon diffusion coefficients, grain size, plasticity, and in situ water content profiles, as well as ^{210}Pb profiles at the time of sampling.

A total of nine soil profiles were analyzed for soil morphology. Focused attention was given to characterization of radon barrier morphology. Observations indicate that design assumptions about radon diffusion modeling may not accurately account for de facto as-built and emergent radon barrier heterogeneity (density, moisture, macropores, roots, mineralogy, etc.). Samples were collected and will be analyzed in the laboratory in FY 2018.

Publications, Reports, and Presentations: Below are the research group's draft and published papers and presentations. Team members also began drafting an NRC NUREG report.

Benson, C., W. Albright, M. Fuhrman, W. Likos, N. Stefani, K. Tian, W. Waugh, and M. Williams, 2017. "Radon Fluxes from Two Earthen Barriers over Uranium Mill Tailings After Two Decades of Service," *Proceedings of Waste Management 2017 Symposium*, Phoenix, Arizona.

Williams, M.M., 2016. "Patterns of Decadal Soil Change on Technogenic Soil Systems Employed for Radioactive Waste Containment," *Proceedings of the Third International Conference on Hydropedology*, Beijing, China, August 16–19, 2016 (presented by collaborator from academia).

Williams, M.M., W.H. Albright, C.H. Benson, M. Fuhrman, W.J. Likos, N. Stefani, K. Tian, W.J. Waugh, 2017. "The Spatial Extent of Evolved Soil Architecture Along a Bioturbation Sequence on an Engineered Cover for Uranium Mill Tailings Containment in New Mexico," Ninth Annual Conference on Soils from Urban, Industrial and Mining Areas, Moscow, Russia, May 22–27, 2017 (presented by collaborator from academia).

Williams, M.M., W.H. Albright, C.H. Benson, M. Fuhrmann, L.G. Larsen, W.J. Likos, W.J. Waugh. Draft "Pedogenic Process in Engineered Soil Systems: Emergence of Pedoturbation Induced Hydraulic Conductivity Gradients."

4.6.2 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 AS&T's 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.

AS&T 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, AS&T chose to conduct an empirical field study that includes a range of UMTRCA sites with wide applicability. The study's four objectives are to:

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.

This study is part of an educational collaboration with a graduate student at UA. An AS&T scientist serves as an adjunct faculty member of the student's graduate committee.

Prior Activities: AS&T and UA 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. The team 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) near the disposal cells.

Analysis of variance was used 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 sites. The region is known for soils that are naturally seleniferous, and because plants growing 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 2017 Activities: A UA graduate student and collaborators (Table 11) continued working on a revision of a manuscript for publication. Table 12 shows UMTRCA sites studied, plant species sampled, and elements of concern. The student's revised draft manuscript 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 of radium-226 activity in plant tissues for a subset of samples, (3) a literature review of seleniferous soils and plants, (4) an analysis of the potential for soil bioaccumulation of metals beneath plant canopies, and (5) a review of the Native American ethnobotany of plant species sampled.

Table 11. 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] LM Applied Studies and Technology Navarro Research and Engineering, Inc.

Notes:
[a] In-kind funding through UA
[b] Funding through Alfred P. Sloan Foundation Indigenous Graduate Partnership
[c] Funding through LM

Table 12. Plant Uptake Study Sites, Plants, and Elements of Concern

Study Site	Plant Species Sampled	Elements of Concern
Tuba City, Arizona, Disposal Site	fourwing saltbush, burning bush	As, Mo, Pb, ^{226}Ra, Se, Th, U
Lowman, Idaho, Disposal Site	ponderosa pine, redosier dogwood	Th, U
Bluewater, New Mexico, Disposal Site	fourwing saltbush, Siberian elm	Mo, ^{226}Ra, Se, Th, U
L-Bar, New Mexico, Disposal Site	fourwing saltbush, rubber rabbitbrush	As, Mo, Pb, ^{226}Ra, Se, Th, U
Lakeview, Oregon, Disposal/Processing Site	big sagebrush, antelope bitterbrush	Th, U
Sherwood, Washington, Disposal Site	ponderosa pine, antelope bitterbrush	Th, U
Split Rock, Wyoming, Disposal Site	rubber rabbitbrush	Mn, U

Abbreviations:
As = arsenic; Mn = manganese; Mo = molybdenum; Pb = lead;
^{226}Ra = radium-226; Se = selenium; Th = thorium; U = uranium

4.6.3 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 2016e). 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 LTCP long-term study is to understand the 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 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 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. AS&T 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.

AS&T installed instrumentation for a large lysimeter within the cover during construction of the Monticello site 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. AS&T designed and imbedded instrumentation for a 3-hectare lysimeter within the Monticello site 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 site 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. AS&T 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. AS&T annually measure species composition, percent cover, shrub density, and 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 AS&T 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. AS&T wanted to know if soil-forming processes are also changing water balance covers. AS&T 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 2017 Activities: AS&T and collaborators (Table 13) replaced aging lysimeter monitoring instrumentation, continued monitoring the 3-hectare lysimeter and changes in vegetation, and gave a presentation on the project to the LM director.

Table 13. Collaborators (Past and Present) on the Monticello Site Water Balance Study, 2000–2016

William Albright, PhD[a, b] Division of Hydrologic Sciences Desert Research Institute	Steve Rock, PhD[b] Office of Research and Development Environmental Protection Agency
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
Glendon Gee, PhD (emeritus)[b] Hydrology Technical Group Pacific Northwest National Laboratory	Aaron Tigar, research assistant Applied Studies and Technology Navarro Research and Engineering, Inc.
John Gladden, PhD (emeritus)[c] Environmental Sciences and Biotechnology Savannah River National Laboratory	William Waugh, PhD[a] Applied Studies and Technology 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.

In May 2017, AS&T replaced aging instrumentation that provides continuous monitoring of soil water storage, soil water potential, runoff, and percolation from the 3-hectare drainage lysimeter. The new equipment included two custom-made fiberglass instrument basins that AS&T installed below frost depth at the lower corner of the lysimeter. Instrumentation placed in the basins included flouts and mechanical float switches to monitor high-volume runoff and percolation events, in-line tipping buckets (70 milliliter [ml] and 1.0 liter) for redundant monitoring of low-volume runoff and percolation, and a pressure transducer for added redundancy. All new flow instrumentation has been calibrated.

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 FY 2017 for a percolation rate of less than 0.4 millimeter per year (mm/year) over almost 17 years of monitoring, or less than 0.1% of annual precipitation. More than half of the total percolation over the 17 years occurred in 2005, the second wettest winter on record, and before vegetation had become well-established on the Monticello ET cover. Zero percolation occurred during in FY 2017. In contrast, average percolation in conventional low-permeability covers located in similar environments, as measured during EPA's Alternative Cover Assessment Program, also using large lysimeters, was about 35.0 mm/year, or 9.1% of precipitation.

An AS&T scientist gave the following presentation to the LM director:

> Waugh, W.J., 2017. "Design and Long-Term Performance of Engineered Covers for Uranium Mill Tailings," July 12, Monticello, Utah.

The following tasks are planned for FY 2018 and out years:

- Continue monitoring percolation and the hydraulic performance of the Monticello site water balance cover.
- Continue monitoring changes in the plant community on the cover.
- 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 site 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.

4.6.4 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 2016e). 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.

