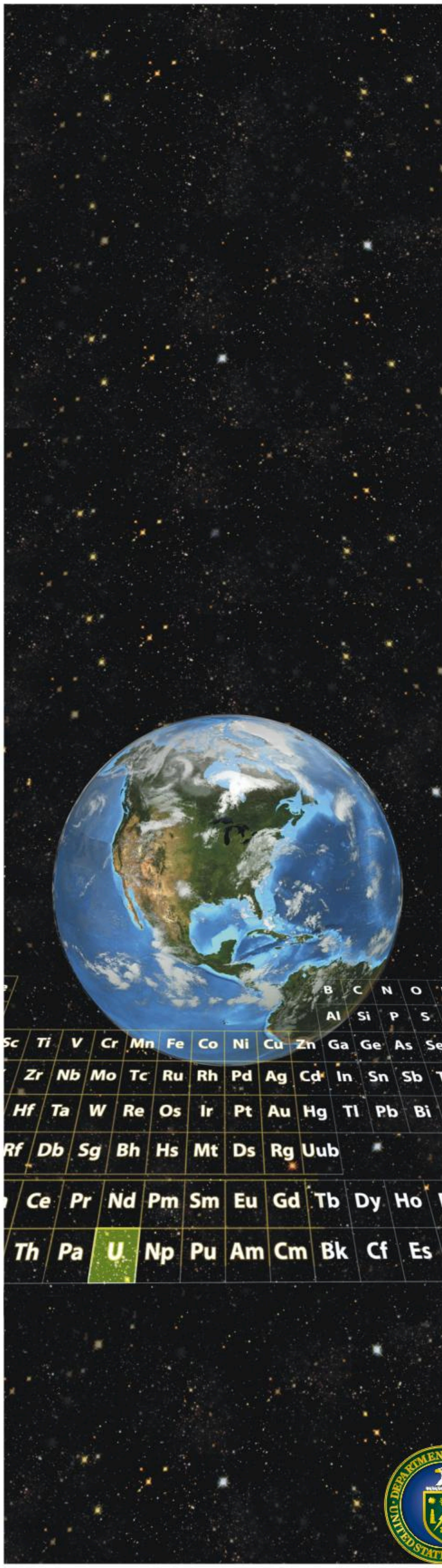
LMS/ESL/S12203
ESL-RPT-2014-03

Environmental Sciences Laboratory



Long-Term Surveillance Operations and Maintenance

Fiscal Year 2014 Year-End Summary Report

September 2014

Prepared for

U.S. DEPARTMENT OF ENERGY | Legacy Management

This page intentionally left blank

LMS/ESL/S12203
ESL-RPT-2014-03

Long-Term Surveillance Operations and Maintenance

Fiscal Year 2014 Year-End Summary Report

September 2014

This page intentionally left blank

Contents

Figure

Tables

Abbreviations

cm	centimeter
CS	conventional shank
DMA	data mining and analysis
DOE	U.S. Department of Energy
ECAP	Enhanced Cover Assessment Project
EMS	Environmental Management System
EPA	U.S. Environmental Protection Agency
ESL	Environmental Sciences Laboratory
ET	evapotranspiration
FY	fiscal year
IDL	Interactive Data Language
ISR	in-situ recovery
LM	Office of Legacy Management
LMS	Legacy Management Support
LTS&M	long-term surveillance and maintenance
LTS–O&M	Long-Term Surveillance Operations and Maintenance
LTSP	Long-Term Surveillance Plan
m	meter
$mg\ kg^{-1}$	milligrams per kilogram
mm	millimeter
mm/yr	millimeters per year
MS	master of science (academic degree)
MTL	Maximum Tolerance Level
NRC	U.S. Nuclear Regulatory Commission
NUREG	NRC regulatory guide
POS	parabolic oscillating shank
QA	quality assurance
SC	specific conductivity
SCT	specific conductivity/temperature
SOARS	System Operation and Analysis at Remote Sites
TDSP	Technology Deployment Strategic Planning
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978
USGS	U.S. Geological Survey
WCR	water content reflectometers
WTS	wing-tipped shank

This page intentionally left blank

1.0 Introduction

The Long-Term Surveillance Operations and Maintenance (LTS–O&M) subtask has a critical long-term surveillance and maintenance (LTS&M) role for the U.S. Department of Energy (DOE) Office of Legacy Management (LM). LM needs knowledge and tools to ensure that implementation of LTS&M will be informed, efficient, and cost-effective. This effort includes moving long-term stewardship strategies and methods into the "state of the practice" at LM sites. Site leads also need better information and resources to work more effectively with regulators and stakeholders to ensure that improved approaches meet compliance better than baseline technologies. The overriding goal is to explore and apply innovative ways to reduce LTS&M costs and risks to human health and the environment.

LTS–O&M is divided into three main focus areas: (1) Surface Projects, (2) Subsurface Projects, and (3) Remote Monitoring, Analytics, and Environmental Sciences Laboratory (ESL). Surface Projects addresses disposal cell covers, phytoremediation, and other technology that is at or near the ground surface. Sustainability of disposal cell covers is critical to the long-term containment of legacy wastes. Subsurface Projects addresses the flow of groundwater and its ability to transport contaminants. It includes evaluation of groundwater remediation methods. Remote Monitoring, Analytics, and ESL includes the maintenance of a nationwide telemetry system called SOARS (System Operation and Analysis at Remote Sites) and the ESL. The ESL is a facility containing a geochemical laboratory, an ecology laboratory, a petrography facility, and an instrument calibration facility.

Each of the three main focus areas has a lead scientist. Core projects are authorized through technical task plans. The work is conducted by various Legacy Management Support (LMS) contractor personnel and occasionally through outside subcontractors. Many of the projects are conducted at LM sites and involve close collaboration with LM site leads. Work conducted in the ESL and through SOARS is often directed by site personnel.

This page intentionally left blank

2.0 Objectives

LTS–O&M is a subtask of LM Task Order 501. This subtask addresses objectives outlined in the *2011–2020 Strategic Plan* (DOE 2011) and in the AS&T Five-Year Plan (DOE 2012). In particular, a principle objective is to enhance protection of human health and environment through application of current and proven technology. The subtask objectives are summarized as follows:

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

This page intentionally left blank

3.0 Subsurface Projects

Groundwater contaminant plumes still remain at many LM sites, including many sites associated with former uranium-processing facilities. Groundwater models constructed over the past 30 years generally predicted that the contaminant concentrations in the plumes would decrease to acceptable values much faster than has been observed. Many hydrologic, geochemical, and biochemical processes are interacting in the subsurface environment, all of which could be responsible for this recalcitrant behavior. Compliance strategies are often based on the time frame of groundwater cleanup; thus, making accurate predictions of cleanup rates is important to the LM program. One focus of the LTS–O&M Subsurface Projects is to identify and evaluate the dominant subsurface processes acting to decrease the rate of groundwater remediation.

Physical, chemical, and biochemical processes in the subsurface are highly variable, a condition referred to as heterogeneity. Conditions can change radically over millimeter- to kilometer-length scales. It is typically unreasonable to collect and analyze sufficient numbers of samples to accurately account for the high levels of variability in the subsurface, so interpretations must be made from a limited data set. To help establish reliable interpretations of incomplete data sets, another focus of the LTS–O&M Subsurface Projects is to determine the variability in subsurface data.

3.1 Variation Project

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

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

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

Specific conductivity is a function of the concentration of dissolved ions. The SCT profiles are made by slowly lowering a sonde through the water column. Because no pumping is required, this method has minimal disruption to the water column and provides a semicontinuous set of concentration data that can be used to evaluate the degree of well stratification. The simplicity of the method allows a large quantity of data to be collected at relatively low cost.

Another objective of the Variation Project is to determine if there is a correlation between specific conductivity and contaminant concentrations (e.g., SC vs. uranium). A goal of this effort would be to test the assumption that stratification in SC indicates similar stratification in contaminant concentrations. Also, if a suitable correlation exists, specific conductivity may be a viable surrogate that could be measured in lieu of more costly sampling and analysis of chemical concentrations. (The efficacy of using SC as a surrogate for contaminant measurements would probably vary from site to site or even from well to well at a given site.) To meet this objective, some wells will be sampled for a suite of chemical concentrations in combination with SCT profiling.

An SCT profile provides direct information only about stratification in a well bore. At many LM Uranium Mill Tailings Radiation Control Act (UMTRCA) sites, there is a need for information about conditions in the aquifer so as to improve groundwater transport models. Thus, another goal of the Variation Project is to determine what, if any, information the SCT profiles provide about conditions in an aquifer. To best accomplish this goal, an effort is underway to develop a test facility at an LM site that would use a high density of multilevel monitoring wells to provide an accurate 3-dimensional characterization of a segment of a uranium plume. Comparison of SCT profiling in wells with long screens to the multilevel data from the test site will help determine the extent to which SCT profiling can be used to interpret aquifer conditions.

Wells often contain stagnant zones that contain old water and can contribute to stratification. A technique using radon-222 concentrations was developed for this project to help assess the degree of stagnation. Radon-222 occurs naturally in aquifers because it is supported by emanation from radionuclides in the sediments. When groundwater enters a well bore, the radon-222 is no longer supported and it starts to decay. Thus, the activity of radon-222 can be used to detect stagnant water. With a half-life of 3.8 days, this method can be used to detect water that has resided in a well bore for periods of a few days to a few weeks.

Well stratification could be permanent or it could be ephemeral. If ephemeral, consistent sampling might be accomplished by occasionally pumping the water from the well bore or circulating it to eliminate dead zones. A method referred to as circulation testing was developed for the Variation Project to address the issue of stratification permanence. The method uses a small pump to circulate water from the bottom to the top of the water column. A string of specific conductivity/temperature sensors spaced over the entire water column collect data throughout the test. Data collected during rebound are being used to help delineate the groundwater flux through the well. These data will also help predict the causes of the stratification and relate well-bore stratification to chemical conditions in the aquifer.

FY 2014 Activities: The technical task plan for this project was revised to reflect slight changes in objectives and to accommodate the revised technical task plan management process described in Section 9.0. A central activity in FY 2014 was the measurement of SCT profiles at 15 LM sites (Table 1). All of the fieldwork, except at the Bluewater site, was completed. Although originally slated for SCT profiling, the Monticello site was removed from consideration as directed by the LM site lead.

Table 1. Summary of Profiling Activities

Site Name	Number of Wells Profiled	Data Entered?
Bluewater, NM, Disposal Site	Scheduled (Oct-2014)	No
Durango, CO, Disposal Site (Bodo Canyon)	7	Yes
Durango, CO, Processing Site	24	Yes
Grand Junction, CO, Processing Site (Climax)	4	Yes
Grand Junction, CO, Office Site	8	Yes
Green River, UT, Disposal Site	20	Yes
Monument Valley, AZ, Processing Site	80	Yes
Naturita, CO, Processing Site	26	Yes
New Rifle, CO, Processing Site	29	Yes
Old Rifle, CO, Processing Site	22	Yes
Riverton, WY, Processing Site	33	Yes
Shiprock, NM, Disposal Site (Floodplain)	85 (2013) 78 (2014)	Yes
Shiprock, NM, Disposal Site (Terrace)	6	Yes
Slick Rock, CO, Processing Site	32	Yes
Tuba City, AZ, Disposal Site	23	Yes

Data Mining and Analysis (DMA) programs were written in FY 2014 to enable rapid visualization of data in user-defined subsets (Section 7.0 has details of the DMA project). Data can be viewed in various 2- and 3-dimensional formats using data sets controlled by the user. The programs allow for a wide range of user control such as the ability to view contours of the maximum, minimum, mid-screen, or average values. As needs develop, the programs can easily be extended to meet most requirements. Nearly all of the SCT profile data have been entered into digital form for use with the DMA programs. Preliminary screening of the SCT profiles indicates that specific conductivity in some wells has little variation, whereas in other wells it varies by more than a factor of 2, and in some extreme cases, by an order of magnitude.

