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NUREG/CP-0312

Proceedings of the Radon Barriers Workshop

July 25–26, 2018
NRC Headquarters, Rockville, MD

Office of Nuclear Regulatory Research

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Prepared by: Mark Fuhrmann[1], Craig Benson[2], Jody Waugh[3],
Morgan Williams[4], and Hans Arlt[1]

[1] U.S. Nuclear Regulatory Commission
[2] University of Virginia
[3] Navarro Research and Engineering, Inc.
[4] University of California Berkeley

Mark Fuhrmann, NRC Project Manager

Office of Nuclear Regulatory Research

ABSTRACT

The "Radon Barriers Project" is a research program to study the effects of changes in the properties of in-service engineered earthen covers over uranium mill tailings as these covers age. Field studies were conducted at four mill tailing disposal sites: Falls City in Texas, Bluewater in New Mexico, Shirley Basin South in Wyoming, and Lakeview in Oregon. Small areas on these sites were excavated, radon fluxes were measured, numerous observations were made, and samples were taken for a variety of parameters, such as saturated hydraulic conductivity, root counts, moisture, density, lead-210 concentrations, soil texture, structure, chemistry, and nematode counts.

On July 25–26, 2018, a one-and-a-half-day workshop took place at NRC Headquarters to discuss findings from the project with regard to the current state of the barriers and comparison to their as-built condition and natural analog sites, prediction of long-term evolution, monitoring approaches, and long-term implications. Presentations included detailed background and project findings on the following:

- NRC and DOE/LM activities that led to the Radon Barriers Project
- radon fluxes and their variability, radon diffusion coefficients, and radon travel times through the covers
- hydraulic conductivity of the barriers at various depths and comparisons to hydraulic conductivity at nearby natural analog sites
- ecological evolution of covers and the impact of vegetation on cover properties, especially on water percolation, radon flux, and evapotranspiration
- soil architecture observations, including soil structure, biology, and chemistry
- potential use of lead-210 as a long-term indicator of radon transport within barriers

A facilitated discussion followed each presentation to discuss long-term evolution of the sites as suggested by the project findings, use of the findings for maintenance and prediction, future information needs, and policy implications.

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ABBREVIATIONS AND ACRONYMS

ACAP	Alternative Cover Assessment Program
ADAMS	Agencywide Documents Access and Management System
Bq/m^2-s	becquerel(s) per meter square per second
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	*Code of Federal Regulations*
CNWRA	Center for Nuclear Waste Regulatory Analysis
DOE	U.S. Department of Energy
ECTG	Engineered Covers Technical Group
EM	Office of Environmental Management (DOE)
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
K_{sat}	field-saturated hydraulic conductivity
K_s	field-saturated hydraulic conductivity
LFRG	Low-Level Waste Disposal Facility Federal Review Group
LM	Office of Legacy Management (DOE)
LTS&M	long-term surveillance and maintenance
m^2	square meter(s)
m^2/s	square meter(s) per second
m/s	meter(s) per second
NMSS	Office of Nuclear Material Safety and Safeguards
NRC	U.S. Nuclear Regulatory Commission
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978

1 INTRODUCTION

The Radon Barriers Project (formally called *Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings*) is a research program created to study the effects of changes in the properties of in-service engineered earthen covers over uranium mill tailings as these covers age. On July 25–26, 2018, a one-and-a-half-day workshop on the Radon Barriers Project took place at U.S. Nuclear Regulatory Commission (NRC) Headquarters to present and discuss findings from the project with regard to the current state of the barriers and comparison to their as-built condition, prediction of long-term evolution, monitoring approaches, and long-term implications. Participants included the project principal investigators and key team members; NRC staff from the Office of Nuclear Regulatory Research, the Office of Nuclear Material Safety and Safeguards, and the NRC's Region IV; and staff from the U.S. Department of Energy (DOE) Office of Environmental Management (EM). Appendix A to this report lists the attendees.

The purpose of this study is to evaluate the effects of soil structure formation by abiotic and biotic processes on the hydraulic conductivity and gaseous diffusivity of radon barriers, how structural development varies with depth and thickness of the radon barrier, and how structure influences transmission of radon and seepage of water through radon barriers. This research is a collaboration between the DOE Office of Legacy Management (LM) and the NRC, with investigators at the University of Wisconsin, University of Virginia, University of California at Berkeley, and Navarro Research and Engineering Inc. (the DOE contractor). Additional support was provided by DOE/EM through the Consortium for Risk Evaluation with Stakeholder Participation (CRESP).

The research team visited four uranium mill tailing sites: Falls City in Texas, Bluewater in New Mexico, Shirley Basin South in Wyoming, and Lakeview in Oregon. Small areas on these sites were excavated, radon fluxes were measured, numerous observations were made, and samples were taken for a variety of parameters, such as saturated hydraulic conductivity, root counts, moisture, density, lead (Pb)-210 concentrations, soil texture, chemistry, and nematode counts.

These conference proceedings provide an extended abstract and the slides from each presentation, as well as key points from the discussions, which are summarized. In addition to results from this project, presentations often gave background information and discussed other related work at a number of sites to better define the context of the Radon Barriers Project.

1.1 Background

1.1.1 Regulations

The NRC regulates uranium mill tailings under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). Two types of sites are defined: (1) Title I sites are those that were inactive or no longer in use when UMTRCA was passed, and (2) Title II sites are those that were in use or issued a license after UMTRCA was passed. Currently, there are 21 Title I sites and 27 Title II sites, although more will be added over time.