ECAP project objectives are to:

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 GJDS to achieve the study objectives. One facility consists of two large lysimeter test sections; the other is a large test pad. AS&T selected the GJDS because (1) it is near the LM office in 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. 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 (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 “enhanced” 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, AS&T repeated field tests first conducted in 2007 to determine changes in key soil hydraulic properties since construction of the test covers. AS&T 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
AS&T 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 2017 Activities: AS&T scientists and collaborators (Table 14) replaced monitoring instrumentation in the ECAP lysimeters, drafted a manuscript on interim results for the lysimeter study, monitored the revegetation study on the test pad, and made preparations for a revegetation study on the disposal cell cover.

Table 14. Collaborators on the AS&T Enhanced Cover Assessment Project

William Albright, PhD[a, b] Division of Hydrologic Sciences Desert Research Institute	Aaron Tigar[a] Applied Studies and Technology 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
Danika Marshall[a] Environmental Services Navarro Research and Engineering, Inc.	William Waugh, PhD[a] Applied Studies and Technology Navarro Research and Engineering, Inc.

Notes:
[a] Funding through LM
[b] Funding through DOE Consortium for Risk Evaluation with Stakeholder Participation III (CRESP III)

Lysimeter Instrumentation

In December 2016, AS&T upgraded instrumentation that provides continuous monitoring of soil water storage, soil water potential, runoff, and percolation from the two ECAP lysimeters. The new equipment included four custom-made fiberglass instrument basins that were buried below frost depth on the west end of the test facility. Instrumentation placed in the basins included flouts and mechanical float switches to monitor high-volume runoff and percolation events, in-line tipping buckets (70 ml and 1.0 liter) for redundant monitoring of low-volume runoff and percolation, and a pressure transducer for added redundancy. All new flow instrumentation was calibrated at the time of the installation.

Lysimeter Monitoring

In FY 2017, percolation rates continued to increase in both lysimeter test sections, and the species and abundance of vegetation establishing on the "enhance" lysimeter were quantified.

AS&T began monitoring lysimeter test sections in November 2007. Between 2007 and 2017, 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. Cumulative percolation between 2007 and 2014 was similar in the two test sections (25.0 mm and 27.0 mm, respectively) despite marked differences in the timing and soil water content during significant percolation events. 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. Between July 1, 2016, and June 30, 2017, percolation levels were lower for both lysimeters (6.27 mm in the control test section and 1.5 mm in the enhanced test section) as a consequence of much lower precipitation.

An objective of this study is to determine if allowing vegetation growth will effectively transform a rock UMTRCA cover into a water balance or ET cover. AS&T may be seeing the start of this transformation. Lower percolation rates in the enhanced test section since 2015 may be attributable to transpiration by plants that have been allowed to establish. Volunteer plants were allowed to establish on the enhanced test section beginning in 2015, but AS&T continued to keep the control test section denuded by applying herbicides. Scientists seeded the enhanced test section in spring 2016 using the most promising seed mix based on the test pad revegetation study with the objective of accelerating ecological succession, increasing ET rates, and reducing percolation rates. By spring 2017, a mixed but sparse stand of desert shrubs and grasses was growing on the enhanced test section.

Manuscript

AS&T scientists and collaborators are drafting a manuscript for publication on the results of the lysimeter study; it will be titled "Field Hydrology of Armored Hydraulic Barrier Covers for Waste Containment."

Vegetation on the Test Pad

Transformation of conventional covers into water balance covers would rely on sustainable vegetation and higher ET rates. AS&T 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. AS&T irrigated half of the plots to wet the seedbed for the first growing season. In FY 2016 and again in FY 2017, transect sampling was used 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 rubber rabbitbrush (*Ericameria nauseosa*).

4.7 Enhanced Natural Attenuation (ENA)

Introduction: LM is responsible for maintaining remedies for residual contamination in soil and shallow groundwater at several UMTRCA sites. ENA 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 ENA 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

Two of these studies are complete: Monument Valley, Arizona, Subpile Soil Phytoremediation and Tuba City, Arizona, Evapotranspiration.

Relevance: These studies address needs related to the LM Strategic Plan (DOE 2016e). 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.

4.7.1 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. Characterize and delineate different vegetation types or zones. 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 site 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.

AS&T 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. The team used a modified relevé method to estimate species abundance in selected stands and then grouped and classified stands as plant associations. A simplified gradient analysis was used to illustrate how the abundance of dominant species varied along the north-south transect and to define separate plant associations. AS&T then produced a map of discrete vegetation and 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 MODIS sensors on the Terra satellite, acquired at approximately daily satellite overpass intervals. AS&T used the USGS MOD13 product, which is a composite image over 16-day periods. The 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 site analyses, MODIS EVI pixels corresponding to shape files for each vegetation and ET zone were obtained from February 2000 to December 2012. The LAI was determined from MODIS EVI imagery using an algorithm AS&T developed at the Monument Valley site. The team used a relationship between LAI and EVI to calibrate ET estimates for vegetation zones at the Tuba City site. Changes in ET in response to grazing and climate were analyzed by estimating ET for years of heavy grazing and light grazing and for wet and dry years.

AS&T scientists and collaborators wrote a final DOE report (*Evapotranspiration Dynamics and Effects on Groundwater Recharge and Discharge at the Tuba City, Arizona, Disposal Site*, [LMS/TUB/S13751]) (DOE 2016d) and published a journal article, in 2016:

> 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.

FY 2017 Activities: This project is complete. In FY 2017, AS&T scientists and collaborators presented components of the Tuba City site ET research at two conferences: Waste Management 2017 and MODFLOW and More 2017:

> Bush, R., E. Glenn, C. Jarchow, W. Waugh, A. Laase, and T. Bartlett, 2017. "Effects of Rangeland Evapotranspiration on Groundwater Recharge, Discharge, and Flow at the Tuba City, Arizona, Disposal Site," *Proceedings of Waste Management 2017 Symposium*, March 5–9, Phoenix, Arizona.

> Laase, A., T. Bartlett, J. Waugh, and R. Bush, 2017. "Estimating Evapotranspiration and Recharge Rates Using a Remote Sensing Algorithm," MODFLOW and More 2017, May 21–24, Golden, Colorado.

The abstract in the Waste Management 2017 proceedings paper provides a summary of the project:

> The U.S. Department of Energy Office of Legacy Management is modeling groundwater flow and contaminant transport at a former uranium mill site near Tuba City, Arizona. A goal is to project groundwater travel times and flow volumes between the former mill site and Moenkopi Wash, a downgradient stream. Aquifer recharge and discharge are sensitive model parameters; however, assigning representative rates is inexact and involves approximations. We applied a remote sensing algorithm to determine spatially variable evapotranspiration (ET), precipitation recharge, and groundwater discharge rates for use in a large

scale groundwater flow model for the site. ET is the combination of evaporation and plant transpiration from soil and groundwater. We estimated landscape-scale ET over a 13-year period (2000 to 2012) for distinct plant communities within a 3531-hectare groundwater model domain (GMD), and then evaluated effects of ET on groundwater recharge and discharge within the GMD. Our empirical algorithm was derived from ground ET measurements, multispectral satellite imagery, and temperature data. Groundwater recharge or discharge rates were calculated for each plant community (or ET Zone) as the difference between precipitation (PPT) and ET rates. Recharge occurred in plant communities where PPT exceeded ET; discharge occurred where ET exceeded PPT.