In FY 2014, DMA programs were also written to evaluate circulation test data. The first few circulation tests conducted at well 0618 on the Shiprock floodplain showed that the SCT profiles rebounded to their original state within about 12 hours after circulation was discontinued. This result indicates that the SCT profile is permanent and suggests that groundwater is flowing rapidly through the well bore. LTS–O&M personnel are evaluating these data in conjunction with modeling approaches in the scientific literature to determine if the data are sufficient to quantify the groundwater flux. These evaluations are potentially important because knowledge of groundwater flux improves estimates of contaminant transport and cleanup rates.

3.2 Plume Persistence Project

Overview: The main motivation for the Plume Persistence Project 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. The project is divided into three study areas to accomplish this goal: (1) contaminant residence, (2) rate-limited processes, and (3) modeling. These three study areas were recommended in the *Five-Year Plan for Applied Science and Technology* (DOE 2012). LM approved the original technical task plan for Plume Persistence on August 8, 2013.

Previous studies have shown that contaminant desorption rates decrease as contaminants age in an aquifer. Therefore, a focus of this project is to measure rates of uranium desorption from sediments that have been contaminated for several decades. Geoprobe drill core samples for the investigation were collected in 2012 from an alluvial aquifer at the Grand Junction (Colorado) office site. Uranium, the principal contaminant in these core samples, was introduced into the aquifer from a milling operation about 60 years ago. It is expected that aging processes acting during these 6 decades has caused some uranium to become more closely associated with the sediment in a manner that causes its release to be rate-limited.

The Geoprobe coring was conducted at 22 locations over the uranium plume at the Grand Junction office site. Core samples were collected every foot for a total of 366 samples. The samples were air dried and sieved. A SOARS station, with water-level and specific-conductivity sensors, was established at a well in the central portion of the cored area.

Batch tests were conducted on the core samples to determine the mass of uranium removed by four different extracting media. The different extractants are intended to release uranium that is bound in different forms. The extractants (in order of those expected to release only loosely held uranium to those expected to release more tightly bound uranium) are (1) bicarbonate/carbonate solution (labile fraction), (2) 5 percent nitric acid, (3) concentrated nitric acid (microwave digestion), and (4) lithium metaborate fusion (total digestion). The results of these extractions are being used in conjunction with data from petrography and column testing to evaluate the mineralogical residences of the uranium. The results provide information to help determine how tightly the uranium is bound to the aquifer solids.

Polished thin sections were prepared for a subset of the samples. Fission-track maps of the polished thin sections were prepared on mica detector plates affixed to the thin sections. The mica–thin-section packages were subjected to a prescribed flux of slow neutrons to fission the uranium, which produces tracks in the detector plates. The detectors were then etched to make the tracks large enough to be visible for microscopic analysis. To analyze the fission-track maps, significant improvements were made to the ESL petrography laboratory. Two existing petrographic microscopes were outfitted with digital cameras. Software was purchased that allows images of the polished thin section and the fission-track map to be projected side by side so that fission tracks can be accurately mapped to the mineral and textural feature in the thin section. These techniques provide a unique means to identify the mineralogical associations of uranium. The same suite of samples used for fission tracking was subjected to preliminary column tests. The columns had periods of intentional interruption to evaluate the effects of rate-limited uranium desorption.

This project is still largely in the data collection stage. Results indicate that uranium is bound to the sediments in variable ways, as evidenced by the different removal efficiencies using various extraction media. Fission-track analyses indicate that some uranium resides in mineral coatings on grain surfaces. Fission tracks are also concentrated in the fine-grained matrix of composite sedimentary grains. The grain coatings and the fine-grained matrix containing the uranium appear to be associated with iron oxide or oxyhydroxide. Column test results indicate that some of the uranium is bound in a way that causes variable desorption rates.

FY 2014 Activities: The technical task plan for this project was revised to accommodate the revised technical task plan management process described in Section 9.0.

Twelve "small" column tests have been conducted. Analysis of the effluent uranium samples from these columns, database entry, and preliminary visualizations were completed. The small column tests are being used to determine the prevalence of rate-limited uranium desorption over a large area of plume at the Grand Junction office site. The column tests involved passing a simulated groundwater through the columns at a constant flow rate. The flow was intentionally interrupted twice during each column test. Uranium released from the sediment during the flow interruptions indicated the presence of rate-limited desorption. Most of the tests showed rate-limited desorption, suggesting that it is a common occurrence at the site.

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

In FY 2015, analysis of the fission tracks and petrography will be completed. Data evaluation, including 3-dimensional visualizations, will also be completed in FY 2015. In FY 2015 and 2016, the column test data will be simulated using 1-D numerical models that incorporate multispecies chemical equilibrium and rate-limited desorption. Depending on the results of the column simulations, modeling may be extended to predict effects of rate-limited desorption on remediation scenarios.

3.3 Dewey Burdock Project

Overview: Reactive transport modeling is being used as a tool for prediction of downgradient uranium fate and transport at uranium in-situ recovery (ISR) sites. This project was originally initiated in 2010 by the U.S. Environmental Protection Agency (EPA) Region 8 and the U.S. Geological Survey (USGS) in Denver in response to the proposed Dewey Burdock ISR site near Edgemont, South Dakota. Previous work includes two USGS Open-File Reports and multiple presentations on the unique conditions at the site. EPA is working on the permitting process for this site and needs to develop appropriate requirements to protect downgradient aquifers. The methods being developed at this site include the estimation of uranium sorption parameters and the use of those parameters in reactive transport modeling. The parameter estimation and modeling efforts focus on the natural attenuation processes for uranium in downgradient bedrock. Developing a consistent methodology will assist EPA and other stakeholders in evaluating aquifer protection at the Dewey Burdock site and will be applicable at other uranium ISR sites, including some LM sites. In addition, this project provides general data analysis and modeling techniques that will be applicable to any site with uranium fate and transport issues in groundwater.

FY 2014 Activities: A presentation was given at the EPA Region 8 office in downtown Denver on August 27, 2014. The same presentation was given at the USGS office at the Denver Federal Center the same day. Two draft manuscripts are in co-author review and should have internal reviews completed with submittal to the journal *Mine Water and the Environment* in early 2015 (calendar year). These two draft manuscript titles are "Using solid-phase iron concentrations, batch sorption tests, and generalized composite surface complexation models to determine uranium sorption parameters at a proposed uranium in-situ recovery site" and "Predictive reactive transport modeling at a proposed uranium in-situ recovery site."

3.4 Stanford Support

Overview: Personnel from Stanford University are leading a project that is exploring for naturally reduced zones in alluvial sediments in the Colorado River Basin. Some of the data for their study come from samples collected at former uranium-processing sites in the LM program. In particular, some samples collected at the Old Rifle site contain elevated uranium concentrations that are naturally reduced. This correlation suggests that reduction exerts a control on transport of uranium by groundwater. Through an alternate DOE grant, Stanford personnel are funded to conduct the scientific aspects of the study. LTS–O&M is supporting them by supplying personnel and equipment to collect cores through Geoprobe drilling and arrange the required permits, compliance planning, health and safety analyses, and facilities permissions and notifications. LTS–O&M is also providing logistics for them to conduct geophysical surveys.

FY 2014 Activities: Support provided to Stanford personnel through the LTS–O&M subtask included technical discussions, support to collect cores at the Grand Junction office site, and support to conduct geophysical surveys at two sites. Discussions were also held to identify four additional LM sites suitable for expanding their study. LTS–O&M-funded personnel accompanied Stanford personnel on introductory tours at three of the sites.

The planning process for the Grand Junction Geoprobe drilling was initiated. Discussions were held with the landlord of the site, and the Project Activity Evaluation process was initiated. Several discussions were held regarding Stanford's findings at Old Rifle. Drilling support personnel accompanied Stanford personnel in selection of drill locations, and a map was prepared.

4.0 Surface Projects

A substantial portion of the LM budget funds LTS&M of disposal cells at UMTRCA and other sites. Two key LM goals are to reduce LTS&M costs and to maintain the protectiveness of remedies (DOE 2011). Natural soil-forming processes and ecological succession are changing the as-built engineering properties of UMTRCA covers (and other surface remedies) in ways that could increase LTS&M costs and alter long-term protectiveness. LM funds LTS–O&M Surface Projects (1) to gain a better understanding of the effects of these natural processes on the performance of disposal cell covers and (2) to investigate options for improving LTS&M. Some surface projects are evaluating effects of natural soil-forming processes and ecological succession on the performance of engineered covers with respect to radon gas diffusion and surface flux rates, rainwater percolation into underlying tailings, plant and animal intrusion and bioaccumulation of tailings elements, and erosion and stability of covers. Other projects are investigating the adaptability of covers to climate change and are identifying natural analogs for clues about possible long-term changes in cover performance. Surface projects also include monitoring the performance of alternative cover designs and evaluating techniques to enhance or transform conventional covers with the goal of maintaining protectiveness over the long term.

For all Surface Projects, LTS–O&M scientists seek to establish collaborations with state-of-the science researchers, share costs, foster education with a focus on stakeholder communities, disseminate new knowledge through conferences and workshops, and defend through peer-reviewed publications.

4.1 Enhanced Cover Assessment Project (ECAP)

Overview: ECAP supports two LM strategic goals: (1) increase confidence in the long-term protectiveness of remedies and (2) reduce LTS&M costs (DOE 2011). ECAP is directly monitoring the hydrologic performance of an UMTRCA disposal cell cover—which has never been done. ECAP is also evaluating methods that LM could use to manage or enhance natural soil-forming and ecological processes that are effectively transforming conventional disposal cell covers into water balance covers. Conventional covers rely on a layer of compacted clayey soil to limit exhalation of radon gas and percolation of rainwater. Water balance covers rely on a less compacted soil “sponge” to store rainwater, and on soil evaporation and plant transpiration (evapotranspiration [ET]) to remove stored water and thereby limit percolation. Cover enhancement may include allowing or accelerating plant growth on covers to increase ET. Currently, many Long-Term Surveillance Plans (LTSPs) require the control of plant encroachment on covers, most often using herbicides. Herbicide spraying and other vegetation management costs have increased as habitat for vegetation has become more favorable on covers.

Background: Most engineered earthen covers overlying uranium mill tailings disposal cells include a highly compacted fine soil layer designed to limit the surface flux of radon and to control percolation of rainwater. Compacted soil “protection layers” often overlie the “low-permeability radon barriers” to protect them from frost and desiccation cracking. These compacted soil layers are armored with durable rock riprap placed on a coarse-grained bedding layer. The riprap layer is designed to withstand worst-case water and wind erosion events. UMTRCA covers were designed to control radon flux, maintain low saturated hydraulic conductivity, and withstand erosion "for a period of 1,000 years to the extent reasonably achievable" (40 CFR 192.02).

The as-built engineering properties of compacted disposal cell covers are subject to change by natural soil-forming and ecological processes over relatively short time periods regardless of climate or the type of cover design. Natural soil-forming processes create structure in compacted layers, increasing the porosity and saturated hydraulic conductivity, sometimes by several orders of magnitude. Percolation rates and radon fluxes may increase as a result of these changes. Processes that initiate these changes include freeze-thaw and desiccation cracking, retention of borrow soil structure during construction, and biointrusion. Greater changes in hydraulic properties occur in less permeable, highly compacted clayey soil layers; smaller changes occur in soils that are less compacted and more permeable when placed. Over time, the hydraulic properties of cover soils become similar to the original undisturbed borrow soil properties regardless of the as-built condition.