Requirements for Title I sites in Title 40 of the *Code of Federal Regulations* (40 CFR) 192.02, “Standards,” Subpart A, “Standards for the Control of Residual Radioactive Materials from Inactive Uranium Processing Sites,” include the following:

> Control of residual radioactive materials and their listed constituents shall be designed to: (a) Be effective for up to one thousand years, to the extent reasonably achievable, and, in any case, for at least 200 years, and,
>
> (b) Provide reasonable assurance that releases of radon-222 from residual radioactive material to the atmosphere will not: (1) Exceed an average release rate of 20 picocuries per square meter per second, or (2) Increase the annual average concentration of radon-222 in air at or above any location outside the disposal site by more than one-half picocurie per liter.
>
> Provide reasonable assurance of conformance with [a number of] groundwater protection provisions.

Because the standard applies to design, monitoring after disposal is not required to demonstrate compliance with respect to 40 CFR 192.02(a) and (b). This average applies over the entire surface of the disposal site and over at least a 1-year period.

The NRC regulates Title II sites as stipulated in 10 CFR 40.28, “General License for Custody and Long-Term Care of Uranium or Thorium Byproduct Materials Disposal Sites,” with technical criteria in Appendix A, “Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material from Ores Processed Primarily for Their Source Material Content,” to 10 CFR Part 40, “Domestic Licensing of Source Material.” Title I sites are regulated under 40 CFR Part 192, “Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings,” and are licensed through 10 CFR 40.27, “General License for Custody and Long-Term Care of Residual Radioactive Material Disposal Sites,” to DOE or other Federal agencies. Additional information can be found at https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/mill-tailings.html and https://www.energy.gov/lm/articles/us-department-energy-office-legacy-management-2015-umtrca-title-i-and-title-ii-disposal.

Requirements in 10 CFR Part 40, Appendix A, for Title II sites include the following:

- Criterion 1 states that the “general design goal or broad objective in siting and design decisions is permanent isolation of tailings and associated contaminants by minimizing disturbance and dispersion by natural forces, and to do so without ongoing maintenance.”

- Criterion 4d requires a full, self-sustaining vegetative cover or rock cover to reduce wind and water erosion to negligible levels.

- Criterion 5 incorporates ground water protections standards imposed by the U.S. Environmental Protection Agency (EPA) under 40 CFR Part 192, Subparts D and E, and Criterion 7 requires ground water monitoring.

- Criterion 6 requires an earthen cover (or approved alternative) over wastes and that the site shall be closed “in accordance with a design which provides reasonable assurance of control of radioactive hazards to (i) be effective for 1000 years, to the extent reasonably achievable, and in any case for at least 200 years, and (ii) limit release of radon (Rn)-222 from uranium byproduct materials, ...to the atmosphere so as not to exceed an average release rate of 20 picocuries per meter square per second (pCi/m^2 s) to the extent practicable throughout the effective design life determined pursuant to (1)(i) of this Criterion." The average release rate applies to the entire surface of each disposal area over a period of at least 1 year, but a period that is short compared to 100 years.

1.1.2 Overview of the Radon Barriers Project

1.1.2.1 Drivers and Objectives

Hans Arlt's presentation (see Section 2.2 of this volume) gave a timeline of the NRC's activities with regard to mill tailing covers. A major impetus for much of this work was NUREG/CR-7028, "Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment," issued in December 2011. The report assesses the performance of engineered covers in terms of percolation of water through the covers at disposal sites that were not UMTRCA facilities. All of the covers documented in the report (27 test sections at 12 sites) were vegetated with a mixture of annual and perennial grass mixtures. No covers were studied with a riprap surface or without vegetative root systems. Changes in cover hydraulic properties (saturated hydraulic conductivity and the alpha parameter for the soil water characteristic curve) both increased, indicating the formation of larger pores as a result of pedogenic processes such as wet-dry and freeze-thaw cycling. These changes were observed on materials that had been in place for time periods of 3.8 to 8.9 years.

The NRC established the Engineered Covers Technical Group (ECTG) to discuss and review the implications of NUREG/CR-7028. Their review is documented in Arlt et al. (2011), which noted that an important conclusion of the report is that "compacted soil materials used in cover materials do not retain 'as built' properties over the period of regulatory interest as assumed in most performance assessments. The properties of these materials change to values typical of surrounding soils within 5 to 10 years after installation. For some properties the change may be several orders of magnitude, which may potentially lead to increased water infiltration and augmented radon flux out of the system." However the sites discussed in that report were generally not uranium mill tailing sites and all were vegetated, whereas most mill tailing sites have rock covers.

No radon studies were conducted or reviewed for NUREG/CR-7028; in fact, few, if any, studies of radon emissions after the initial closure survey have been conducted at mill tailings disposal sites. However, that report showed that hydraulic conductivity of barrier materials increases over time. A reasonable inference is that radon emissions may also increase, as discussed in Chapter 5, "Potential for Increased Radon Release due to Processes Documented in NUREG/CR-7028," of Arlt et al. (2011). The ECTG made a number of suggestions, and some of these evolved into the Radon Barriers Project.

1.1.2.2 Radon Barriers Project Sites

The Radon Barriers Project team assembled a list of 24 sites that were evaluated as potential research sites using parameters, such as climatic influence, vegetation, barrier vulnerability, source activity, and NRC priority, derived from Arlt et al. (2011). Four sites were selected; Table 1 gives some of their general properties. Slides from Jody Waugh's presentation on page 2-62 of this report show their locations. Pages 2-62 through 2-81 show climate information, images of the sites, test pit descriptions, and plant ecology information for each site.