Estimates of groundwater recharge rates for upland plant communities that survive on meteoric water ranged from 0 to 88 mm yr^{-1}. Estimates of groundwater discharge for phreatophyte plant communities ranged from 23 mm yr^{-1} to 150 mm yr^{-1}. Phreatophytes are plants that survive by extracting groundwater. Zero recharge occurred in plant communities where ET rates equaled annual average precipitation. An increase in groundwater recharge (PPT > ET) was associated with past land disturbances and heavy livestock grazing in upland areas. Groundwater discharge (ET > PPT) was highest in riparian phreatophyte communities, but lower than optimal in upland phreatophyte communities impacted by heavy grazing. Protecting phreatophyte communities from grazing at Tuba City could potentially increase ET from 153 mm yr^{-1} to at least 500 mm yr^{-1}. The validity of using the ET algorithm to estimate recharge and discharge was evaluated by comparing the net volumetric outflow rate for the model domain with base flow measurements collected from Moenkopi Wash. Modeled outflow approximated measured flow gains in the Wash, increasing our confidence in the ET algorithm and in the model.

Results suggest that rangeland management practices that reduce groundwater recharge rates and increase groundwater discharge rates should be evaluated as part of an overall groundwater remediation strategy.

4.7.2 Study 2: Shiprock Phytoremediation: Hydraulic Control

Overview: The goal of the Shiprock site phytoremediation pilot study is to establish vegetation that can transpire shallow groundwater and thereby help control migration of groundwater contamination. Phytoremediation and hydraulic control occur naturally at the Shiprock site. AS&T 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 15) designed a factorial field experiment (Table 16) 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 15. 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 Applied Studies and Technology Navarro Research and Engineering, Inc.

Table 16. 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 b. Irrigated 2007–2010, not irrigated 2011−2013
Native plant species (phreatophyte)	a. Black greasewood (*Sarcobatus vermiculatus*) b. Fourwing saltbush (*Atriplex canescens*)

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. AS&T transplanted fourwing saltbush and black greasewood plants randomly along drip irrigation lines within the plots at each location. Scientists 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 at the Arizona Laboratory for Emerging Contaminants following an EPA protocol. AS&T used the hydrogen/deuterium ratio and oxygen-18/oxygen-16 ratio values to infer water sources for plants, soils, and shallow groundwater. Soils and plants were sampled on July 11, 2013. Groundwater was sampled in 2006, 2007, and 2013. AS&T analyzed water isotopes for a combination of samples from the 2006, 2007, and 2013 data. San Juan River water data were from 2007.

Fieldwork was funded by the Shiprock site with some in-kind funding for faculty and graduate students at UA and for faculty and intern students at Diné College.

FY 2017 Activities: All fieldwork for the Shiprock pilot study is complete. In FY 2017, AS&T published a DOE final report, gave a presentation to LM, and then presented the research at Ecological Society of America (ESA) 2017.

The DOE final report for the Shiprock phytoremediation project, *Growing Desert Phreatophytes for Hydraulic Control of Groundwater at the Shiprock, New Mexico, Disposal Site* (LMS/SHP/S14558), was published in April 2017 (DOE 2017c). The AS&T lead scientist gave a seminar on the study to LM and LMS managers in February 2017.

AS&T scientists and collaborators presented the study at ESA 2017 on August 9, 2017.

> Waugh, W., E. Glenn, D. Moore, P. Nagler, R. Bush, and M. Kautsky, 2017. "Growing Desert Phreatophytes to Control Flow of Contaminated Groundwater at a Uranium Mill Site," in *Proceedings of Ecological Society of America 2017*, August 6–11; Portland, Oregon.

The published ESA abstract provides a recap of this research:

> Background/Question/Methods. The U.S. Department of Energy is investigating the feasibility of establishing large plantings of native desert phreatophytes to enhance hydraulic control of shallow contaminated groundwater at a former uranium mill site. We designed a study to (1) evaluate methods to accelerate establishment of native phreatophytes above contaminated groundwater, (2) determine if irrigated transplants would transpire groundwater after irrigation ceased, (3) evaluate uptake and accumulation of groundwater contaminants in aboveground plant tissue, and (4) estimate phreatophyte transpiration rates for input to groundwater flow simulations. We transplanted and irrigated seedlings of *Atriplex canescens* (ATCA) and *Sarcobatus vermiculatus* (SAVE), grown in a greenhouse from locally-harvested seed, into four test plots overlying a shallow groundwater plume. Students annually measured plant growth in the test plots and in reference areas outside the plume. We analyzed stable isotopes of hydrogen

and oxygen in plant tissue, soil, and groundwater to test hypotheses regarding sources of transpiration water. We sampled and analyzed levels of groundwater contaminants in the stems and leaves of ATCA and SAVE growing in test plots and in reference areas. Finally, we applied empirical relationships between fractional cover, air temperature, and satellite imagery to estimate transpiration rates for hypothetical large-scale plantings.

Results/Conclusions. Overall, 77% of irrigated seedlings grew to maturity, SAVE mortality was higher, ATCA grew larger than SAVE, and the largest plants were in river terrace plots. Two years after irrigation ceased, oxygen and hydrogen isotope data indicated that healthier plants growing on a river terrace were primarily transpiring shallow groundwater. Less healthy plants growing away from the river terrace were primarily using a combination of rainwater and residual irrigation water. Uranium in stems and leaves was statistically higher in test plots overlying the plume than in reference areas outside the plume; however, uranium, strontium, and selenium were all well below toxicity thresholds for grazing animals. Transpiration rates for ATCA and SAVE growing on the river terrace overlying the plume ranged from 258 to 352 mm yr^{-1}, and transpiration discharge of groundwater (calculated as the difference between mean annual transpiration and precipitation) for a hypothetical 9.6 hectare planting ranged from 7603 to 16,707 m3 yr^{-1}. Results suggest that a large-scale desert phreatophyte planting could transpire a significant volume of groundwater without creating unacceptable exposure to grazing animals. An ongoing study is refining the transpiration algorithm by combining field measurements of leaf area index and multispectral data from both high-resolution unmanned aircraft systems and low-resolution satellite imagery.

4.7.3 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. AS&T 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 (i.e., 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 it was not enough to account for a rapid drop in total soil nitrogen as monitored through soil sampling and analysis.

Prior Activities: AS&T 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 ET—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, no additional drop in total nitrogen was measured. In 2012, AS&T began empirically testing the hypothesis that, without irrigation, subpile soil nitrogen levels would resume dropping. AS&T 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.

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.

FY 2017 Activities. This project is complete. In FY 2017, AS&T collaborated with LMS groundwater scientists who modeled groundwater flow and transport for the nitrate plume at the Monument Valley site that incorporated hydraulic control of the plume source, as demonstrated in the 2016 *Land Degradation and Development* publication cited above, and landscape-scale ET estimates published previously (Glenn et al. 2008; Bresloff et al. 2013). This modeling study was presented at the Waste Management 2017 conference:

> Denny, A., J. Gillespie, A. Laase, W. Waugh, A. Ranalli, R. Zinkl, R. Johnson, and D. Dander, 2017. "Use of Groundwater Flow, Solute Transport, and Geochemical Modeling to Evaluate Long-Term Nitrate Plume Concentrations Following Phreatophyte Source Control," *Proceedings of Waste Management 2017 Symposium*, Phoenix, Arizona.

The abstract in the published Waste Management 2017 proceedings paper provides a summary of the modeling study.

> The Monument Valley, Arizona, Processing Site is a former uranium mill site within the Navajo Nation in northeastern Arizona. Milling activities between 1955 and 1968 have contaminated the shallow underlying groundwater. Site remediation activities between 1992 and 1994 removed surficial source material and other site-related contamination but did not address soil contamination, primarily nitrate, remaining between the excavation depth and the water table. This residual nitrate has continued to contaminate groundwater. Two native phreatophytes, fourwing saltbush and black greasewood, were planted in 2000 and 2005 within the footprints of the former tailings piles to control the remaining source material. The objectives of the plantings were to increase nitrate removal from soil water through root uptake and, because phreatophyte water usage is expected to equal or exceed annual precipitation, to halt nitrate loading to

groundwater. Recent evaluation showed more than an 80% decrease in soil nitrate concentrations and no effective groundwater recharge in the planting area.