Designers of UMTRCA covers expected the rock riprap layers to also inhibit plant germination and establishment. Research and experience have shown that the rock-armored soil creates a favorable habitat for deep-rooted plants, even in the desert, by reducing soil evaporation, increasing soil water storage, and trapping windblown dust, thereby providing water and nutrients for plant germination and establishment. Excavations have shown that roots can extend vertically into and through radon barriers where they became fibrous root mats following soil structural planes.

Conversely, soil-forming and ecological processes may be beneficial in the long term. These processes can increase soil water storage, soil evaporation, plant growth, and plant transpiration, and thereby introduce an alternative means for controlling percolation. In arid and semiarid ecosystems, relatively low precipitation, high potential ET, and thick unsaturated soils limit percolation and recharge. Disposal cell covers designed to mimic this natural soil water balance, often referred to as water balance covers or ET covers, can provide sustainable hydraulic isolation in semiarid and arid regions. Therefore, natural soil-forming and ecological processes that are slowly transforming engineered earthen covers with compacted soil layers, such as those specified under UMTRCA, to vegetated soil profiles resembling water balance covers, may provide long-term advantages compared with the original compacted soil designs. ECAP and other surface projects are evaluating the tradeoffs of potentially detrimental and beneficial changes, and methods to enhance beneficial changes, thus providing LM with the knowledge and tools to improve LTS&M of disposal cells.

LTS–O&M staff constructed two ECAP test facilities at the Grand Junction, Colorado, Disposal Site (described below) to monitor the hydraulic performance of an UMTRCA cover and to evaluate cover enhancement methods. One facility consists of two large drainage lysimeters; the other is a large test pad. The test facilities were designed to address four objectives as defined in the ECAP technical task plan:

1. *Directly monitor the water balance and hydraulic performance of an UMTRCA cover:* Monitoring the soil water balance will provide (1) a direct measure of field percolation and hydraulic performance and (2) baseline data to evaluate enhancement methods. Rainwater percolation through UMTRCA covers has been estimated but never measured directly.
2. *Evaluate natural changes in the soil engineering properties of an UMTRCA cover:* ECAP activities will include measuring natural pedogenic changes in as-built soil engineering

properties of the test section covers, properties that govern the hydraulic performance of a low-permeability radon barrier.

3. *Evaluate natural and enhanced ecological succession on an UMTRCA cover:* Assuming that the natural transformation to water balance covers can be beneficial, ECAP results will be used to evaluate revegetation methods for accelerating plant establishment and creating conditions on rock covers that are more favorable to plant growth, thereby increasing ET rates.
4. *Demonstrate, monitor, and model hydraulic performance enhancement methods:* Large test facilities will be used to evaluate effects of enhancement methods on revegetation success and cover hydraulic performance. Because the establishment of desert vegetation can take many years, long-term monitoring will be necessary to acquire meaningful results.

FY 2014 Activities: In FY 2014, LTS–O&M staff continued soil water balance monitoring in two lysimeter test sections, recalibrated lysimeter instrumentation, completed a cover soil manipulation study, evaluated changes in cover soil hydraulic properties, and continued the revegetation study. We planned and carried out these activities in collaboration with Dr. Craig Benson, University of Wisconsin-Madison, and Dr. Bill Albright, Desert Research Institute-Reno.

4.1.1 Lysimeter Test Sections

The two ECAP drainage lysimeters are like large, HDPE plastic swimming pools containing highly instrumented disposal cell test covers. Placement of soil and rock layers in the lysimeters matched the engineering design, materials, and construction of the in-service Grand Junction disposal cell cover. The instrumentation monitors the water balance of the simulated covers—how much water falls on the soil surface as precipitation, sheds as runoff, becomes stored in the soil sponge layer, evaporates and transpires out of the soil sponge by plants (ET), and, most important, how much water percolates through the cover. LTS–O&M staff will evaluate cover enhancement options (transformation to a water balance cover) in one lysimeter; the other lysimeter will be maintained to simulate the existing Grand Junction cell cover.

In FY 2014, LTS–O&M staff continued monitoring the water balance of test covers in the two ECAP lysimeters, checked calibration of instrumentation, evaluated changes in as-built soil hydraulic properties, and began drafting a paper on the field hydrology the UMTRCA cover.

Water Balance Monitoring: Percolation rates in the test covers increased in 2014. The site received 388 millimeters (15 inches) precipitation from July 2013 through June 2014, so far the wettest water year since lysimeters were constructed in 2007. As a consequence, percolation increased from an average of 1.9 millimeters per year (mm/yr) from 2007 to 2013 to 8.8 millimeters (mm) for 2014. Percolation totals for the two lysimeters were nearly identical for the 2013–2014 water year. However, percolation was less than 3 percent of precipitation, runoff also continued to be very low (about 0.1 percent of precipitation), and evaporation was the dominant water balance flux. Percolation flux continued as an intermittent or stair-step pattern, which is commonly associated with the formation of preferential flow paths.

Lysimeter Calibration: LTS–O&M staff conduct quality assurance (QA) evaluations and reduce and plot lysimeter data (16 different parameters) on a quarterly schedule. A 2013 QA evaluation indicated that the calibration of water content reflectometers (WCRs) in both lysimeters should be checked. (WCRs are soil moisture monitoring instruments.) In FY 2014, new laboratory calibration equations were developed for the WCRs using bulk samples of cover soils from stockpiles at the Grand Junction disposal site.

Changes in Soil Hydraulic Properties: EPA, the U.S. Nuclear Regulatory Commission (NRC), and DOE studies have shown that the as-built engineering properties of cover soils can change by several orders of magnitude 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 a mulch, reducing evaporation and potentially limiting the amount of soil cracking caused by wet-dry and freeze-thaw cycles. In FY 2014 LTS–O&M staff and university collaborators repeated field tests to determine changes in key soil hydraulic properties since construction of the test covers in 2007. We measured soil hydraulic properties in the field and in the laboratory. Saturated hydraulic conductivity in the radon barrier and frost protection layer was measured in the field using large borehole permeameters. We also hand-excavated large intact blocks of the cover soil layers and, in the laboratory, measured saturated hydraulic conductivity using a flexible wall permeameter, and determined soil water characteristics curves (SWCCs) using a large-scale pressure plate method plus a chilled mirror hygrometer method for the dry end of the SWCC. Results show that the geometric mean of the saturated hydraulic conductivity in both the radon barrier and the frost protection layer increased by almost 2 orders of magnitude between 2007 and 2013 (Table 2).

Table 2. Changes in saturated hydraulic conductivity (K_{sat}) of the frost protection and radon barrier layers in the ECAP lysimeter test sections.

Cover Layer	K_{sat} (cm/s)	
	2007	**2013**
Frost Protection		
max	1.8E-04	7.2E-04
geometric mean	6.1E-07	1.1E-05
min	1.3E-08	8.7E-07
Radon Barrier		
max	7.4E-07	3.3E-04
geometric mean	4.3E-08	1.4E-06
min	7.4E-09	5.4E-08

cm/s = centimeters per second

Cover Field Hydrology Paper: In FY 2014, LTS–O&M staff and university collaborators began drafting a manuscript on the field hydrology of an UMTRCA cover using the ECAP lysimeter data. The paper will present an evaluation of the hydraulic performance of the cover based on water balance monitoring and changes in soil hydraulic properties over a 7-year period. We are delaying completion of the paper to incorporate data from the abnormally wet summer of 2014.

4.1.2 Test Pad

LTS–O&M staff constructed a test pad at the Grand Junction disposal site to demonstrate and evaluate cover enhancement methods, including soil manipulation and revegetation options. The 25 meter (m) by 50 m test pad was constructed on a stockpile of the fine-textured soil that DOE used to construct the protection layer in the Grand Junction 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 Grand Junction disposal cell cover. The test pad is divided into three areas: two larger areas for the revegetation study and a smaller central area for the soil manipulation study. 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. The test pad was constructed in June 2010, ripped in August 2011, and sampled in May 2012. Delays exposed the cover profile to seasonal soil settling, wet-dry cycles, and freeze-thaw cycles, both before and after ripping. In FY 2014 we completed laboratory tests of soil properties, published a DOE final report on the soil manipulation study, drafted a journal manuscript, and continued the revegetation study.

Soil Manipulation Study: A goal of ECAP is to test methods that could accelerate the transformation of a conventional UMTRCA cover into a water balance cover. The simulated cover profile consisted of compacted layers of fine-grained soil overlain with a gravelly sand bedding layer and a cobble riprap armor layer. Seven soil manipulation treatments designed to blend and loosen compacted soil layers were compared on the test pad. The objectives of these manipulations are to trap seed, increase seed-soil contact, capture runoff in the seedbed, increase soil water storage in the protection layer, and enhance rooting depth and water extraction. The intent is to create a cover that stores infiltration in the protection layer and sustains a plant community that seasonally removes stored water. We evaluated combinations of soil ripping implements (conventional shank, CS; wing-tipped shank, WTS; and parabolic oscillating shank with adjustable wings, POS), ripping depths, and number of passes with a ripping implement.

We determined, for each ripping treatment combination, the dimensions, dry density, moisture content, and particle size distribution of disturbance zones in two trenches excavated across rip rows on the test pad. All treatments created V-shaped zones of disturbance as measured on trench faces. The size of the disturbed zone was most influenced by ripping depth followed by type of implement; winged implements (WTS, POS) created larger zones of disturbance. Mixing of bedding and protection layers with the conventional (CS) and winged (WTS and POS) treatments were comparable. All ripping treatments lifted fines up into the bedding layer, moved gravel and cobble down into the protection layer, and thereby disrupted the capillary barrier at the layer interface. Changes in dry density within disturbance zones were comparable for the CS and WTS treatments but highly variable among POS treatments. Mixing the layers increased the water content of the bedding layer and decreased the water content of the protection layer. Overall, the POS drawn at a 1.2 m depth and two passes created the largest zone of disturbance, the lowest dry density in the protection layer, and moved more fine soil up from the protection layer up into the bedding and riprap layers. However, ripping also created large soil aggregates and voids in the protection layer that may create preferential flow paths and reduce soil water storage capacity.

Revegetation Study: Transformation of conventional covers into water balance covers will rely on sustainable vegetation and transpiration of soil water. Successful enhancement and acceleration of natural plant succession—revegetation—involves first understanding and then manipulating the plant ecology of the cover. LTS–O&M staff designed and began installing a revegetation study on the test pad in FY 2014 to address gaps in our understanding of methods for establishing vegetation on rock-armored compacted soil.

We designed the study to evaluate effects of soil-ripping practices, plant species mixes, planting methods, and irrigation, on plant germination, species composition, diversity, and abundance. The study is designed to compare combinations of soil manipulation treatments (described above) and four species mixes that we selected based on literature surveys and characterization of reference areas. The study also compares two planting methods, and ambient precipitation with irrigation. The planting methods are broadcast seeding and broadcast seeding paired with transplanting seedlings of dominant species. One-half of the plots will be irrigated enough to wet the seedbed for the first growing season. All plots will receive an organic fertilizer and mycorrhizal fungi inoculum. We designed the irrigation system and began growing transplants in FY 2014. Seeding, transplanting, and installation of the irrigations system is scheduled for FY 2015.

4.2 Plant Uptake of Contaminants on Disposal Cells

Overview: The uptake and bioaccumulation of tailings constituents by plants rooted in disposal cells is a potential ecological exposure pathway that has previously received only limited consideration at LM sites. Other aspects of plant growth have been investigated. LTS–O&M staff and others have studied root intrusion effects on soil morphology and percolation, and we are evaluating methods to enhance plant growth and ET as a way to limit percolation (Section 4.1). We are also designing an investigation of the effects of plant growth and transpiration on radon attenuation (Section 4.6.1).