Table 1. Radon Barriers Project Research Sites

Site	Title	Closure Date	Cover Area Acres	Type of Cover	Waste Tons	Waste Activity (curies of radium-226)
Falls City	I	1994	127	Veg	7,100,000	1277
Bluewater	II	1995	354 main cell	Rock	23,000,000	11200
Shirley Basin S	II	2000	142	Veg	5,300,000	974
Lakeview	I	1988	16	Rock/Veg	926,000 cubic yards	42

Navarro Research and Engineering staff prepared an extensive field work plan document for the work to be conducted at each site. These plans include maps and cover diagrams and the field workflow for excavation, sampling, measurements, and site restoration to the original construction criteria. They also contain sections on safety and health, training requirements, and environmental management. The NRC staff conducted a National Environmental Policy Act review in accordance with NUREG-1748, "Environmental Review Guidance for Licensing Actions Associated with NMSS Programs," issued August 2003, and concluded that the actions were categorically excluded under 10 CFR 51.22(c)(6). As such, the NRC staff did not prepare an environmental assessment; a categorical exclusion checklist provided documentation. Field work was planned at analog sites for each location. If needed, a cultural resources survey (archeological reconnaissance (Phase III)) was conducted.

After completion of the field research, each pit was refilled with the various soil types that had been excavated and saved in separate piles. The radon barrier material was restored to the required density, and moisture content and a radon flux check was conducted. Closure reports were prepared Navarro Research and Engineering, documenting the test results to demonstrate that the excavations had been closed to the required criteria.

2 PRESENTATIONS

2.1 Introductory Remarks

2.1.1 Welcome by Ray Furstenau, Director of the NRC Office of Nuclear Regulatory Research

I am the new, by about 3 weeks, director of the NRC's Office of Nuclear Regulatory Research. I came from DOE, and this work reminds me of some of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) work done at DOE sites. This is a jointly funded effort between DOE/LM and the NRC. Research dollars are limited, so this is a great example of a collaborative effort with the NRC on the regulatory side and DOE/LM, under Carmelo Melendez, with whom I worked quite a bit. I certainly like to see these things happen, and I understand that it has been pretty successful.

DOE/LM put out a newsletter with an article called, "Got it Covered, Are Natural Processes Changing Engineered Disposal Cells?" It is a very good article. It gets across why we are doing this sort of work. These are sites that were built with some assumptions about time frames that can go beyond human history, and so we need to validate these assumptions. Are these covers getting worse or getting better? The article shows pictures of some of you down in holes that you dug in these sites. Hopefully you replaced the dirt before you left. These are long-term effects, and they are probably different at each site. The weather is different, the hydrology is different, and the natural cover is different. So this is a timely workshop.

We want to have free-flowing discussions to really try to understand how these sites are behaving and how they may change over time. Is maintenance necessary or not necessary? What are the implications for long-term performance of these barriers? It is important not just for covers on uranium mill tailings, but in the DOE world it applies to CERCLA sites as well.

2.1.2 Remarks by Justin Marble from DOE/EM

I am with the DOE/EM Office of Waste Disposal. DOE designs, constructs, operates, and ultimately closes waste disposal facilities under CERCLA and also for our unique, self-regulating role under DOE Order 435.1, "Radioactive Waste Management," for the radioactive materials part of the waste. So covers do matter to LM and to EM.

Design of the cover is a crucial part of the document package submitted in order to get disposal authorization under DOE Order 435.1 to build and operate the disposal facility. Compliance is ensured in part through one of the groups I am involved with, the Low-Level Waste Disposal Facility Federal Review Group (LFRG). I am one of the co-chairs of this group, and Sherri Ross is the other co-chair. She came from the DOE Savannah River Site but now is at headquarters. The two of us are the leads in LFRG for the DOE Order 435.1 process for the authorization of low-level radioactive waste disposal facilities. Covers play a large part in the review process. Specifically, we have performance objectives for radon that we try to meet to the extent possible, during the institutional control period of 100 years and for the 1,000-year compliance period.

2.2 A Timeline of NRC Activities on Engineered Surface Barriers Used at Disposal Sites for Radioactive Material

Presented by Hans Arlt
Senior System Performance Analyst
U.S. Nuclear Regulatory Commission

2.2.1 Abstract

Engineered surface barriers help to isolate harmful waste and can be a risk-significant barrier at many disposal sites, including sites with uranium mill tailings. The purpose of covers can include (1) preventing waste from getting to the environment (stability), (2) preventing the environment from getting to the waste (keep dry), and (3) preventing people from getting to the waste (no direct dose). NUREG-1623, “Design of Erosion Protection for Long-Term Stabilization,” issued September 2002, provides guidance on long-term erosion protection for soil covers. To better understand whether the properties of these earthen covers evolve over time, the NRC issued NUREG/CR-7028, which shows that changes to the engineered properties of certain surface cover components, especially saturated hydraulic conductivity, have occurred relatively quickly (over about 10 years). The influence of coupling erosion and hydrology on the long-term performance of engineered surface barriers was examined and described in NUREG/CR-7200, “Influence of Coupling Erosion and Hydrology on the Long-Term Performance of Engineered Surface Barriers,” issued May 2016.

The NRC staff’s level of interest in engineered surface covers has increased since the release of NUREG/CR-7028. Because of this interest, the NRC staff have been active in trying to understand more about engineered barrier systems, and staff from the Center for Nuclear Waste Regulatory Analysis (CNWRA) have reviewed and evaluated numerous aspects of surface covers, including evaluating approaches to simulating engineered cover performance and degradation. Codes best suited for these tasks were selected, and software verification testing was performed. CNWRA staff documented modeling of infiltration through Title II soil covers and methods for monitoring net inflow through soil covers, in addition to analyzing mill tailings cover performance and bottom liner performance for mill tailings impoundments.