Numerical groundwater flow, solute transport, and geochemical modeling were performed to evaluate the long-term response of the existing nitrate plume to the phreatophyte source control measures. The results showed that nitrate concentrations in the alluvial aquifer are expected to drop below the standard of 10 mg/L as N in approximately 70 years as a result of the phreatophyte planting. Companion sensitivity analysis was also performed to better understand how uncertainty in groundwater flow model and solute transport model inputs would impact cleanup times. Even considering input uncertainty, nitrate concentrations are expected to reach the standard everywhere in the alluvial aquifer within 100 years.

Recognizing that model predictions are not absolute, but represent the general potential for an event to occur, the model was used to identify key sampling locations to verify that the nitrate plume will attenuate as predicted. The evaluation identified locations that can be used to assess the viability of the modeling predictions within the next 50 years. If nitrate plume attenuation proves problematic, other remedial strategies will be explored.

4.7.4 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 site 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 the 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. AS&T selected two native shrubs as crop plants: fourwing saltbush and black greasewood. Seedlings grown from locally collected seed were transplanted 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 eight different treatment combinations (nitrate level × crop).

Irrigation, soil nitrogen sampling, soil moisture monitoring, risk assessments, and an evaluation of beneficial uses are complete. AS&T 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 LAI were estimated using QuickBird data that were calibrated and validated against ground monitoring data. AS&T used LAI from Licor 2000 meter readings as a ground calibration and then estimated landscape-scale LAI from QuickBird normalized difference vegetation index data. Scientists 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. AS&T sampled for soil nitrogen at the beginning of the study and then again 5 years later and monitored volumetric soil water content monthly during the growing season using a neutron hydroprobe.

AS&T 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). Scientists 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 2017 Activities: All fieldwork for this study is complete. AS&T scientists presented and collaborators drafted a manuscript in FY 2017. The work to date was funded by the Monument Valley site and in-kind contributions through various grants at UA, Vanderbilt University, and the DOE Consortium for Risk Evaluation with Stakeholder Participation (CRESP). AS&T is funding writing and publication of the paper.

4.7.5 Study 5: USGS UAS Evapotranspiration Study

Overview: This project, a collaboration with USGS and UA, is using UAS to acquire high-resolution spectral data needed to estimate spatial and temporal variability in floodplain ET for input to groundwater flow evaluations. AS&T combined 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 and Moab sites. AS&T is scaling data 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 UAS Technologies Workshop at the USGS National Center in Reston, Virginia, on May 19–21, 2015, and collaborated on a 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. In FY 2016, AS&T, USGS, and UA scientists wrote a long-term study, selected study sites, drafted a fieldwork plan (DOE 2016b), and acquired multispectral data for the San Juan River floodplain adjacent to the Shiprock site and for the Colorado River floodplain adjacent to the Moab site tailings pile.

FY 2017 Activities: AS&T scientists and collaborators (Table 17) calculated and mapped ET using UAS multispectral data, used the ET algorithm to evaluate temporal changes in plant populations on water use, presented research at technical conferences, and submitted a paper for publication in a technical journal.

Table 17. Collaborators on the USGS UAS Evapotranspiration Study

Edward Glenn, PhD Environmental Research Laboratory University of Arizona	Pamela Nagler, PhD Southwest Biological Science Center U.S. Geological Survey
Christopher Jarchow, PhD Southwest Biological Science Center U.S. Geological Survey	William Waugh, PhD Applied Studies and Technology Navarro Research and Engineering, Inc.

Results for the Shiprock and Moab sites show that remotely sensed monitoring is improved using high resolution aerial imagery acquired with a UAS. Landscape-scale estimates of ET using UAS could be used to evaluate recharge and discharge and, coupled with 30 m Landsat and 250 m MODIS sensors, could be used to depict the spatial and temporal variability in ET. AS&T demonstrated how imagery derived ET estimates could be used to refine groundwater flow evaluations and may be useful for improving remediation strategies. Because groundwater elevation, flow, and contaminant transport may vary seasonally and annually in response to changes in the health of tamarisk (saltcedar), effects of tamarisk and beetle (see below) interactions on ET are particularly relevant at these sites.

Northern tamarisk beetles (*Diorhabda carinulata*) were released in the Upper Colorado River Basin in 2004–2007 to defoliate introduced tamarisk trees in river riparian zones. The primary purpose was to control the invasive trees and reduce ET by tamarisk in an attempt to increase stream flows. AS&T evaluated beetle–tamarisk interactions with MODIS and Landsat imagery on 13 river systems, with vegetation indexes used as indicators of the extent of defoliation and ET. Beetles are widespread and exhibit a pattern of colonize defoliate–emigrate, so that riparian zones contain a mosaic of completely defoliated, partially defoliated, and refoliated tamarisk stands. Based on satellite data and ET algorithms, mean ET before beetle release (2000–2006) was 416 mm/year compared to postrelease (2007–2015) ET of 355 mm/year for a net reduction of 61 mm/year. This is lower than initial literature projections that ET would be reduced by 300–460 mm/year. Reasons for the lower-than-expected ET reductions are because baseline ET rates are lower than initially projected, and percentage ET reduction is low because tamarisk stands tend to regrow new leaves after defoliation and other plants help maintain canopy cover. Overall reductions in tamarisk green foliage during the study are 21%. However, ET in the Upper Basin has shown a steady decline since 2007, and equilibrium has not been reached. Defoliation is proceeding from the Upper Basin into the Lower Basin at a rate of 40 kilometers per year, much faster than initially projected.

AS&T presented two papers on this research at the American Geophysical Union in 2016 and a paper at ESA in 2017. A paper was accepted for publication in the journal *Ecological Restoration*.

Nagler, P.L., W.J. Waugh, E.P. Glenn, U. Nguyen, C. Jarchow, and J. Vogel, 2017. "Methods for Measuring Effects of Changes in Tamarisk Evapotranspiration on Groundwater at Southwestern Uranium Mill Tailings Sites," in *Proceedings of Ecological Society of America 2017*, August 6–11; Portland, Oregon.

Nagler, P.L., U. Nguyen, H.L. Bateman, C. Jarchow, C. Van Riper, W.J. Waugh, E.P. Glenn, 2016. "Potential for Water Savings by Defoliation of Saltcedar (Tamarix spp.) by Saltcedar Beetles (Diorhabda carinulata) in the Upper Colorado River Basin," Abstract B53H-0608, presented at 2016 American Geophysical Union Fall Meeting, San Francisco, California.

Nagler, P.L., U. Nguyen, H.L. Bateman, C.J. Jarchow, E.P. Glenn, W.J. Waugh, C. van Riper III (accepted for publication). "Northern Tamarisk Beetle (Diorhabda carinulata) and Tamarisk (Tamarix spp.) Interactions in the Colorado River Basin," *Restoration Ecology*, August 25, 2017.

Waugh, W.J., P.L. Nagler, J. Vogel, E.P. Glenn, U. Nguyen, and C.J. Jarchow, 2016. "Methods for Measuring Effects of Changes in Tamarisk Evapotranspiration on Groundwater at Southwestern Uranium Mill Tailings Sites," Abstract B43A-0556, presented at 2016 American Geophysical Union Fall Meeting, San Francisco, California.