Why is LM concerned about plant uptake of tailings elements? LTSPs currently require vegetation removal on many disposal cell covers, while on other covers, LTSPs allow plant growth. LM needs a consistent policy that can be used to develop site-specific vegetation management plans for disposal cells. Developing a consistent policy will require an understanding of the balance of potential benefits and detriments of plant growth on disposal cells. The goal of this project is to acquire field data that can be used to evaluate risks of contaminant uptake by plants rooted in disposal cell covers. If risks are negligible, and if other projects show that the potential benefits of plants growing on disposal cell covers outweigh potential detriments, then LM may choose to discontinue vegetation removal on selected disposal cell covers as a way to reduce LTS&M costs.

The objectives of this ongoing plant uptake study 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 similar to those on the disposal cell cover), (2) evaluate bioaccumulation of tailings contaminants in leaf litter and surface soil, and (3) if warranted, assess risks to human health and the environment.

FY 2014 Activities: A field comparison of tailings elements in stem and leaf tissues for plants rooted in seven disposal cell covers, with plants growing in reference areas, began in FY 2011. A University of Arizona Master of Science (MS) student participated in the study. The student began laboratory analyses of plant tissues in FY 2012 and drafted her thesis based on results from two of the sites. LTS–O&M staff and university colleagues completed the initial laboratory analysis of plant tissues in FY 2013 for the remaining five sites. In FY 2014 we assessed ecological risks of plant uptake, completed laboratory analyses of radium in archived tissue samples, began drafting a DOE project report, and had an abstract accepted for presentation at the 2014 Ecological Society of America meetings. In FY 2015 we plan to complete the DOE report, incorporating results of the radium analyses, and draft a journal manuscript.

The study measured concentrations of uranium, radium. molybdenum, thorium, selenium, manganese, lead, and arsenic in aboveground tissues harvested from plants growing on seven UMTRCA cells in the western United States (Table 3). Ecological risks were screened by comparing analyte levels in plants 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 adjacent to the disposal cells. In 14 of 46 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 in New Mexico. The area is known for soils that are naturally seleniferous, and since plants growing both on these disposal cell covers and in reference areas had elevated selenium levels, the contamination likely originated from local borrow soils rather than the underlying tailings.

Table 3. Plant Species Sampled and Analytes Listed

LM Site	Plant Species	Analytes
Tuba City, Arizona, Disposal Site	Fourwing saltbush, kochia	U, Ra, Th, As, Se, Mo, Pb
Bluewater, New Mexico, Disposal Site	Fourwing saltbush, Siberian elm	U, Ra, Th, Mo, Se
L-Bar, New Mexico, Disposal Site	Fourwing saltbush, rabbitbrush	U, Ra, Th, As, Se, Mo, Pb
Lowman, Idaho, Disposal Site	Ponderosa pine, mock orange	U, Ra, Th
Lakeview, Oregon, Disposal/Processing Site	Sagebrush, bitterbrush	U, Ra, Th
Sherwood, Washington, Disposal Site	Bitterbrush, ponderosa pine	U, Ra, Th, As,
Split Rock, Wyoming, Disposal Site	Rabbitbrush	U, Ra, Mn, Mo

Abbreviations: U = uranium, Ra=radium, Th = thorium, As = arsenic, Se = selenium, Mn = manganese, Mo = molybdenum, Pb = lead

LTS–O&M staff and collaborators are currently conducting analysis of variance and regression analysis for uranium, radium, and other elements of concern in tissues of woody plants rooted in seven UMTRCA disposal cell covers. We are also conducting a literature survey of the potential long-term bioaccumulation of tailings elements in plant litter and soil beneath canopies of plants rooted in disposal cell covers. In FY 2015 we plan to draft a journal manuscript on uptake of elements of concern by plants rooted in UMTRCA covers. The paper will include (1) statistical comparisons of tissue concentrations for uranium and other metals in plants rooted in covers with plants growing in reference areas (control sites), (2) results of analyses for radium-226 activity in plant tissues, and (3) an evaluation associated human health and ecological risks.

4.3 Long-term Value of Revegetation Practices

Overview: Revegetation is an integral component of LM site remediation and LTS&M. Remediation at many LM sites included reclamation and revegetation of disturbed tracts of land. Revegetation methods at western LM sites generally followed principles and guidance developed over many years for mine land reclamation, roadside revegetation, rangeland management, and ecological restoration. Reclamation and revegetation have attempted to restore the ecological integrity and productivity of disturbed LM land. Revegetation objectives included erosion control, weed management, habitat restoration, and livestock forage production. Revegetation practices included manipulation and management of the physical, chemical, and biological properties of soils. Practices also included seedbed preparation, planting, and maintenance of vegetation.

The natural succession of revegetated LM sites is ongoing. The success of revegetation practices has been highly variable and usually evaluated only in the short term. Long-term revegetation success may be dependent on many factors, including the severity of ecological disturbance, initial soil properties, quality of revegetation efforts, climatic variability, and ongoing land management. Short-term evaluations have indicated that revegetation can be a challenging tradeoff between cost and probability of success. Low-cost practices are generally less successful, especially at arid and semiarid sites. Well-planned and higher-cost methods often improve short-term success.

The long-term success of revegetation practices and grazing management at LM sites is not well understood. Long-term studies are rare in the ecological sciences. Many projects have been evaluated just 2 or 3 years following revegetation, leaving questions of long-term success unaddressed. Uniform, long-term quantitative monitoring and the application of knowledge gleaned from past projects to new ones are often lacking. Because LTS&M will continue indefinitely, LM has a unique opportunity to evaluate the long-term success of revegetation and grazing management at sites remediated more than 20 years ago and, with that knowledge, potentially reduce costs and improve future ecosystem management and sustainability at many sites.

The Environmental Management System (EMS) Land Stewardship team contributed to the conceptual approach for this project.

FY 2014 Activities: In FY 2014, LTS–O&M scientists (1) organized and began collaboration (and cost sharing) with the University of Arizona to develop the study as an MS thesis, (2) designed the project as a repeat of published revegetation studies conducted at the Tuba City site in the 1990s, and (3) began vegetation and soil sampling at the Tuba City site.

We designed the study to evaluate the success of different revegetation efforts at the Tuba City site, 26 years after DOE remediated the site. The objective is to determine the long-term (decades) effectiveness of past revegetation and grazing practices at the site by acquiring field data to answer the following questions, and to apply the new knowledge to improve ecosystem management:

- Did revegetation accelerate natural succession?
- Were high-cost revegetation methods more successful than low-cost methods?
- Have revegetation practices achieved plant community targets that were based on undisturbed reference areas?
- Which resulted in better weed control: revegetation or natural succession?
- How well did past, short-term evaluations predict long-term revegetation success?
- Has grazing management improved revegetated and native rangeland ecology?

The study began in June 2014 and is comparing five ecological conditions at the Tuba City site: three revegetation trials on areas bladed to remove windblown contamination, and two grazing scenarios.

Revegetation Trials	Grazing Scenarios
1. Transplanted and irrigated	4. Grazed native vegetation
2. Reseeded and irrigated	5. Native vegetation protected from grazing
3. Reseeded and not irrigated	

The study is repeating characterization of areas revegetated in 1986 and 1996. Short-term evaluations of these areas are well documented. Large tracts bladed during remediation to remove windblown contamination were first seeded in 1986. In 1999, DOE and University of Arizona published a comparison of the seeded areas with native plant communities, both grazed and protected from grazing. A second study, started in 1996 and published in 2001, compared low-cost and high-cost revegetation methods consisting of different combinations of transplanting, seeding, and irrigation. In June 2014, we began repeat sampling of plant community composition and diversity, plant density and canopy cover, and soil fertility and morphology.

We organized this project as a collaboration (and cost-sharing) with Dr. Karletta Chief (University of Arizona extension specialist to Native American communities, and Assistant Professor in the Department of Soil, Water, and Environmental Science). Quentin Benally is a student working on the project in partial fulfillment of requirements for an MS in environmental science. Mr. Benally drafted a work plan and completed spring sampling of plant cover in revegetated and native plant communities that have been protected from grazing for 25 years. Dr. Chief is Mr. Benally's MS committee chairperson. An LTS–O&M scientist serves on Mr. Benally's committee. Mr. Benally receives funding through the Alfred P. Sloan Foundation Indigenous Graduate Partnership.

4.4 Adaptation of Covers to Climate Change

Overview: Goals of this project are to help LM comply with Executive Order 13514 and DOE's Climate Change Adaptation Plan, and to support the EMS Climate Change Adaptation team. Our overall objective is to project the long-term performance and adaptability of LM disposal cell covers to climate change and related changes in cover ecology and soil morphology. In the 1990s, LTS–O&M scientists and collaborators conceived a framework for projecting long-term cover performance that links (1) probabilistic, numerical, ecohydrology models, (2) monitoring of existing covers to calibrate and validate models, (3) climate change models, and (4) characterization of natural analogs.

We demonstrated the framework while designing the Monticello water balance cover. We combined predictions of different global climate change models with paleoecological evidence of past climate states to establish first approximations of possible future climate states for the Monticello disposal site (for example, warm/dry and cool/wet scenarios). Soil development and ecological analog sites were defined and selected by finding geographical locations with (1) instrumental climate records that match different climate change scenarios for a site, (2) soil types similar to the soil used to construct a cover, and (3) a range of plant succession stages, including climax vegetation. The soil morphology, soil physical and hydraulic properties, and plant ecology of the analog sites were characterized and results input to probabilistic models to project cover performance.

As currently conceived, this project will refine the long-term cover performance evaluation framework, use more-current climate models that include climate variability and extreme events, and refine methods for selecting and characterizing analog sites that are intended to represent future environmental scenarios for a site. A scenario, for example, might include a future climate state for a site based on global change models, future ecological conditions for the climate state, and a different land use. Future ecology and soil morphology would be inferred from characterization of natural analogs for the climate state. This information, along with climate variables, would be input to an ecohydrology model to project cover performance for that environmental scenario.

FY 2014 Activities: In FY 2014, LTS–O&M scientists (1) organized and began collaboration (and cost sharing) with the University of Arizona to develop components of the project as part of a doctoral (PhD) program, (2) outlined an approach to refine the conceptual framework that incorporates recent Executive Orders and DOE directives, and (3) supported the EMS Climate Change Adaptation team.

This project was also (see Section 4.3) developed as a collaboration (and cost-sharing) with Dr. Karletta Chief (University of Arizona extension specialist to Native American communities, and Assistant Professor in the Department of Soil, Water, and Environmental Science). Dr. Chief's PhD student, Carrie Joseph, is developing a work plan to demonstrate an approach for LM to investigate the long-term adaptation of disposal cell covers near Native American communities to a changing climate. Ms. Joseph is also funded through the Alfred P. Sloan Foundation Indigenous Graduate Partnership.

LTS–O&M scientists supported the EMS Climate Change Adaptation team by contributing to the Climate Change Adaptation Section for the 2013–2014 Site Sustainability Plan, and to an *ECHOutlook* newsletter article.