The NRC staff organized a workshop on engineered barrier performance in 2010 involving the participation and attendance of a wide range of stakeholders. All aspects of cover performance and changes of component properties were presented and discussed, in addition to experiences gained by state and Federal regulators, cover monitoring devices and systems, modeling experiences, model support, and multiple lines of evidence to gain confidence in long-term performance. The NRC documented the workshop in NUREG/CP-0195, “Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities,” issued August 2011.

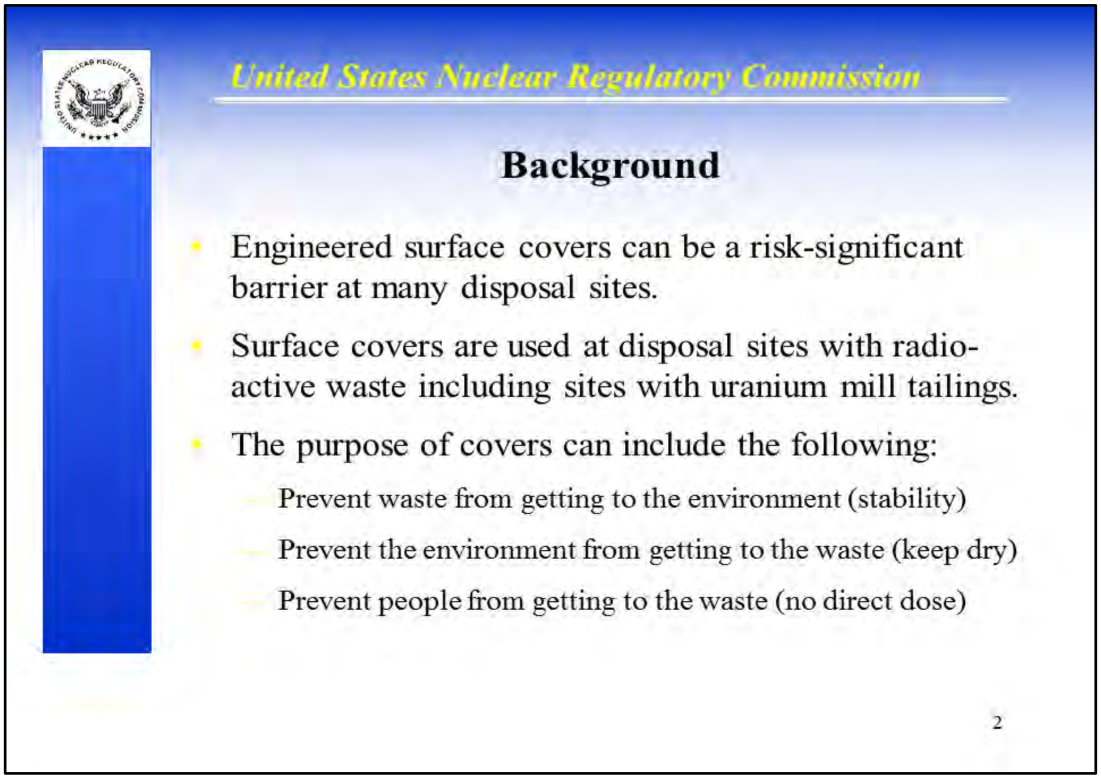
2.2.2 Presentation

United States Nuclear Regulatory Commission

A Timeline of NRC Activities on Engineered Surface Barriers Used at Disposal Sites for Radioactive Material

Hans Arlt
Division of Decommissioning, Uranium Recovery, and Waste Programs
Office of Nuclear Material Safety and Safeguards
U.S. NRC

Presented on July 25, 2018 during the
Radon Barriers Project Workshop
North Bethesda, MD



United States Nuclear Regulatory Commission

Background

- Engineered surface covers can be a risk-significant barrier at many disposal sites.
- Surface covers are used at disposal sites with radioactive waste including sites with uranium mill tailings.
- The purpose of covers can include the following:
  - Prevent waste from getting to the environment (stability)
  - Prevent the environment from getting to the waste (keep dry)
  - Prevent people from getting to the waste (no direct dose)

United States Nuclear Regulatory Commission

Background

- NRC staff level of interest in engineered surface covers has been high since Part 61 (LLW) and Appendix A in Part 40 (U/Th tailings) were promulgated.
- NRC staff level of interest in covers has been even higher since the release of NUREG/CR-7028 (Prepared by Craig Benson, Bill Albright, and others with Jake Philip as Project Manager from NRC's Office of Nuclear Regulatory Research).
- Due to this interest, NRC staff have been active in trying to understand more about this engineered barrier system, and the following slides give a brief overview of that activity.

United States Nuclear Regulatory Commission

Activities and Products Related to Engineered Surface Barriers

- NUREG-1623: Design of Erosion Protection for Long-Term Stabilization
- Released: September 2002
- Methods, guidelines, and procedures for designing erosion protection at U mill tailings sites.
- Guidance is presented for the design of soil covers, slopes and swales, rock riprap for slopes, channels, aprons, outlets, and stream banks.

Activities and Products Related to Engineered Surface Barriers

- Evaluation of Approaches to Simulate Engineered Cover Performance and Degradation
- A report by the Center for Nuclear Waste Regulatory Analyses (CNWRA) to NRC. Released: October 18, 2007
- 21 hydrologic, erosion, and other types of codes were reviewed.
- Most erosion codes could not simulate processes such as stability and gully formation.
- Exceptions were SIBERIA, CHILD, and LISEM-Gullies which could simulate long-term changes in cover thickness and topography under variable hypothetical climate and vegetation conditions.