4.8 Educational Collaboration

Introduction: In 2017, the Secretary of Energy reaffirmed a DOE commitment to educational outreach in STEM: "Think about what you can do to engage the next generation in STEM careers and government service. Can you be a mentor or role model? Speak to a classroom of young minds. Think about the ability that you have, that we collectively have before us. We can change the world through our work in government on scientific, technical, and groundbreaking issues."

The Educational Collaboration initiative was created to strengthen and build LM's long-standing commitment to environmental science and STEM education. Its goals are to strengthen existing partnerships with tribal colleges and Native American graduate students and to explore opportunities for new partnerships with colleges and universities. For many years, AS&T studies related to engineered cover performance and ENA 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 Educational Collaboration initiative outlined the continuation of this practice of partnering 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 UA. 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.

4.8.1 Initiative 1: Diné College Partnership

Overview: This initiative is a continuation of AS&T's partnership with Diné College. It supports DOE's commitment to tribal partnerships with an emphasis on STEM education for Native American youth. The partnership is a two-way exchange of ideas. AS&T shares ideas about scientific methods, and Diné College faculty and students share ideas about the cultural acceptability of scientific approaches. The partnership in 2017 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 ENA 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 AS&T's 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 research projects and remediation actions 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 site and the Shiprock 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 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.

The 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 has also received recognition from EPA, CRESP, and the National Academy of Sciences (NAS).

EPA

In 2011, EPA invited a Diné College instructor and an AS&T scientist to give a tag-team presentation, in English and Navajo, at a national tribal colleges and universities workshop titled "Building EPA/TCU Partnerships."

CRESP

Researchers with the DOE Consortium for Risk Assessment with Stakeholder Participation invited AS&T to contribute a chapter on the 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 *Stakeholders and Scientists: Achieving Implementable Solutions to Energy and Environmental Issues*, ed. Burger, J., Springer, New York.

NAS

The AS&T educational partnership with Diné College was featured in a NAS documentary film, "Weaving STEM Education and Culture: The Faces, Places, and Projects of the Tribal Colleges and Universities Program."

FY 2017 Activities: Teaching at the Tsaile, Arizona, and Shiprock, New Mexico, campuses of Diné College during fall 2016 and spring and summer 2017 involved lecture classes, lab classes, seminars, and field trips:

> *Geology Class Lecture and Lab:* "Applied Geology and Ecology: Engineered Covers for Uranium Mill Tailings" (October 31, 2016, Tsaile campus).
>
> *Botany Class Lecture and Lab:* "Phytoremediation: Growing Desert Phreatophytes to Control Groundwater Flow at the Shiprock Uranium Mill Site" (November 1, 2016, Tsaile campus).
>
> *Ecology Class Lecture:* "Applied Ecology: Rangeland Evapotranspiration and Groundwater Flow at a Uranium Processing Site" (November 1, 2016, Tsaile campus).
>
> *Seminar and Monument Valley Field Trip:* "Helping Mother Earth Heal: Environmental Science at the Monument Valley Uranium Mill Site." Environmental science students from the Tsaile and Shiprock campuses listened to a seminar on Monument Valley site research, toured phytoremediation research projects, and observed groundwater sampling for the uranium biosequestration study at the Monument Valley site. The field trip finished with a tour stop at the Mexican Hat site (February 14, 2017).
>
> *Diné College Lunch Science Seminar:* "Phytoremediation: Using Plants to Help Clean up Uranium Processing Sites on Navajo Land" (February 15, 2017, Tsaile campus).
>
> *Shiprock Campus Seminar:* "Phytoremediation: Using Plants to Help Clean up Uranium Processing Sites on Navajo Land" (February 16, 2017, Shiprock campus).

Intern Field Sampling: Diné College Environmental Science intern students helped GPS sample points and measure dormant-season LAI for phreatophytes on the San Juan River floodplain below the Shiprock site. Data acquired by students were used for the DOE/USGS UAS Evapotranspiration Study (February 16, 2017).

Summer Field Biology Class: Seminar and Field Trip: "Helping Mother Earth Heal: Biology and Environmental Science at the Monument Valley Uranium Mill Site" (June 9, 2017, Goulding's Lodge, Monument Valley and Mexican Hat sites).

4.8.2 Initiative 2: University of Arizona Partnership

Overview: AS&T created a partnership in FY 2013 with a UA faculty member to help fund Native American graduate student research projects that support LM goals, objectives, and compliance actions. An AS&T scientist received an adjunct faculty appointment at UA and served on graduate student committees for two students in FY 2017: Ms. Carrie Joseph, a member of the Hopi Tribe, and Mr. Quentin Benally, a member of the Navajo Nation. 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 Ms. Joseph and Mr. Benally. Both students received grants through an Alfred P. Sloan Foundation Indigenous Graduate Partnership. Ms. Joseph's research is addressing aspects of the long-term management of UMTRCA sites near Native American communities. Mr. Benally is evaluating the long-term effectiveness of revegetation at the Tuba City site.

4.8.2.1 Long-Term Management of UMTRCA Sites Near Native American Communities

Background and Prior Activities: Ms. Joseph's research addresses three objectives and accompanying strategies associated with remedy performance, climate change, and tribal interactions in the LM Strategic Plan (DOE 2016e):

- Goal 1, Objective 3: Improve the long-term sustainability of environmental remedies.
  - Record and analyze data on long-term performance of radioactive and hazardous material storage sites and environmental treatment systems.
  - Assess the effect of climate change on environmental remedies and develop plans to mitigate significant impacts.
- Goal 4, Objective 1: Enhance sustainable environmental performance for facilities and personal property, and account for climate change in LM site management.
  - Understand regional climate-change predictions and evaluate potential impacts of these changes on the performance of remedies and facilities at LM sites.
- Goal 6, Objective 3: Consult, collaborate, and partner with the people and governments of tribal nations.
  - Engage tribal nations about how to improve LTS&M effectiveness to better understand their concerns, keep them informed, ask for and listen to their input, and involve them in decisions.

Remedy Performance

LTCP (Section 4.6) is evaluating effects of natural processes on the performance of engineered disposal cell covers and investigating options for improving long-term sustainability. One issue that is being addressed is the unanticipated establishment of deep-rooted woody plants on engineered covers. Plants may have potentially detrimental or beneficial effects on cover performance (see Section 4.6). Site managers want to know under what conditions vegetation should either be removed or allowed to establish. Project 2 under LTCP is investigating uptake of contaminants in plants currently growing on disposal cells and thereby informing LTS&M decisions. Ms. Joseph studied plant uptake at three sites near tribal lands in the Southwest for her master's degree in Environmental Science. However, long-term effects of plant succession on cover performance in response to potential changes in climate and other environmental variables are largely unknown.

Climate Change

In 2016, AS&T scientists developed a conceptual approach for investigating how climate might influence the long-term performance of LM disposal cells, in part as a guide for Ms. Joseph's research. The conceptual 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.

Tribal Interactions

The LM Strategic Plan (DOE 2016e) states that "LM is committed to effective dialog with tribal nations to make informed decisions … and to demonstrate respect for natural and cultural resources. We have learned from our engagement with Native Americans that an approach to waste isolation that works with the natural environment can be more acceptable to stakeholders and often more sustainable, as well." Ms. Joseph is uniquely qualified to initiate dialog and understand tribal perceptions of past uranium milling and LM's present LTS&M activities.

FY 2017 Activities: In FY 2017, Ms. Joseph was accepted in the PhD program at UA, drafted a research prospectus, and served as an invited speaker at LM meetings with tribes. Her research is underway.