LTS–O&M scientists outlined a conceptual approach for LM to investigate climate change impacts and adaptation, as required by Executive and DOE orders, with application to the long-term performance of disposal cell covers for uranium mill tailings. The conceptual approach has seven components:

1. *Climate Change Directives:* Keep current with DOE orders, directives, and LM administrative plans that address climate change adaptation, and the applicability of these directives to an assessment of the long-term performance of disposal cell covers.
2. *Climate Scenarios:* Identify climate change scenarios for UMTRCA disposal sites. Develop criteria and select a subset of UMTRCA sites for a range of variables such as climates, ecology, cover designs, and risks. Develop scenarios of past, present, and future climate using paleoclimate data, meteorological data, and climate change models. Document climate change trends and extreme events for all three time frames.
3. *Conceptual Evaluation: Future Vulnerability and Risk:* Identify potential impacts of climate change on the function and performance of UMTRCA disposal cell covers and risks

(e.g., risks to human health and the environment and risks of not satisfying design and performance criteria).

4. *Conceptual Evaluation: Adaptability and Building Resilience:* Identify if and how covers were designed to adapt to climate change, if and how ongoing natural processes may actually increase cover resilience, and in what ways LM could enhance resilience.
5. *Tools for Projecting Long-Term Performance:* Assess current models and other tools for projecting the long-term performance of covers, and identify key performance parameters. For example, identify models and input parameters that are applicable for simulating cover soil water balance, ecological change, radon flux, and erosion.
6. *Natural Analogs:* Use steps 2–4 to develop an approach for selecting and investigating natural analogs of the impacts of climate change on the soils and ecology of disposal cell covers. This would require recent climate data, and soil and vegetation surveys, to find present-day settings that match selected future-environment scenarios. And then characterize key soil and ecological parameters of analog sites for input to the cover performance models in Step 5.
7. *Model Future Cover Performance and Risk:* Develop a framework for using Steps 1–6 to model future performance of covers. Document and interpret results with respect to cover performance, risk to human health and the environment, regulatory requirements, future site inspections and monitoring, and cover enhancement options (if warranted).

4.5 Water Balance Cover Monitoring and Modeling

Overview: LM is investigating alternatives to conventional cover designs for cells containing uranium mill tailings. The Monticello, Utah, Disposal Site cell, completed in 2000, has a conventional, low-conductivity composite cover overlain with an alternative cover designed to mimic the natural soil water balance as measured in nearby undisturbed native soils and vegetation. To limit percolation, the alternative cover design, sometimes called a water balance cover or ET cover, relies on a 160-centimeter (cm) (63 inch) layer of sandy clay loam soil overlying a 40 cm (16 inch) sand capillary barrier for water storage, and a planting of native sagebrush steppe vegetation to seasonally release soil water through ET. The study is addressing four objectives:

- Demonstrate methods for large-scale monitoring of an in-service ET cover.
- Characterize changes in soil engineering properties.
- Monitor the long-term responses of the soil water balance to soil-forming processes, ecological succession, and climate change.
- Use the lysimeter data to evaluate different soil water balance models.

The Monticello site is a good location for a long-term test of a water balance cover because of the relatively short growing season and semiarid to subhumid climate—it is at the cool-wet climatic fringe for locations where water balance covers might work. EPA and DOE installed a large pan lysimeter in 2000 during construction of the disposal cell cover at the Monticello site. EPA, DOE, NRC, and others are using the unique data from the large in-service lysimeter at the Monticello site to help guide decisions on the use of water balance covers at other sites.

FY 2014 Activities: Lysimeter monitoring continued for a 14th year in collaboration with University of Wisconsin and Desert Research Institute, and the project continued to be valued by DOE and other agencies (nationally and internationally) involved in the design and monitoring of disposal cells.

Water balance monitoring within a 3-hectare (7.5-acre) drainage lysimeter provides convincing evidence that the cover has performed well in limiting percolation over the 14-year period (2000–2014). Precipitation, water storage, percolation, and ET are monitored in real time in the embedded lysimeter. Lysimeter water balance data collected using SOARS (Section 6.0) were reduced and plotted quarterly. As of July 2014, the large embedded lysimeter had recorded zero percolation in 2014, for a percolation rate of about 0.4 mm/yr during 14 years of monitoring, or about 0.1 percent of annual precipitation. More than 50 percent of the total percolation over 14 years occurred in 2005, which was the second wettest winter on record. In contrast, average percolation in conventional low-permeability covers located in similar environments, as measured by EPA's Alternative Cover Assessment Program using large lysimeters, was about 35.0 mm/yr, or 9.1 percent of precipitation.

Because the unique Monticello study is based on direct, real-time, large-scale, and long-term monitoring of an in-service water balance cover, it has attracted national and international attention. LTS–O&M scientists gave two invited presentations on the Monticello water balance study during FY 2014:

- Uranium Recovery and Reclamation Workshop, American Nuclear Society Annual Meeting, Washington DC, November 2013.
- International Atomic Energy Agency workshop and tour, Monticello, Utah, March 2014.

4.6 Erosion, Hydrology, and Ecology of Rock/Soil Covers

Overview: This project was authorized to evaluate effects of mixed rock and soil armoring on the erodibility, hydraulic performance, and ecology of disposal cell covers. The scope includes evaluations of (1) effects of soil manipulation options to enhance cover protectiveness (Section 4.1) on the erodibility and stability of cover slopes, and (2) effects of both natural and deliberate soil deposition in rock armor on the hydraulic performance of covers and the trajectory of ecological succession.

FY 2014 Activities: LTS–O&M scientists prepared a conceptual approach for this study, investigated the feasibility of resampling study plots established by DOE in 1980 that were designed to address this issue, and interacted with University of Wisconsin regarding an applicable draft NRC regulatory guide (NUREG).

Conceptual Approach: Soil can become mixed with the rock armor on UMTRCA disposal cell covers either deliberately, as part of efforts to enhance the hydraulic performance of covers, or naturally due to windblown and organic deposition. LM is currently evaluating the deliberate mixing of soil and rock (Section 4.1) to create conditions more favorable for plant establishment, growth, and transpiration. Natural soil deposition occurs when windblown dust becomes trapped in rock layer interstices at drier sites, or as leaf litter decays and fills the rock interstices with organic soil at more humid sites.

Of importance to LM are the effects of deliberate or natural mixing of soil in rock layers on soil erosion, slope stability, and plant succession. Rock armor designs for UMTRCA covers are based on explicit NRC guidance regarding rock size, durability, and layer thickness to control worst-case water and wind erosion events. Deliberate mixing or natural deposition of soil may alter the rock armor designs. A draft NRC NUREG reported simulations of fluvial erosion and soil hydrology for several scenarios—combinations of climate, surface layer, topography, and vegetation—using coupled landform evolution and soil hydrology models. The simulations included rock and soil mixtures in arid, semiarid, and humid climates, both with and without vegetation, and with different slope angles and lengths. (The draft NUREG is based on a University of Wisconsin MS thesis that used the Grand Junction disposal cell topography and cover design as a starting scenario for performance modeling.)

Also of importance to LM are the effects of soil deposition on the hydraulic performance of covers as influenced by changes in water storage capacity, the trajectory of plant succession, root water extraction depths, and transpiration. For example, as a rock layer fills with windblown dust or decayed plant litter, will deep-rooted species persist or will soil evaporation increase, drying the soil layer and creating habitat more favorable for shallower-rooted species?

This study will apply a combination of numerical modeling, field investigations, and natural analogs to project the long-term stability, hydraulic performance, and regulatory acceptance of covers that may undergo these changes. Tasks will include,

- Determine if the draft NUREG modeling study encompasses LM disposal cell cover scenarios for rock-soil mixtures, topography, climate, and vegetation; and whether the scenarios are acceptable to NRC as an evaluation of the sustainability of applicable cover enhancement methods.
- Evaluate mineral and organic soil deposition and plant habitat in rock armor on in-service UMTRCA covers.
- Characterize existing study plots and natural analogs for clues as to the long-term stability, ecology, and hydraulic performance of slopes armored with rock and soil mixtures.

1980 Rock/Soil Cover Study: LTS–O&M scientists are investigating the feasibility of resampling disposal cell cover test plots established for DOE in 1980 to evaluate the effects of surface rock and rock/soil mixtures on soil water and vegetation. The tests were installed at the San Juan Coal Mine near Waterflow, New Mexico, to simulate cover options for disposal cells at Shiprock and in similar climates. The treatment and design structures for the field experiment follow:

Treatment Structure:

Factor (Independent Variable)	Level	Design Structure: Split-split-plot analysis of variance:
Surface Layer	1. Cobble riprap / soil	1. Percent canopy cover
	2. Pit-run river rock / soil	2. Species diversity index
	3. Soil only	3. Volumetric soil moisture
Seed Mix	1. Shrub & forb dominated	Dependent (Response) Variables:
	2. Grass dominated	1. Percent canopy cover
Planting Method	1. Seeded only	2. Species diversity index
	2. Seeded and transplants	3. Volumetric soil moisture
	3. Transplants only	
Irrigation	1. 120 cm/year	
	2. 60 cm/year	
	3. No irrigation	

Results published in 1984 indicated that excluding vegetation on rock covers, even for short time periods, can increase the moisture content of the cover, leading to percolation or destabilization of the cover. Surface rock favored the establishment of vegetation, as DOE has since learned observing in-service UMTRCA covers (Section 4.1). However, covers with surface rock and rock/soil mixtures that were planted had no significant effect on soil moisture relative to soil covers without rock. The most successful seed mixture was predominantly shrub and forb species that have adapted to the local environment.

The field test plots for this study have been protected intact by San Juan Coal Mine for over 34 years. The plots provide LM a realistic, long-term simulation of conditions on disposal cell covers in similar environments (e.g., Shiprock) if natural succession were allowed to progress (i.e., if LM ceased herbicide applications). The plots also simulate the long-term condition for different soil manipulation and revegetation options that LM might use to transform existing conventional covers into water balance covers (Section 4.1).

4.7 Depth of Soil-Forming Processes in Covers

Overview: LM authorized this project to determine if natural soil-forming processes, which have been shown to change as-built engineering properties of thinner UMTRCA covers (Section 4.1), also alter the performance of thicker covers.

FY 2014 Status: LTS–O&M scientists prepared a conceptual approach for this study and began collaborating with University of Wisconsin on a work plan. We currently envision combining this project with “Effects of Soil-Forming and Ecological Processes on Radon Attenuation” (Section 4.8), with LM and NRC sharing the costs.

Natural soil-forming processes change key engineering properties of earthen covers over relatively short time periods regardless of climate or the type of cover design. By creating cracks and fissures in compacted soil layers, natural processes increase permeability, porosity, and percolation, sometimes by several orders of magnitude, and potentially increase radon flux rates. Within 5 to 10 years, natural soil-forming processes increase saturated hydraulic conductivity, saturated volumetric water content, and the air-entry suction, all of which reflect the formation of larger soil pores.

The processes that bring about these changes include freeze-thaw and desiccation cracking, retention of borrow soil structure (peds or clods) during construction and development of soil structure after construction, and biointrusion. The greatest changes in hydraulic properties occur in highly-compacted clayey soil layers such as low-permeability radon barriers; the least amount of change occurs in less-compacted soils such as water balance covers. Over time, cover engineering and hydraulic properties trend back to the original undisturbed borrow soil properties regardless of the as-built condition.

The depth that natural processes will alter compacted soils in thick UMTRCA covers is not well understood. Although recent research and field tests have shown that soil development and associated changes in soil engineering properties that influence water percolation and radon flux should be expected in thinner covers (about 1.0 m thick), less is known about how soil development affects engineering properties of compacted soil layers that are overlain with protective layers of soil and rock riprap (for example, the Rifle disposal cell), or that are in the lower portions of exceptionally thick, low-permeability radon barriers (for example, the Shiprock disposal cell).