Activities and Products Related to Engineered Surface Barriers

- Evaluation of Approaches to Simulate Engineered Cover Performance and Degradation

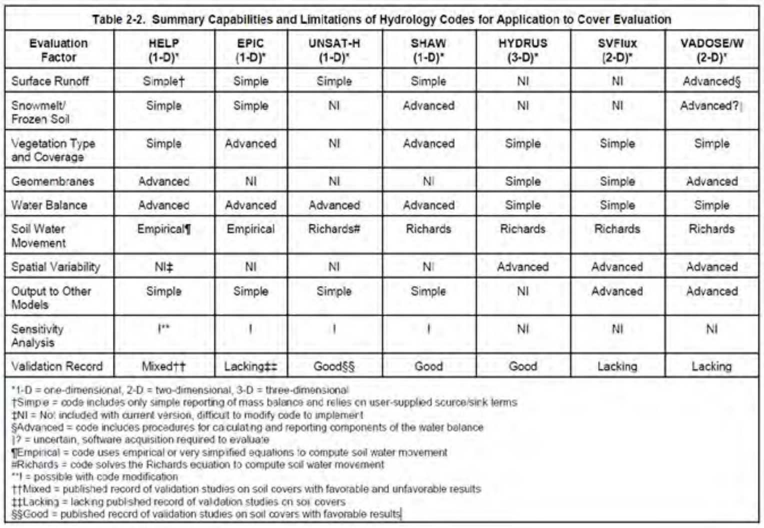
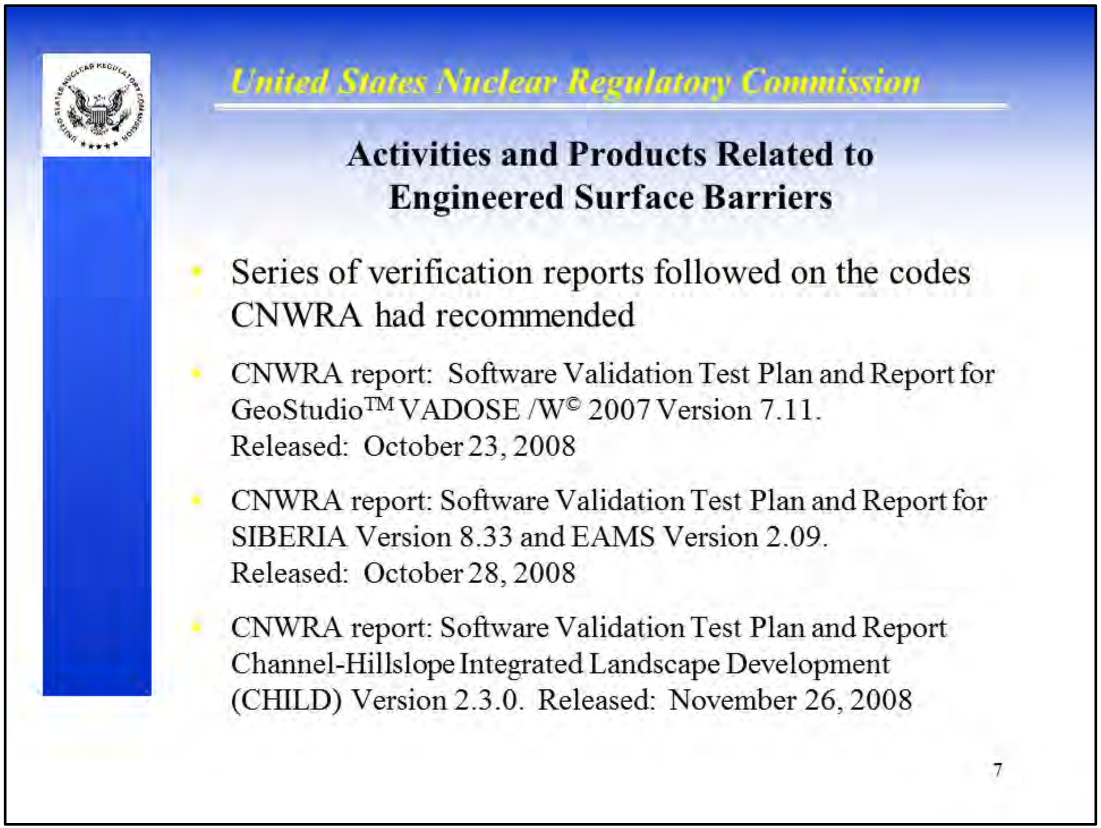


Table 2-2. Summary Capabilities and Limitations of Hydrology Codes for Application to Cover Evaluation