In December 2016, Ms. Joseph passed a written and oral doctoral comprehensive examination that granted her admission to candidacy for the doctoral degree in the Department of Soil, Water and Environmental Science at UA. An AS&T scientist served as an adjunct faculty member of her graduate committee. Ms. Joseph has also completed all required coursework and can now focus on her research.

Every student in a doctoral program at UA needs to have an approved dissertation prospectus. An option other than writing a dissertation for completing the doctoral research requirements at UA is for the student to conduct original research that leads to the publication of three professional papers. Ms. Joseph submitted a draft prospectus to her graduate committee in August 2017 that proposes publication of three studies designed to answer the following research questions.

Study 1. Are woody plants growing on engineered disposal cell covers accumulating uranium and other contaminants of concern to hazardous levels? Are these plants creating an exposure pathway to livestock? Are contaminants bioaccumulating in plant litter?

Study 2. Was adaptation to climate change considered in the design of engineered disposal cell covers located in the Southwest? How might vegetation growing on disposal cell covers change spatially and temporally in response to climate? How could LTS&M management plans be improved to prepare for the interactive effects of plant distribution and climate change cover performance at southwestern sites?

Study 3. How do members of two Hopi village communities located hydraulically downgradient from the Tuba City site perceive risk to human health and the environment? How well informed are community members about the history and remediation of the Tuba City site? What are the community concerns, priorities, and recommendations for addressing the potential impacts of the Tuba City site?

4.8.2.2 Long-Term Effectiveness of Revegetation at Tuba City

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, 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 is 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 trade-off 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. Understanding the long-term effectiveness of past revegetation efforts at UMTRCA sites will lead to improved plans, implementation, and maintenance.

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. Nearly 30 years ago, DOE stripped the vegetation and soil from a large parcel east of the current Tuba City 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 its 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 surrounding rangeland recovering after decades of overgrazing?

Prior Activities: Mr. Benally started his study in FY 2014 and continued with field and laboratory work in FY 2015 and FY 2016. Mr. Benally and LMS collaborators drafted a work plan, field-characterized vegetation, remotely estimated ET, evaluated soil fertility, and characterized soil morphology. AS&T contributed an article about his study for the LM Quarterly Update.

Mr. Benally and AS&T colleagues measured the composition and health of vegetation in three zones—revegetated, grazed, and protected—both on the ground and with remote sensing to determine if the ecological condition of revegetated and overgrazed areas has improved. A line transect method was used to estimate percent cover of species. AS&T also estimated LAI and ET for the three areas using an empirical algorithm linking MODIS EVI satellite data, stem flow data for desert plants at the Monument Valley site, and published atmospheric flux tower data for several sites in the Southwest. Scientists 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.

FY 2017 Activities: Mr. Benally completed his data analysis in October 2016, submitted his thesis in November 2016, passed his thesis defense in December 2016, and graduated from UA in May 2017 with a master's degree in Environmental Science. He also drafted a paper, "Long-Term Effectiveness of Revegetation at an Arid Uranium Mill Site," to be submitted for publication in a technical journal.

Summaries of answers to his land stewardship questions follow:

> *Did DOE achieve its revegetation goals?* The completion report for Tuba City (DOE 1995) included the following revegetation goal: "The disturbed areas will be restored and revegetated to control erosion and restore land to unrestricted use." The term "restoration" is a legally and technically specific term for returning a disturbed site to an undisturbed baseline condition. At Tuba City, the baseline condition is the aforementioned parcel of native rangeland that has been protected from grazing for over 30 years. Mr. Benally compared ecological conditions in the revegetated and protected areas. His measures of ecological

health (percent plant canopy cover, LAI, and plant species diversity) were all significantly lower in the revegetated area than in the protected area. However, in 2014, percent plant cover in the revegetated area had more than doubled since 1999, 10 years after DOE seeded the site, and some desirable native plant populations were well established. Conclusion: More than 25 years after DOE revegetated disturbed land at Tuba City, the ecology has not been restored but appears to be on a trajectory of improvement.

How well did short-term evaluations predict long-term revegetation success? The success of mine land revegetation is typically evaluated 5 to 10 years after seeding. Mr. Benally's study shows that an evaluation conducted after 10 years provided an inadequate assessment of revegetation efforts at the arid Tuba City site. Plant species, diversity, and percent cover changed significantly between 1999 and 2014.

Did revegetation limit the spread of harmful weeds? A common land management issue at UMTRCA sites is the infestation of undesirable and noxious weeds on disturbed land. A common revegetation goal is the establishment of desirable native plants that can compete with and exclude weedy species. Mr. Benally's comparison of 1999 and 2014 plant species data indicates that DOE's revegetation efforts successfully controlled weed infestations at Tuba City.

Is the surrounding rangeland recovering after decades of overgrazing? Rangeland on the Navajo Nation has historically been overgrazed by livestock. Over time, overgrazing changes the composition and reduces the health of rangeland vegetation. According to local range managers, in recent years grazing management has improved on rangelands adjacent to the Tuba City disposal site. Mr. Benally's comparisons of plant species composition and percent plant cover in grazed versus protected areas provided evidence that rangeland health has indeed improved since 1999.

4.8.3 Initiative 3: Grow Higher Education Collaborations

Background and Prior Activities: In FY 2105, LM approved a program plan called "Grow Higher Education Collaborations." The plan was added to Version 1.0 of the long-term study in October 2015. In FY 2016, under this program plan, AS&T scientists initiated collaboration on UA's environmental educational modules for tribal colleges, identified potential AS&T projects linked to LM Goal 1 (Protect Human Health and the Environment) that match graduate student research requirements, and continued to cultivate new educational partnerships with tribal and local colleges and universities linked to stakeholder communities. The program plan includes a table listing LM sites and local stakeholder colleges and universities.

AS&T 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.

FY 2017 Activities: AS&T scientists initiated a new partnership with CMU, gave seminars in CMU classes during the 2017 spring semester, recruited intern students, and teamed with faculty and graduate students on several projects.

AS&T scientists are collaborating with Dr. Cassandra Fenton, a geology professor at CMU. Three possible areas were identified for partnering: (1) LM and LMS scientists would serve as guest instructors and lead field trips for environmental and natural science classes at CMU, (2) LMS and CMU scientists would identify opportunities for collaborating on graduate and undergraduate research, and (3) CMU would solicit LMS and LM feedback on new graduate programs in geology and environmental science.

AS&T scientists also delivered presentations to an Applied Geochemistry class and a Pollution Investigation and Monitoring class using examples from AS&T projects. Dr. Ray Johnson explained how LM applies geochemistry principles to the real world settings of environmental remediation and compliance (Section 4.3). Teaching materials included a combination of geochemical and hydrogeologic interpretations from field investigations at the former uranium mill site in Riverton, Wyoming. Dr. Jody Waugh used a land-farm phytoremediation study at the Monument Valley site to teach experimental design, sampling design, and data analysis.

A CMU geology intern assisted with thin-section preparation and fission-track radiography interpretations in the ESL microscope lab. The internship was funded under the Persistent Secondary Contaminant Sources long-term study. Table 18 lists all higher education collaborations in FY 2017.