This study will be designed to evaluate the depths at which natural soil-forming processes could alter the compaction, porosity, saturated hydraulic conductivity, and water retention characteristics of low-permeability radon barriers in UMTRCA covers. As currently planned, tasks will include (1) identify pedogenic processes that may alter engineering properties during a cover's 1,000-year design life, (2) compile evidence from the literature regarding the depths of changes in soil engineering properties, (3) characterize natural analogs of the depths of soil-forming processes in covers, and (4) measure compaction, porosity, saturated hydraulic conductivity, and water retention characteristics in existing thick covers.

4.8 Effects of Soil-Forming and Ecological Processes on Radon Attenuation

Overview: LM authorized LTS–O&M to collaborate with NRC to achieve the common goal of understanding the long-term effects of soil-forming processes and plant encroachment on radon flux in UMTRCA disposal cell covers.

FY 2014 Status: LTS–O&M scientists prepared a conceptual approach for this study and began collaborating with University of Wisconsin on a work plan. We currently envision combining this project with "Depth of Soil-Forming Processes in Covers" (Section 4.7), with LM and NRC sharing the costs.

Soil-forming processes are inevitable and will create cracks and planes of weakness in low-permeability radon barriers, increasing permeability and loosening soil compaction—even in the absence of vegetation (Section 4.1)—potentially increasing radon flux. Plants accelerate natural soil-forming processes, which increase permeability by creating fissures in the soil structure. Plants could potentially increase radon flux by drying low-permeability radon barriers, by contributing to the formation of macroporosity (channels), and by transporting radon to the surface through the transpiration stream.

We designed this study to address three knowledge gaps in our understanding of the potential detrimental effects of natural processes on radon attenuation:

1. *Whether plant transpiration will dry a low-permeability radon barrier to a soil moisture content low enough to cause radon flux rates to exceed the regulatory standard*. Soil moisture content greatly influences radon flux from covers; as soil moisture decreases, radon flux increases. UMTRCA covers were designed to satisfy a regulatory flux standard even when relatively dry. We do not know whether covers with mature vegetation and high transpiration rates will dry the radon barrier and cause radon flux rates to exceed the standard.
2. *Effects of natural soil-forming processes on radon diffusion and flux.* As designed, the primary purpose of low-permeability radon barriers is radon attenuation. As described above, within a few years, natural soil development will likely form fissures or cracks in these barriers. We do not know whether the fissures will increase radon flux to unacceptable levels at the surface of a given low-permeability radon barrier.
3. *Methods for monitoring radon flux on low-permeability radon barriers with well-developed soil structure.* The typical device used to measure radon flux rates on compacted soil is a

canister with activated charcoal. Because these devices are designed to be sealed to the soil surface, they may be inaccurate for soil layers that have developed cracks and fissures.

LTS–O&M scientists and university collaborators plan to evaluate effects of plant encroachment and soil development on radon flux at the surface of radon barriers. To be representative of a likely long-term scenario, the study will include existing UMTRCA covers that have (1) a low-permeability radon barrier with well-developed soil structure, (2) woody plants rooted through the radon barrier, (3) a well-developed plant community (not sparse) that has seasonally dried the radon barrier, and (4) ideally undergone an exceptionally dry year. An expanded version of the study would measure radon flux for ranges of these conditions. The study will also characterize natural analogs of covers for clues about long-term effects of soil-forming processes and plant succession on radon flux.

We propose five tasks:

1. *Site Selection:* At least three UMTRCA disposal cells will be selected that have radon barriers varying in age, depth, and thickness that are in locations representing a range of soils, vegetation, and climates.
2. *Field Measurement of Radon Fluxes:* Radon fluxes at each site will be measured directly at the surface of the radon barrier. Large-scale flux chambers adapted from the inner ring of sealed-double ring infiltrometers will be used to ensure that radon flux measurements are made over an area sufficiently large to capture flow through macro-pore structure present in the radon barrier.
3. *Depth-Dependent Hydraulic Properties:* After the flux chamber tests are complete and the chambers are removed, large-scale (450 mm diameter) undisturbed block samples will be collected vertically through the radon barrier, and soil structure will be mapped on the face of the excavation. Saturated hydraulic conductivity and soil water characteristic curves will be determined for each block.
4. *Natural Analogs:* A nearby natural soil analog will be identified for each location to provide a realistic representation of long-term soil formation in the cover profile. Large, undisturbed block samples will be collected, macro-pore structure will be mapped, and hydraulic properties will be determined using the same procedures described in Task 3.
5. *Analysis:* Data collected in Tasks 2–4 will be used to assess percolation rates and radon fluxes for each of the UMTRCA covers relative to the predictions made during design. Percolation rates will be predicted using the program WinUNSAT-H. Radon fluxes will be estimated using source concentrations assumed during design, NRC's RADON (RAECOM) program, lead-210 profiles, water saturation profiles predicted by WinUNSAT-H, and gaseous diffusivity profiles, both for current conditions in covers and for analog soil conditions.

5.0 Natural and Enhanced Attenuation Projects

Overview: LTS–O&M supports natural and enhanced attenuation studies at the Monument Valley, Arizona, Processing Site, and the Shiprock, New Mexico, and Tuba City, Arizona, Disposal Sites. Phytoremediation and bioremediation pilot studies at the Monument Valley and Shiprock sites originated as feasibility studies funded under predecessors of LTS–O&M. Technology employed for the Tuba City ET study was initially developed for the Monument Valley pilot studies. Fieldwork on these projects is funded through site budgets; publications are funded through LTS–O&M.

FY 2014 Activities: In FY 2014, we (1) sampled for changes in soil nitrogen in phytoremediation test plots in the source area for the nitrate and ammonium plumes at Monument Valley, (2) analyzed stable isotopes of hydrogen and oxygen in plant, soil, and groundwater to test hypotheses about the sources of water used by plants in phytoremediation test plots at Shiprock, and (3) estimated ET for upland and phreatophytic vegetation for input to groundwater modeling of the contaminant plume at the Tuba City site. LTS–O&M also facilitated a University of Arizona proposal to use the Monument Valley site as a "test bed" for a uranium biosequestration study. These studies are planned and carried out through collaboration and cost-sharing with the Department of Soil, Water, and Environmental Science at the University of Arizona.

5.1 Monument Valley Enhanced Attenuation

Subpile Soil Nitrogen: In 2012 LM completed a suite of pilot studies designed to evaluate, on a landscape scale, proposed natural and enhanced attenuation remedies—phytoremediation and bioremediation—for ammonium, nitrate, and sulfate in an alluvial aquifer at the monument Valley site, and in the source area for the aquifer. Soils remaining in an area where a uranium mill tailings pile was removed (subpile soils) is a source of groundwater contamination. Removal of soil ammonium and nitrate was a goal of the subpile soil pilot study. LM submitted a draft final report to NRC and the Navajo Nation in 2013.

Starting in 2000 and continuing at least every other year since then, LTS–O&M scientists have sampled soils by hand auger at 40 random locations and analyzed samples in the Environmental Sciences Laboratory for nitrate as N, ammonium as N, and sulfate as SO_4^{2-} (Figure 1). Samples were taken at 0.3 m intervals to a maximum depth of 5 m. In 2000, mean concentrations of soil nitrate-N and ammonium-N were 163 milligrams per kilogram (mg k^{-1}) and 184 mg kg^{-1}, respectively. Nitrate levels fell sharply, by more than 50 percent, from 2000 to 2002, then dropped slightly through 2010 (we included the 2010 values in the 2013 draft final report). Mean total nitrogen had dropped from 355 mg kg^{-1} in 2000 to 181 mg kg^{-1} in 2010. We attributed the initial rapid drop to microbial denitrification, and we did not anticipate much additional change after 2010.

We sampled subpile soils again in 2012 and 2014 after submitting the draft final report. In 2012 we found very little change since 2010; total nitrogen levels remained at about a 50 percent drop since 2000. However, nitrogen levels dropped rapidly between 2012 and 2014. Mean nitrate and ammonium levels had decreased by 78 percent and 86 percent, respectively, from 2000 to 2014. Over 15 years, total nitrogen dropped from 347 mg kg^{-1} to 64 mg kg^{-1} in the subpile soils. The delta nitrogen-15 ($\delta^{15}N$) analysis and denitrification assays indicate that coupled microbial nitrification and denitrification reactions were responsible for the loss of N.

LTS–O&M scientists are co-authoring a draft journal manuscript with Dr. Ed Glenn and co-workers at University of Arizona to publish the results of subpile soil phytoremediation at Monument Valley after 15 years of monitoring.

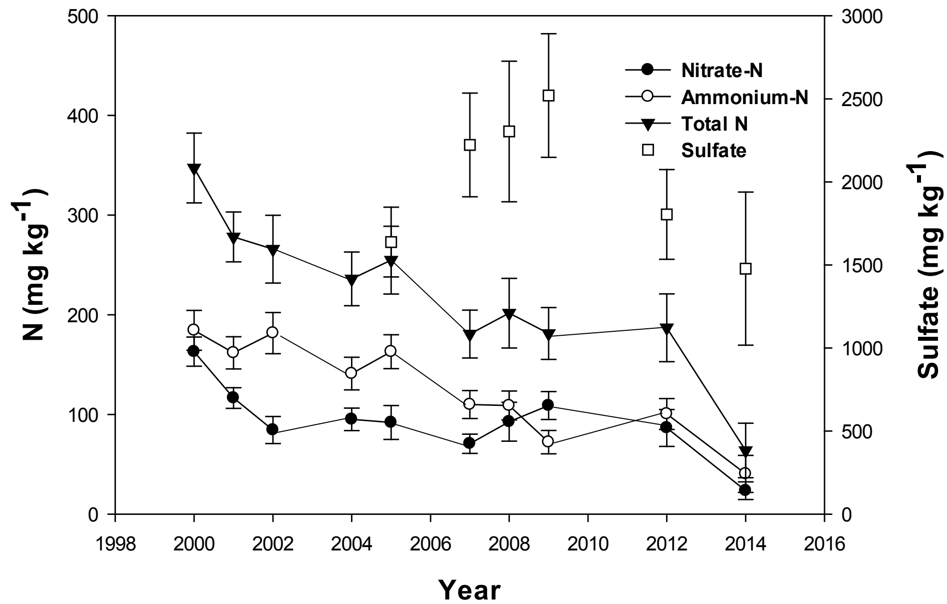


Figure 1. Means and standard errors of nitrate-N, ammonium-N, total N, and sulfate in the subpile soil area at the Monument Valley UMTRCA site, 2000–2014.

Uranium Biosequestration Proposal: In FY 2014 Dr. Mark Brusseau and co-workers at the University of Arizona submitted a proposal to use the Monument Valley site as a "test bed" for an investigation of "In-situ Biosequestration for Remediation of Uranium in Groundwater." (The next three paragraphs contain excerpts from Dr. Brusseau's proposal.)

Dr. Brusseau and co-workers had collaborated with LM between 2006 and 2010 on pilot-scale field tests at the Monument Valley site to investigate the feasibility and sustainability of in-situ bioremediation to treat groundwater contaminated by nitrate and sulfate. The field tests were supplemented by bench-scale tests, stable-isotope analysis, and mathematical modeling. The results of site characterization activities conducted prior to the test indicated slow rates of denitrification and the absence of measurable bacterial sulfate reduction. The injection of an electron donor induced denitrification and bacterial sulfate reduction, as confirmed by exponential decreases of nitrate and sulfate concentrations in concert with changes in oxidation-reduction potential, redox species, alkalinity, production of hydrogen sulfide, and fractionation of δ^{15}N-nitrate and δ^{34}S-sulfate.

The induction of reducing conditions caused a significant decrease in the concentration of uranium in groundwater (Figure 3), demonstrating feasibility of in-situ biosequestration at this site. Of great significance, the three-day, single injection of electron donor produced reducing conditions that were sustained for approximately 3 years.