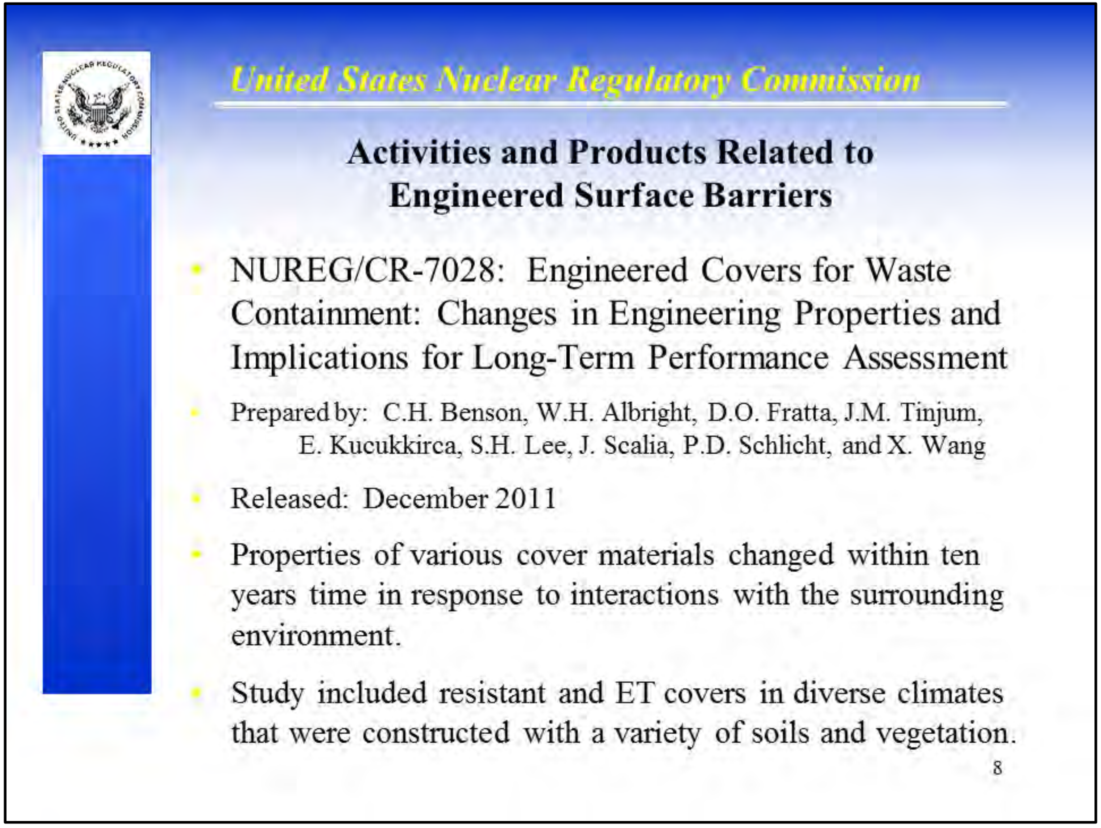
Evaluation Factor	HELP (1-D)*	EPIC (1-D)*	UNSAT-H (1-D)*	SHAW (1-D)*	HYDRUS (3-D)*	SVFlux (2-D)*	VADOSE/W (2-D)*
Surface Runoff	Simple†	Simple	Simple	Simple	NI	NI	Advanced§
Snowmelt/ Frozen Soil	Simple	Simple	NI	Advanced	NI	NI	Advanced?‖
Vegetation Type and Coverage	Simple	Advanced	NI	Advanced	Simple	Simple	Simple
Geomembranes	Advanced	NI	NI	NI	Simple	Simple	Advanced
Water Balance	Advanced	Advanced	Advanced	Advanced	Simple	Simple	Simple
Soil Water Movement	Empirical¶	Empirical	Richards#	Richards	Richards	Richards	Richards
Spatial Variability	NI‡	NI	NI	NI	Advanced	Advanced	Advanced
Output to Other Models	Simple	Simple	Simple	Simple	NI	Advanced	Advanced
Sensitivity Analysis	I**	I	I	I	NI	NI	NI
Validation Record	Mixed††	Lacking‡‡	Good§§	Good	Good	Lacking	Lacking

*1-D = one-dimensional, 2-D = two-dimensional, 3-D = three-dimensional
†Simple = code includes only simple reporting of mass balance and relies on user-supplied source/sink terms
‡NI = Not included with current version, difficult to modify code to implement
§Advanced = code includes procedures for calculating and reporting components of the water balance
‖? = uncertain, software acquisition required to evaluate
¶Empirical = code uses empirical or very simplified equations to compute soil water movement
#Richards = code solves the Richards equation to compute soil water movement
**I = possible with code modification
††Mixed = published record of validation studies on soil covers with favorable and unfavorable results
‡‡Lacking = lacking published record of validation studies on soil covers
§§Good = published record of validation studies on soil covers with favorable results



Activities and Products Related to Engineered Surface Barriers

- Series of verification reports followed on the codes CNWRA had recommended
- CNWRA report: Software Validation Test Plan and Report for GeoStudio™ VADOSE /W© 2007 Version 7.11.
  Released: October 23, 2008
- CNWRA report: Software Validation Test Plan and Report for SIBERIA Version 8.33 and EAMS Version 2.09.
  Released: October 28, 2008
- CNWRA report: Software Validation Test Plan and Report Channel-Hillslope Integrated Landscape Development (CHILD) Version 2.3.0. Released: November 26, 2008



Activities and Products Related to Engineered Surface Barriers

- NUREG/CR-7028: Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment
- Prepared by: C.H. Benson, W.H. Albright, D.O. Fratta, J.M. Tinjum, E. Kucukkirca, S.H. Lee, J. Scalia, P.D. Schlicht, and X. Wang
- Released: December 2011
- Properties of various cover materials changed within ten years time in response to interactions with the surrounding environment.
- Study included resistant and ET covers in diverse climates that were constructed with a variety of soils and vegetation.

Activities and Products Related to Engineered Surface Barriers

- NUREG/CR-7028 (continued)
- Some materials undergo modest changes in engineering properties (e.g., geomembranes), others larger (e.g., dense compacted clay barriers).
- Alterations to cover materials will continue to occur until an equilibrium condition exists.
- Long-term engineering properties should be used as input to models.
- Recommendations for parameter values were made for engineered cover components that had been studied.
- Monitoring associated with engineered cover components recommended including monitoring using pan lysimeters combined with secondary measurements.