Table 18. Higher Education Collaborations in FY 2017

Universities	Faculty and Students	Projects
College of Engineering, University of Virginia	Dr. Craig Benson, dean Dr. Kuo Tian, recent PhD graduate	LTCP Project 1: Effects of Soil-Forming Processes on Cover Engineering Properties
Geological Engineering, University of Wisconsin–Madison	Dr. William Likos, department chair Nicolas Stephani, M.S. student	LTCP Project 1: Effects of Soil-Forming Processes on Cover Engineering Properties
Environmental Systems Dynamics Laboratory, University of California–Berkeley	Morgan Williams, PhD student	LTCP Project 1: Effects of Soil-Forming Processes on Cover Engineering Properties
Soil, Water, and Environmental Science, University of Arizona	Dr. Karletta Chief, assistant professor Carrie Joseph, PhD candidate	LTCP Project 2: Contaminant Uptake by Plants
Soil, Water, and Environmental Science, University of Arizona	Dr. Christopher Jarchow, recent PhD graduate	ENA Project 1: Tuba City Evapotranspiration ENA Project 5: UAS Estimates of Evapotranspiration
Soil, Water, and Environmental Science, University of Arizona	Dr. Mark Brusseau, professor Asma El Ouni, PhD student	Uranium Biosequestration at Monument Valley
Soil, Water, and Environmental Science, University of Arizona	Dr. Karletta Chief, assistant professor Quentin Benally, recent M.S. graduate	EC Project 2: Long-Term Effectiveness of Revegetation

Abbreviation:
EC =Educational Collaboration

4.9 Gold King Mine Release Impact to UMTRCA Sites

Overview: On August 5, 2015, an EPA field team investigating the Gold King Mine (GKM), approximately 6 miles north of Silverton, Colorado, inadvertently triggered the release of an estimated 3 million gallons of acidic, mine-impacted water to a tributary of the Animas River. The release contained elevated concentrations of iron, manganese, aluminum, copper, zinc, and lead. The iron imparted a yellow-orange color to the river; this discoloration was used to monitor the movement of the plume using aerial photography. Over an approximate 9-day period, the plume from the release flowed down the Animas River, past Durango, Colorado, joined the San Juan River at the confluence in Farmington, New Mexico, and ultimately reached the Colorado River at Lake Powell in Utah.

Because the GKM plume had potential to impact groundwater at two former uranium mill sites that are managed by LM, LM initiated this long-term study shortly after the GKM release was reported. The Durango processing and Shiprock sites are about 60 and 150 river miles downstream of GKM, respectively. The Durango processing site is adjacent to the Animas River, and the Shiprock site is adjacent to the San Juan River. Groundwater at both sites is hydraulically connected to the rivers. Aerial surveys, sampling, and assessment of flows conducted by EPA and other agencies indicated that the river plume reached the Durango processing site at about 10 p.m. on August 6 and the Shiprock site between late August 8 and early August 9.

Prior Activities: During FY 2016, AS&T sampled surface water locations and near-river wells at the Durango processing and Shiprock sites for contaminants related to the GKM release. Data from other agencies and organizations (primarily EPA, the USGS, the Mountain Studies Institute, and the Rivers of Colorado Water Watch Network) were also evaluated to support this work.

FY 2017 Activities: This long-term study was completed in FY 2017. The data collected in FY 2016, in conjunction with data collected by USGS, the Colorado Department of Health, and others, were analyzed and compared to historical data to determine if the GKM release impacted and continues to impact surface and groundwater quality at the Durango processing and Shiprock sites. The results were documented in the final project report, *Assessment of Potential Gold King Mine Release Impacts to Durango, Colorado, and Shiprock, New Mexico, LM UMTRCA Sites* (DOE 2017d).

This study concluded that surface water in the Animas River near the Durango processing site was impacted by the release, as demonstrated by other agency data, but LM's analysis indicates there was no apparent incursion of the river-borne GKM contaminants to the groundwater. Analysis of GKM plume-related impacts to the Shiprock site was complicated by the distance of the site from the GKM release, the inability to detect a discernible plume in the river near the site, increased water flows from the Navajo Dam near Archuleta, New Mexico, and rain events. Although review of other agency data indicated slight increases in metals concentrations when comparing preplume vs. postplume arrival sample results, these were of low magnitude and not sustained. As found for the Durango processing site, LM's evaluation of prerelease and postrelease groundwater data for the Shiprock site indicated no discernable change in concentration of any GKM plume-related metals. A summary of the study findings was presented at the March 21, 2017, AS&T semiannual update meeting.

4.10 Unmanned Aircraft System Technology Evaluation

Overview: The overall objective of the UAS 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 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 LM's 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: In FY 2016, AS&T developed the long-term study and associated fieldwork plans for the GJDS and the Original Landfill (OLF) at the Rocky Flats site. The OLF is an approximately 20-acre, nonengineered landfill on a south-facing hillside in the southwestern portion of the Central Operable Unit.

FY 2017 Activities: A USGS subcontractor conducted the UAS photogrammetric survey of the GJDS on May 4, 2017. The USGS conducted UAS photogrammetric, lidar, multispectral, and thermal surveys of the Rocky Flats site OLF and portions of the Walnut Creek drainage between August 14 and August 24, 2017. The USGS completed data processing from these surveys, and the data were delivered to LM.

These data will be evaluated in FY 2018. The GJDS survey data will be used as baseline topographic conditions to estimate waste volumes. Subsequent UAS surveys will be performed and compared to the baseline conditions to determine changes in waste volumes.

The Rocky Flats site OLF UAS data will be compared to traditional land-based surveys and manned aircraft lidar surveys of the OLF that were also performed in 2017.

The multispectral and thermal surveys will be evaluated to identify seeps, springs, groundwater and surface water interactions and to potentially develop or verify vegetation maps. This will provide us information to answer the following study questions:

- 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)?
- How will the quality of data that are typically acquired for a given LTS&M activity improve by using appropriate UAS technologies?
- What new useful and necessary data types will arise from using UAS technologies to support LTS&M actions?
- Do the visualization tools arising from the use of UAS technologies improve AS&T's ability to document site conditions?
- Do the visualization products arising from the use of UAS technologies improve stakeholder communications?

The final report for this long-term study will be issued in FY 2018.

5.0 FY 2017 Short-Term Investigations

The AS&T program includes a portfolio of short-term investigations. 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 2017 short-term investigations.

5.1 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 datasets. The goals of this study are to:

- Evaluate the ArcGIS 2D particle tracking algorithm.
- Evaluate the method using the Gnome-Coach, New Mexico, Site as a test case.

Prior Activities: AS&T worked with Sandia National Laboratories to receive data for the Gnome-Coach site. The site's geology is conducive to 2D conceptualization and 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. The data were processed for testing of the ArcGIS transport modeling, which requires a porosity raster. The dataset provided specific storage, and a porosity raster was estimated from the specific storage dataset.

FY 2017 Activities: This investigation is complete. This study concluded that by incorporating site variability, the ArcGIS particle tracking algorithm can be used to make a more precise estimate of transport distances at a site than a simple Darcy's law calculation. The necessary data are available for most sites, and the required raster files can be constructed with ArcGIS, for example, by kriging water elevations and hydraulic conductivity measurements at wells to create raster files. This simplified approach can provide a quick 2D analysis of potential transport distances with time without the effort required to develop a 3D flow and transport model. This would be applicable for sites that cannot justify a 3D modeling effort or as a preliminary analysis for sites that will potentially be numerically modeled.

5.2 NVOS 3D Visualization Project

Overview: The 3D visualization project is being used to improve the understanding of site subsurface conditions by interactively viewing various datasets such as subsurface features, well locations, concentrations, water levels, model results, and institutional controls in their relative positions. The goals of this study are to:

- Develop 3D visualizations for Nevada Offsites (NVOS) projects using ArcGIS with 3D Analyst.
- Evaluate 3D visualization with respect to the EQuIS rollout.
- Develop 3D visualizations for NVOS and other selected sites.
- Assess if 3D visualizations can be made available to the public through the Geospatial Environmental Mapping System (GEMS).