The objective of the project is to investigate the feasibility and long-term efficacy of in-situ biosequestration for remediation of uranium-contaminated groundwater at the Monument Valley site. The project is designed to address several critical questions and topics regarding the effectiveness of the in-situ biosequestration method for the Monument Valley site:

1. What are the mechanisms that account for the long-term sustainability of reducing conditions (years) after a short addition of electron donor (days)?
2. Can naturally occurring sediment-associated iron be used to form iron sulfides if sulfate reducing bacteria are stimulated at the site?
3. What are the dominant mechanisms of U sequestration? Is the direct reductive biomineralization of U(VI) to UO_2 predominant? Or is the adsorption and chemical reduction of U(VI) by iron-sulfide precipitates more important?
4. The nature and long-term stability of the sequestered phases.
5. The impact of electron donor injection on microbial community structure and diversity (the environmental microbiome), which will help begin to elucidate the role of the microbial community in biosequestration.
6. Can co-contaminants at the site (As, Se, etc.) be sequestered by iron sulfides?
7. Does biomass produced from the cell yield of denitrifying and sulfate-reducing organisms contribute to a long-term, slow release supply of electron-donating substrate?
8. Optimal strategies for field-scale implementation, including selection of cost-effective electron-donor amendments.

5.2 Plant Water Sources at Shiprock

The goal of the phytoremediation pilot study at the Shiprock disposal site is to demonstrate hydraulic control—to establish transplants of native phreatophytic shrubs that can transpire shallow groundwater and thereby help control dispersion of groundwater contamination. We transplanted native phreatophytic shrubs in test plots in 2006 and began irrigating transplants with river water. We discontinued irrigation in half of each plot in 2010 to determine if plant roots had tapped shallow groundwater.

In FY 2014, we completed a preliminary analysis of water sources used by transplants grown in the test plots. Two test plots are located in the former borrow pit area, south of the cell, and overlie shallow groundwater contaminated primarily with nitrate. Two other plots are on the terrace near the escarpment, north of the cell, and overlie shallow groundwater contaminated primarily with uranium. A nitrate plume extends south under the borrow pit plots. A uranium plume extends from beneath the disposal cell north under the two terrace plots toward the San Juan River floodplain.

We analyzed stable isotopes of hydrogen and oxygen in plants, soil, and groundwater to test hypotheses about the sources of water used by plants. Ratios of stable isotopes of hydrogen and oxygen in water can indicate the sources of plant water and can be used to track hydrologic relationships among water sources. We collected water samples from plants, soils, groundwater wells, and the San Juan River in 2006 and 2007, sampled plants and potential water sources again in 2013, and analyzed all samples for ^{2}H (deuterium, D) and ^{18}O (oxygen). Our primary purpose in 2013 was to determine if unirrigated transplants were using water from shallow groundwater contamination plumes.

Below is a summary of preliminary interpretations of the isotopic composition of plant water sources.

- Statistical analyses indicate that there were no significant differences in the sources of water used by the two transplanted species.
- In contrast, statistical analyses indicate that there were significant differences in the isotopic composition of plant water from irrigated versus unirrigated transplants. In all plots, irrigated transplants appear to be using primarily irrigation water for growth.
- Unirrigated transplants overlying the uranium plume near the floodplain escarpment appear to be using primarily shallow groundwater for growth, but only in the plot with deeper groundwater. Unirrigated transplants in the plot with shallower groundwater appear to be using primarily irrigation water, although some individuals may be using a mixture of irrigation water and groundwater. Also, unirrigated plants might be using water moving laterally from the irrigated half of each plot.
- Some of the unirrigated transplants in the borrow pit plot with shallower groundwater were likely using groundwater for growth. Other unirrigated transplants in this plot appear to be using primarily irrigation water. Unirrigated transplants in the borrow pit plot with deeper groundwater appear to be using primarily rainwater for growth. As above, unirrigated plants might be using irrigation water from the adjoining plot.

LTS–O&M scientists are co-authoring a draft manuscript with Dr. Ed Glenn and co-workers at University of Arizona to publish the results of the Shiprock phytoremediation pilot study, including transplant survival and growth, uptake of uranium and other metals by transplants, and sources of plant water.

5.3 Tuba City Evapotranspiration

LM is reviewing and revising groundwater flow and contaminant transport models at the Tuba City site. The conceptual model incorporates effects of vegetation on groundwater recharge and discharge. The desert vegetation is relatively sparse except in areas where plants access groundwater. The sparse and heavily grazed uplands, where annual precipitation exceeds ET, may be sources of recharge. Groundwater may discharge as transpiration in other areas within the model domain where phreatophytic desert shrubs and riparian trees root into groundwater.

In FY 2014 we estimated ET rates using remote-sensing algorithms developed for groundwater-dependent riparian plants in the southwestern United States as modified and validated for desert vegetation types at the Tuba City site that are similar to vegetation types studied at the Monument Valley site. The ET algorithm is based on the Enhanced Vegetation Index from the MODIS sensors on the Terra satellite. Preliminary results indicate that the balance of precipitation and ET over the years tips between recharge and discharge in response to the amount of precipitation and the history of grazing. Similarly, management of grazing in areas with phreatophytic shrubs and riparian trees could significantly increase ET and discharge of groundwater, potentially enhancing hydraulic control of groundwater plume movement.

6.0 System Operation and Analysis at Remote Sites

Overview: The SOARS system was established in 2006 with LTS–O&M funding 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 by project personnel. It has saved money by reducing the number of trips to sites and has improved site evaluations by affording immediate access to detailed data sets. The system has grown considerably since its initiation in 2006 and is staffed by two full-time employees. This project demonstrated the feasibility of collecting data remotely in real time and transmitting them to LM computer servers. Many LM sites are in remote locations, and collecting data by regular field visits is costly. Well pumps and water treatment systems are also controlled remotely through SOARS to further lessen the need for travel. SOARS data are available immediately, expediting corrective actions. SOARS greatly improves the ability to diagnose problems and make timely repairs and adjustments. SOARS improves project teaming efforts because project personnel based at LM sites across the nation can access the data in real time. SOARS data are automatically processed using Vista Data Vision software to produce real-time graphs 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* (DOE 2014) is available as a Level 3 controlled document on the LM Intranet. A Google Earth file is maintained that shows locations of all SOARS stations. 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, water infiltration rate, and energy use. Electrical relays are used for remote control of 23 well pumps. The SOARS field systems are powered by 88 solar panels. Data are downloaded daily through 17 Internet protocol (IP) cell modems, 6 land-line IP connections, 1 satellite link, and 6 land lines. Onsite communication with the modems is accomplished using 105 radios. Approximately 300,000 data points are transmitted and graphed daily.

FY 2014 Activities: SOARS operated continuously through FY 2014 with relatively few issues. Web access to the SOARS system was functional more than 98 percent of the time. Data loggers and radio links functioned well. Project documentation was maintained, including SOARS notes, Job Safety Analyses, Plan of the Day meetings, procurement logs, instrument inventories, metrics, and calibration logs. The SOARS operations and maintenance manual (DOE 2014) was revised and reissued. Improvements were made to postprocessor graphs and data storage and retrieval programs. New graphs were added to better accommodate project 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 DMA programs (see Section 7.0). Calibration checks were conducted on field instruments at many sites. Most of the instruments maintained calibration and functioned successfully. Instruments were regularly lab-tested and calibrated prior to installation at field sites. Outdated or nonfunctional equipment was replaced during maintenance trips.

A major emphasis this year was the preparation of DMA programs for refining the SOARS data. The DMA programs are used to remove and revise erroneous SOARS data. Erroneous data result from field issues such as power interruptions. Details on the DMA project are provided in Section 7.0. This effort is resulting in a high-quality database that can be used with confidence to make groundwater interpretations. Prior to DMA programs, data had to be refined for each project, a time-consuming effort. DMA programs also provide data reformatting algorithms and visualizations tailored to LM projects.

7.0 Data Mining and Analysis

Overview: The motivation for developing DMA programs was the need to rapidly visualize large amounts of data from the Variation Project and the SOARS program. DMA is not a separately funded activity but rather is funded through other projects that have a need for the programs. Most of the DMA effort in FY 2014 was directed at and funded through the Variation Project and SOARS.

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

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

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

SOARS maintains a database containing more than 1.4 billion data values (Section 6.0). These data are graphed in real time and provided to a web-based interface by the Vista Data Vision software. However, these graphs contain "raw" data, that is, the complete and unaltered data that are supplied by the field instruments. These graphs are extremely useful in day-to-day operations of the project sites; however, they often contain erroneous data. Factors that cause inclusion of erroneous data include:

- Power interruptions
- Instrument failure
- Datalogger programming errors
- Instruments being removed from wells (e.g., sampling or calibration checks)

Thus, the data typically require refinement to enable accurate interpretation of site-related processes, such as groundwater flow or plume migration. Unbiased data refinement is carried out through DMA programs by basing all refinement decisions on reliable information. Since its inception in 2006, SOARS has maintained electronic databases containing field notes and calibration records that detail activities relevant to data quality. These notes provide a basis for making unbiased decisions on data refinement. DMA programs are being used to check data quality and to remove or modify bad data. The result is a refined database that contains only data that is relevant to a particular analysis. The raw data are always maintained so that refined data can be readily compared to the original.

FY 2014 Activities: Three software licenses for IDL and two data-miner licenses were procured. Eight DMA programs were completed and are being beta tested. Four of the programs support the Variation Project, and four support the SOARS program. The programs supporting the Variation Project use data obtained from SCT profiles of LM monitoring wells (Variation Project is described in Section 3.1). The programs supporting SOARS mine data directly from the Vista Data Vision mySQL database. Calibration data are mined from the SOARS Microsoft Access-based calibration database and the SEEPro database. All eight programs have menu-driven, user-friendly interfaces. The users can specify data "groups" that focus on their specific problem. Table 4 provides summaries of each program.

Table 4. Summaries of DMA programs

Program Name	Description
Stickball	3D plots of SCT profiles
Vertical Profiles	2D plots of SCT profiles
Spatial Profiles	Contour plots of SCT profile data (e.g., mid-screen values)
Spatial Chemistry	Contour plots of groundwater chemical data
Maintenance	QA program to refine the database
Timelines	SOARS (refined) concentrations vs. time (with zoom)
Elevations	SOARS (refined) groundwater elevation contours
Elevations Plus	SOARS (refined) groundwater elevation, specific conductivity, and temperature contours

In addition to these main DMA programs, other programs were developed to evaluate data from special projects. Because no user interface is provided, these "special purpose" programs are used only by the programmer. One program was written to prepare a phase diagram of output from the USGS geochemical speciation code PHREEQC. Another program is being used to evaluate data from the circulation tests conducted with the Variation Project.

8.0 Environmental Sciences Laboratory

Overview: Funding from the LTS–O&M subtask order is used to maintain the ESL in Grand Junction. The ESL operates a fixed-base laboratory and a mobile laboratory with capabilities to conduct geochemical and ecological projects. Funding requirements include:

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

The ESL continues to be an integral part of the LM program. Due to the large emphasis on groundwater projects inherent in the work conducted in LM, a laboratory is often needed by a wide range of technical staff. The laboratory is now staffed with two full-time employees.

FY 2014 Activities: All laboratory maintenance and calibration tasks were completed, and the laboratory operated trouble-free. Training modules were reviewed and updated. Two audits were conducted by independent evaluators. The Chemical Hygiene Plan and ESL procedures manual were updated, and quarterly inspections were conducted.