Activities and Products Related to Engineered Surface Barriers

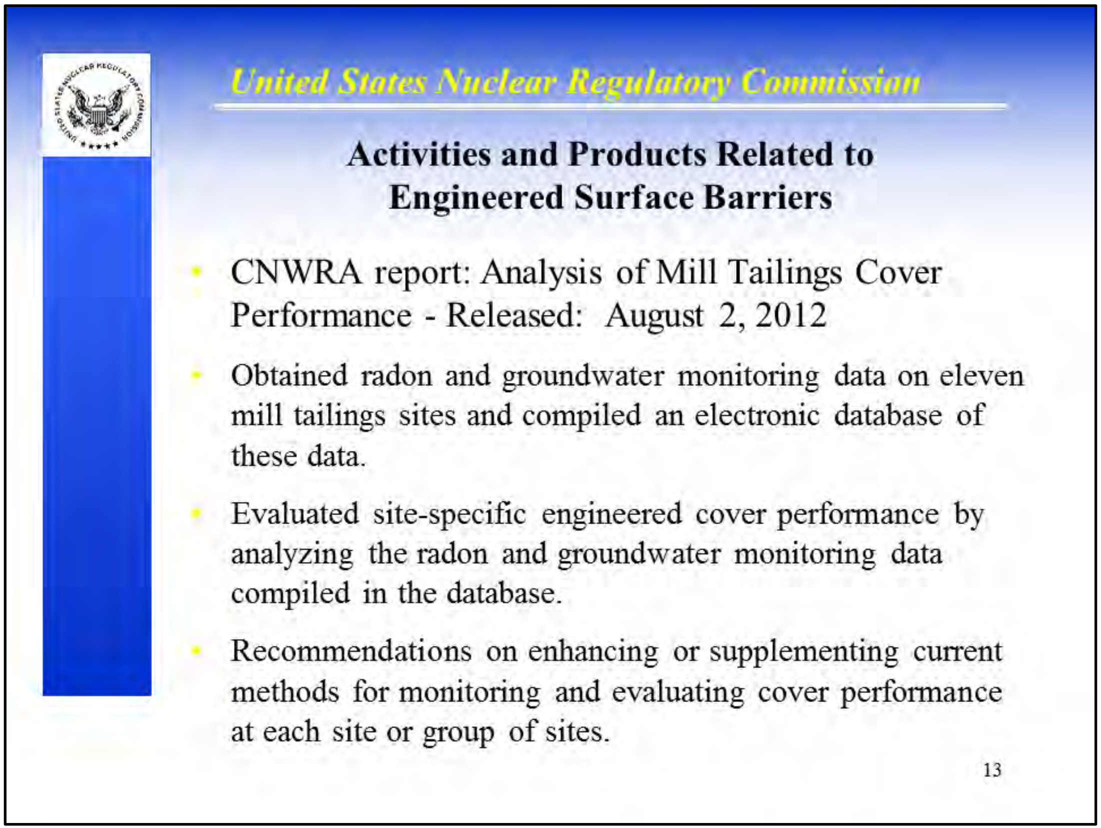
- NUREG/CP-0195: Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities - Released: August 2011
- The 2010 workshop focused on engineered surface covers and bottom liners.
- Attendees included States, Federal agencies, Tribes, and operators, regulators, and researchers of engineered barriers with expertise.
- Topics included engineered barrier performance, modeling, monitoring, and regulatory experiences.
- Observations, insights, and recommendations captured. Some recommendations have been acted upon (next few slides); others are waiting to be acted upon.

Activities and Products Related to Engineered Surface Barriers

- Documentation of the Engineered Covers Technical Group (ECTG) Activities by U.S. NRC Staff
Released: October 2011
- ECTG was convened to discuss and review the implications of NUREG/CR-7028 and conducted a qualitative assessment of uranium mill tailing sites to identify potential increased risks.
- The risk include both increased radon flux from the disposal cell and effects to the groundwater due to the potential of an increased rate of water infiltration through the covers.
- No covers with composite components were assessed since NUREG/CR-7028 reported that covers with geomembranes and GCLs do not appear to significantly degrade.