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 site and to position new monitoring wells that were installed in 2014. The 3D visualization was used as part of a presentation to communicate conceptual model development and monitoring network enhancement at the Shoal site to regulators in late August 2016.

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 site. The 3D visualization of the Rulison site was presented to LM and LMS in a June 2016 brown-bag lunch presentation.

FY 2017 Activities: This investigation is complete. This study concluded that 3D visualization enables site interpretations and conceptual models to be understood quickly, even for people who are unfamiliar with a site. Displaying the surface, subsurface, well geometries, concentrations, water levels, flow directions, and numerical model results interactively and concurrently is much easier to assimilate than viewing these aspects separately. 2D screen shots of a 3D visualization only hint at the overall capabilities.

Developing a 3D project requires effort, but a general framework for a site can usually be developed in a few days. Many of the necessary data are readily queried from SEEPro

(Section 4.5) using MS Access and processed in MS Excel. The processing primarily consists of calculating statistics of sampling results (e.g., average, minimum, maximum for different analytes and for different periods) and associating them with well screen zone geometries. The database transition from SEEPro to EQuIS should cause only a slight disruption and should eventually be beneficial. Routines can be developed using Python coding to automate some of the data processing.

The next step would be to make the 3D visualization projects widely available over the internet. There is currently no easy path, such as using GEMS, which would require a large effort, but the potential exists to use Portal for ArcGIS and ArcGIS Online. The ArcGIS Online service was recently disabled for the LM network and is being evaluated by IT for potential security issues.

The 3D visualizations for a number of sites were used successfully for interactions with regulators and stakeholders. These include those prepared for the Gasbuggy, Rulison, CNTA, Shoal, and Weldon Spring sites.

5.3 LM and Subsurface Insights Modeling Collaboration

Overview: Subsurface Insights LLC was awarded a grant by the DOE Office of Science to further develop real-time modeling capabilities in May 2016. Subsurface Insights specializes in developing, enhancing, commercializing, and applying software and hardware for semiautonomous geophysical and geological data acquisition, processing, and result delivery. LM, through ongoing collaborations at the Old Rifle site, was approached by Subsurface Insights to share existing site data to test and demonstrate predictive assimilation framework (PAF) capabilities. PAF has the capability to evaluate continuous time series, geochemical sampling, and electrical geophysical monitoring data. PAF can process and display these data and use them to automatically update groundwater flow and transport models using parameter estimation calibration techniques. AS&T assisted Subsurface Insights by providing regular automated downloads of SOARS data from multiple LM sites to be used as input to the PAF algorithm.

FY 2017 Activities: This investigation is complete. AS&T continued to provide regular automated downloads of SOARS data from multiple LM sites to be used as input to the PAF algorithm. Subsurface Insights delivered a presentation and demonstration to LM on July 19, 2017.

5.4 Literature Review of Uranium Sequestration through Polyphosphate Injection

Overview: The objective of this study is to conduct a literature review and critical analysis of technologies for remediating uranium contamination, including polyphosphate, in groundwater for potential application at LM sites. This study will be accomplished by a review of published papers, vendor reports, and web-based material. It will include recommendations for bench and pilot-scale testing of one or more remedial technologies.

Prior Activities: None.

FY 2017 Activities: This short-term investigation was initiated in FY 2017, and the literature review was completed. This investigation will be finalized in FY 2018.

5.5 Title II Groundwater Flow and Contaminant Transport Model Evaluation Guidance

Overview: LM has responsibility for uranium processing sites addressed by Title II of UMTRCA. UMTRCA Title II sites were once commercially owned and are regulated under an NRC license. For license termination, the owner must conduct an NRC-approved cleanup of any onsite radioactive waste remaining from former uranium ore-processing operations. The site owner must also provide full funding to the federal government for inspections and maintenance and groundwater monitoring, if needed. Once site cleanup is complete, LM accepts title to these sites on behalf of the United States and assumes long-term management.

Based on the Title II sites that have transitioned to LM, the primary issue remaining at these sites is associated with contaminated groundwater. Title II sites tend to have large disposal cells that were consolidated from onsite uranium tailings, which complicates long-term groundwater issues. The title II sites that will transfer in the future are expected to have some of the most challenging and complicated groundwater issues that LM will face. Therefore, it is critical to ensure that groundwater characteristics and the potential for elevated groundwater concentrations to migrate offsite are understood. The main tools to accomplish this goal are groundwater flow and contaminant transport models. The owners of Title II sites with groundwater issues have used these models to evaluate long-term environmental impacts from past operations. Before a site transitions into the LM program, the site models need to be evaluated by LM in a consistent and defensible manner. Thorough evaluation of site models and identification of potential model deficiencies will allow LM to anticipate and plan for potential future long-term management challenges. Moreover, it may provide the opportunity to have the current owners address issues before the site is transitioned to LM.

Prior Activities: None.

FY 2017 Activities: This short-term investigation was initiated in FY 2017 and is ongoing. A final guidance document for reviewing Title II site models will be issued in FY 2018.

6.0 Environmental Sciences Laboratory

Overview: Funding from the AS&T subtask order is used to maintain the ESL 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. The scope of work includes:

- 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

The ESL continues to be an integral part of the LM program. Because of the emphasis on groundwater studies inherent in the work conducted in LM, the laboratory services various projects throughout LM.

FY 2017 Activities: The ESL performed approximately 17,000 analyses on 2300 samples in FY 2017. These analyses were performed to support LM site activities and AS&T projects. AS&T completed all laboratory maintenance and calibration tasks. The laboratory operated trouble-free. Training modules were reviewed and updated. An industrial hygiene evaluation was performed by an LMS industrial hygienist. AS&T completed a comprehensive review of the ESL Chemical Hygiene Plan, added new procedures to the ESL Procedures Manual (formalized when the manual was reissued November 2016), and completed two laboratory inspections. The chemical hygiene officer initiated a temperature and humidity evaluation to determine the necessity of a heating, ventilation, and air conditioning system upgrade for the ESL. All chemical containers were inspected for integrity. All accumulated hazardous materials and wastes were transported to the Mesa County Hazardous Waste Disposal Facility, and all mercury thermometers were replaced with nonhazardous thermometers. There are no longer mercury-containing items in the ESL. All accumulated purge water from the Gnome-Coach site generated in FY 2017 was evaporated. The remaining evaporites were scanned by Safety and Health and stored in the locked Control Area cabinet.

A new high performance liquid chromatography system was procured and installed. This generates a new solvent-based waste stream that was evaluated by both Environmental Compliance and Safety and Health before generation. Service agreements for the ion chromatography, total organic carbon, inductively coupled plasma, and liquid scintillation counter instruments were renewed. Preventive maintenance was performed semiannually on two fume hoods, the laboratory compressor, and the vacuum pump. The microscope lab was relocated to allow use of that room for office space for a new SOARS employee. A dedicated space in the laboratory soils room was relinquished to segregate potentially radioactively contaminated samples obtained by the Defense-Related Uranium Mines Project.

AS&T provided procurement support to scientific focus areas. Column studies were performed on the Riverton site floodplain soils and Tuba City site soils. Samples were submitted to the ESL for analyses from the Rocky Flats, Durango (processing), Shiprock, Riverton, Monticello, Shoal, and Tuba City sites. Results from these analyses were used to support LM site activities, including construction water disposal, groundwater treatability testing, groundwater characterization, tracer testing, and treatment system evaluation.

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