A new carbon analyzer (Shimadzu model TOC-L_{CSN}) was procured. This instrument is capable of measuring both organic and inorganic carbon in water and solid samples. The instrument was set up, tested, and calibrated. ESL staff were trained in its operation. To assist in carbon analysis, a muffle furnace (Thermo Scientific model FB1415M) was procured. A drying oven (Fisher Scientific model Isotemp 700) was procured to replace an existing one that was not repairable. An ion chromatograph (Dionex model DX-120) that had been put in storage was restored for field use in the ESL mobile laboratory. The field ion chromatograph was used at the Shoal, New Mexico, Site.

Samples were submitted to the ESL from the Old Rifle, Shiprock, Rocky Flats, Durango, Monticello, and Tuba City sites for analysis. Although most funding for these analyses are from sources other than LTS–O&M, LTS–O&M funds are used to maintain the laboratory to enable these activities.

9.0 Technical Task Plan Process

Overview: A process was developed for the identification, selection, study plan definition, tracking and reporting, and completion of LTS–O&M tasks. The main objective of this process is to support LM decision-making and subtask management.

The process involves two work categories:

Category 1: Applied studies where the deliverable is new knowledge, enhanced technical capability, advancements to LM/LMS operations (e.g., sampling, modeling), or development of new or improved technology applications.

Category 2: Consultation to LM/LMS site and task managers.

Category 1 work is the primary focus for LTS–O&M and is approved as part of the annual baseline work approval process or as a baseline change control addition to the approved baseline work. Category 2 work is supplementary work identified on an ad hoc basis as beneficial to LM.

Category 1 tasks will be managed using a technical task plan that includes:

- Study plan that includes background information and demonstrates application to LM strategic needs.
- Management plan that includes scope of work, budget, schedule, milestones, and deliverables.

Category 2 tasks are focused on providing a short-term (typically from 1 month up to 3 months) response to a specific question/request posed by the LM/LMS site and task managers. Category 2 work may require a Supplementary Work Plan documenting the scope of work and an approval from the LM subtask (LTS–O&M) manager.

FY 2014 Activities: The technical task plan process was developed during FY 2014. A template for a technical task plan format was prepared using the Plume Persistence project as an example. LM is reviewing the template.

This page intentionally left blank

10.0 Strategic Planning

LTS–O&M supported two strategic planning initiatives in FY 2014: Technology Deployment and Land Stewardship.

10.1 Technology Deployment

Overview: The LTS–O&M subtask supports the Technology Deployment Strategic Planning (TDSP) initiative. The scope of the TDSP initiative is to facilitate the investigation, evaluation, and deployment of promising environmental technologies for LM, focusing on technologies that improve groundwater remediation and characterization, disposal cell cover performance, and modeling.

The TDSP site is on the LM Intranet at https://lmportal.lm.doe.gov/Contractor/Departments/Technology_Deployment.aspx. The TDSP site contains the *Handbook of Technology Deployment for DOE Legacy Management Program.* The Handbook is divided into five sections: (1) Technologies Currently Deployed at LM Sites, (2) LM Future Needs, (3) Proven and Developing Technologies, (4) Direction for Technology Deployment for LM, and (5) the Applied Studies and Technology Program. Each section is further subdivided, and numerous links to internal documents and websites are available in the Handbook. Section 5 of the Handbook provides links to the various documents that have provided guidance and direction for the LTS–O&M subtask, including the subtask order, life-cycle baseline, Five-Year Plan, quarterly meeting summaries, annual reports, weekly reports, cost savings report, summary sheets, technical task plans, and various presentations.

The TDSP Intranet site also contains a link to electronic copies of published papers relevant to LTS–O&M studies. EndNote, a widely used bibliographic software program, is used to organize and search the database of in-house holdings.

FY 2014 Activities: All of the hyperlinks on the TDSP Intranet site were lost because of network changes. These links were recently reestablished. The site was continually updated and revised, and the Handbook of Technology Deployment was edited. Twenty papers were added to the EndNote database, which now contains 3,288 citations. Most of the papers are in PDF files and can be read while in EndNote.

This page intentionally left blank

11.0 Educational Outreach, Collaboration, Technology Transfer, Presentations, and Publications

Overview: This section describes FY 2014 activities related to four LTS–O&M objectives:

- Use LTS–O&M projects to create and promote opportunities, discourse, and achievements in environmental education.
- 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 and present LTS–O&M project results in peer-reviewed journals and at professional meetings to provide a measure of credibility in defending LM decisions, to bring visibility to LM initiatives, and to enable others to utilize the results.

11.1 Educational Outreach

LTS–O&M scientists contributed the following educational outreach activities:

- Renewed adjunct faculty appointment and served on the graduate committees for Carrie Joseph and Quentin Benally, PhD and MS students, respectively, in the Department of Soils, Water, and Environmental Science at the University of Arizona. Both students are working on Surface Projects: Disposal Cell Adaptation to Climate Change (Ms. Joseph), and Long-term Value of Revegetation Practices (Mr. Benally). These projects are a collaboration (and cost-sharing) with Dr. Karletta Chief (University of Arizona extension specialist to Native American communities, and Assistant Professor in the Department of Soil, Water, and Environmental Science). Ms. Joseph and Mr. Benally are funded, in part, by the Alfred P. Sloan Foundation Indigenous Graduate Partnership.
- Gave an invited seminar at the Colorado Mesa University Seminar series, Natural Resources of the West, on October 21, 2013: "Helping Mother Earth Heal: Natural and Enhanced Attenuation of Soil and Groundwater Contamination at a Uranium Mill Site on Navajo Land."
- Gave a tour of the ECAP lysimetry and test pad projects at the Grand Junction disposal site for Dr. Russ Walker's Environmental Sampling class at Colorado Mesa University.
- Taught the following seminars and classes at Diné College:
  - Introduction to Phytoremediation Science
  - Natural and Enhanced Attenuation Pilot studies at Monument Valley, Arizona
  - Shiprock Phytoremediation: Objectives, Hypotheses, Experimental Design, and Sampling Methods
  - Environmental Data Reduction and Analysis

11.2 Collaboration and Cost Sharing

In FY 2014, LTS–O&M staff collaborated and shared costs of Surface Projects with the following scientists:

Dr. William H. Albright, Research Hydrogeologist, Division of Hydrologic Sciences, Desert Research Institute, Reno, Nevada.

- Enhanced Cover Assessment Project
- Water Balance Cover Monitoring and Modeling

Dr. Craig H. Benson, Chair of Civil & Environmental Engineering and Geological Engineering, Director of Sustainability Research & Education, and Co-Director of the Office of Sustainability, University of Wisconsin-Madison.

- Enhanced Cover Assessment Project
- Water Balance Cover Monitoring and Modeling
- Erosion, Hydrology, and Ecology of Rock/Soil Covers
- Depth of Soil-Forming Processes in Covers
- Effects of Soil-Forming and Ecological Processes on Radon Attenuation

Dr. Mark L. Brusseau, Professor, Department of Soil Water and Environmental Science, University of Arizona, Tucson, Arizona.

- Monument Valley Enhanced Attenuation
- Uranium Biosequestration Proposal

Dr. Karletta Chief, Assistant Professor, Department of Soil Water and Environmental Science, American Indian Studies, Institute of the Environment, University of Arizona, Tucson, Arizona.

- Long-term Value of Revegetation Practices
- Adaptation of Covers to Climate Change

Dr. Edward P. Glenn, Professor, Environmental Sciences Laboratory, Department of Soil Water and Environmental Science, University of Arizona, Tucson, Arizona.

- Monument Valley Enhanced Attenuation
- Shiprock Phytoremediation
- Tuba City Evapotranspiration

11.3 Publications and Presentations

LTS–O&M scientists often publish project results. Through publication, others can utilize the findings, and LM gains visibility in the technical arena. Publication is also a measure of expertise, which can be of value in defending the credibility of project decisions.

Published, Accepted, and Draft Journal Articles

Miao, Z., H.N. Akyol, A.L. McMillan and M.L. Brusseau, 2013. "Transport and fate of ammonium and its impact on uranium and other trace elements at a former uranium mill tailings site," *Appl. Geochem,* 38:24–32. (Product of Monument Valley pilot studies.)

Miao, Z., K.C. Carroll, and M.L. Brusseau, 2013. "Characterization and quantification of groundwater sulfate sources at a mining site in an arid climate: The Monument Valley site in Arizona, USA," *J. Hydrol*., 504: 207–215. (Product of Monument Valley pilot studies.)

Waugh, W.J., W.H. Albright, C.H. Benson, and G.M. Smith (draft). "Evaluation of Soil Manipulation Methods to Transform Engineered Earthen Covers for Long-Term Waste Containment."

Waugh, W.J., and E.P. Glenn (draft). "Land-Farm Phytoremediation of Groundwater Nitrate at a Former Uranium Mill Site."

Glenn, E.P., F. Jordan, and W.J. Waugh (draft). "Phytoremediation of a Nitrogen-Contaminated Desert Soil by Native Shrubs and Microbial Processes."

Albright, W.H., C.H. Benson, and W.J. Waugh (draft). "Field Hydrology of a Final Cover for Uranium Mill Tailings."

Conference Presentations

Waugh, W.J., C.H. Benson, W.H. Albright, and R.P. Bush, 2013. "Uranium Reclamation Experience: Evolution, Enhancement, and Long-Term Performance of Engineered Covers at DOE Legacy Waste Sites," American Nuclear Society, November 14, 2013, Washington DC (invited paper).

Published and Draft DOE Reports

DOE (U.S. Department of Energy), 2013. *Long-Term Surveillance Operations and Maintenance: Fiscal Year 2013 Year-End Summary Report*, LMS/ESL/S10692, prepared by The S.M. Stoller Corporation, a wholly owned subsidiary of Huntington-Ingalls Industries, for the Office of Legacy Management, Grand Junction, Colorado.

DOE (U.S. Department of Energy), 2014. *Enhanced Cover Assessment Project: Soil Manipulation and Revegetation Tests*, LMS/ESL/S11342, prepared by The S.M. Stoller Corporation, a wholly owned subsidiary of Huntington-Ingalls Industries, for the Office of Legacy Management, Grand Junction, Colorado.

Newsletters

Morrison, S.J., 2014. "Tracking Uranium Atoms," *Program Update*, January–March 2014.

Ravelojaona, D., (W.J. Waugh, contributor), 2014. "Preparing the U.S. for the Effects of Climate Change." *ECHOutlook Newsletter,* 5(4), Spring 2014.

This page intentionally left blank

12.0 References

DOE (U.S. Department of Energy), 2011. *2011–2020 Strategic Plan, Managing Today's Change, Protecting Tomorrow's Future*, DOE/LM-0512, Office of Legacy Management, Washington, DC.

DOE (U.S. Department of Energy), 2012. *Five-Year Plan for Applied Science and Technology (AS&T) FY 2013 through FY 2017*, Office of Legacy Management, Grand Junction, Colorado.

DOE (U.S. Department of Energy), 2014. *Operation and Maintenance of the System Operation and Analysis at Remote Sites (SOARS) Network*, LMS/PRO/S08736. Office of Legacy Management, Grand Junction, Colorado.

Environmental Sciences Laboratory Chemical Hygiene Plan, LMS/PLN/S04615, continually updated, prepared by The S.M. Stoller Corporation, a wholly owned subsidiary of Huntington Ingalls Industries, for the U.S. Department of Energy Office of Legacy Management.

Environmental Sciences Laboratory Procedures Manual, LMS/PRO/S04343, continually updated, prepared by The S.M. Stoller Corporation, a wholly owned subsidiary of Huntington Ingalls Industries, for the U.S. Department of Energy Office of Legacy Management.

This page intentionally left blank