Activities and Products Related to Engineered Surface Barriers

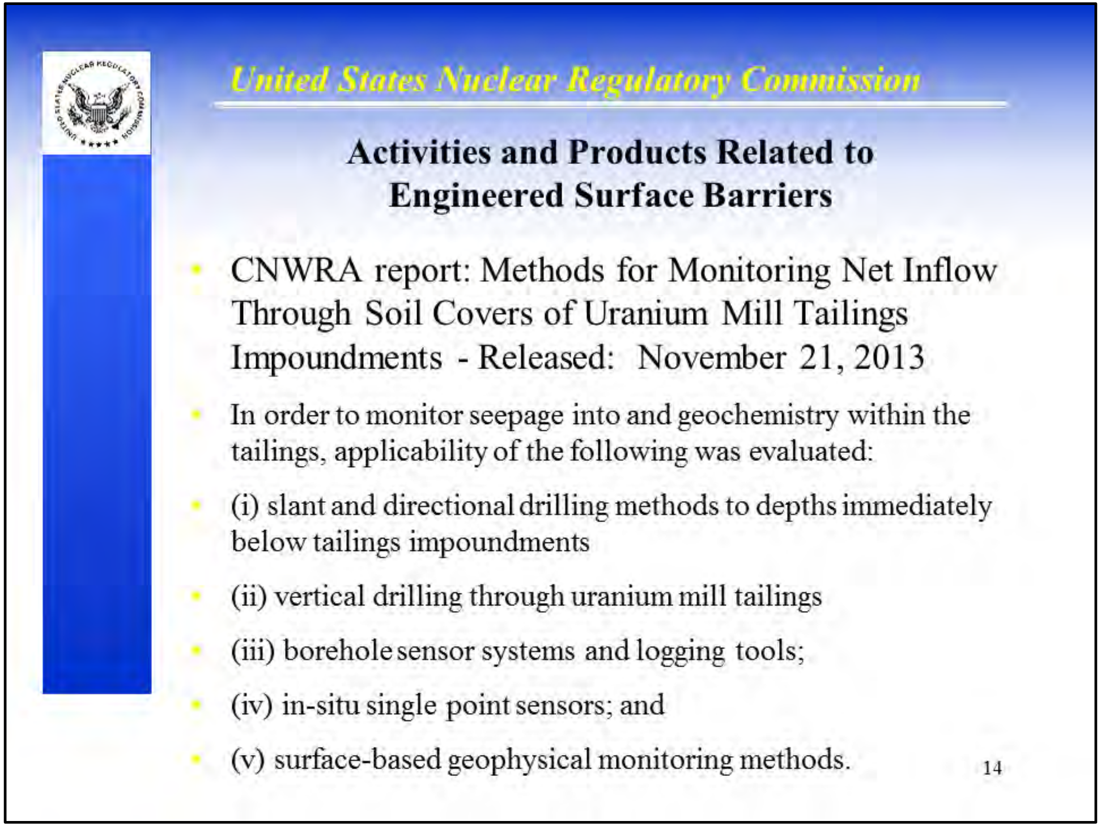
- ECTG Activities (continued) For Radon Release:
- Licensees need to verify one time after construction that the final radon barrier is effective in limiting releases of Rn-222 to 20 pCi/m^{2}s [10 CFR Part 40].
- However, there is no requirement for further testing so that information on radon release after construction is scarce.
- In addition, there is uncertainty associated with measurements of radon concentration and flux.
- Typically radon migration is controlled by diffusion which is dependent on the inter-connected porosity and moisture content of the soil or clay radon barrier.
- In addition to enhanced diffusive transport, advection may also contribute to significant migration of radon due to well-defined clay aggregates and planes of weaknesses in the soil.
- After ECTG made short- and long-term recommendations, the project of today's workshop were initiated, and the CNWRA was given several tasks related to cover infiltration and radon release.



United States Nuclear Regulatory Commission

Activities and Products Related to Engineered Surface Barriers

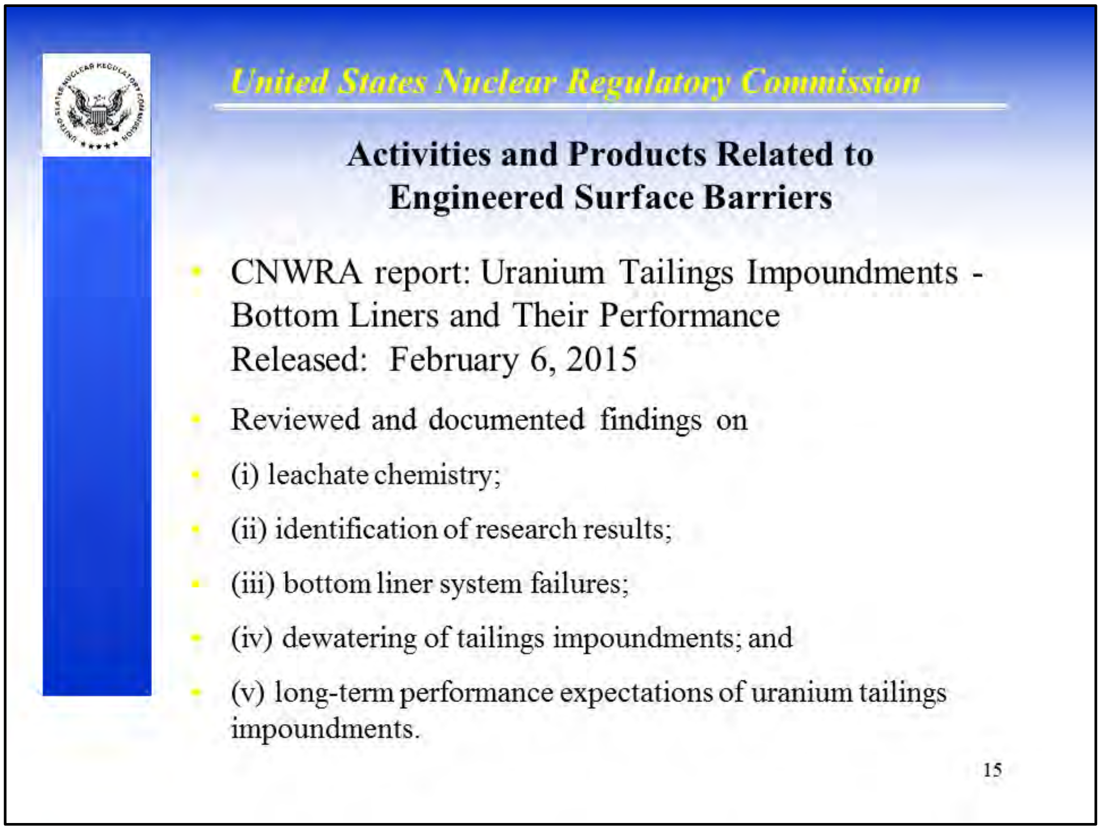
- CNWRA report: Analysis of Mill Tailings Cover Performance - Released: August 2, 2012
- Obtained radon and groundwater monitoring data on eleven mill tailings sites and compiled an electronic database of these data.
- Evaluated site-specific engineered cover performance by analyzing the radon and groundwater monitoring data compiled in the database.
- Recommendations on enhancing or supplementing current methods for monitoring and evaluating cover performance at each site or group of sites.



United States Nuclear Regulatory Commission

Activities and Products Related to Engineered Surface Barriers

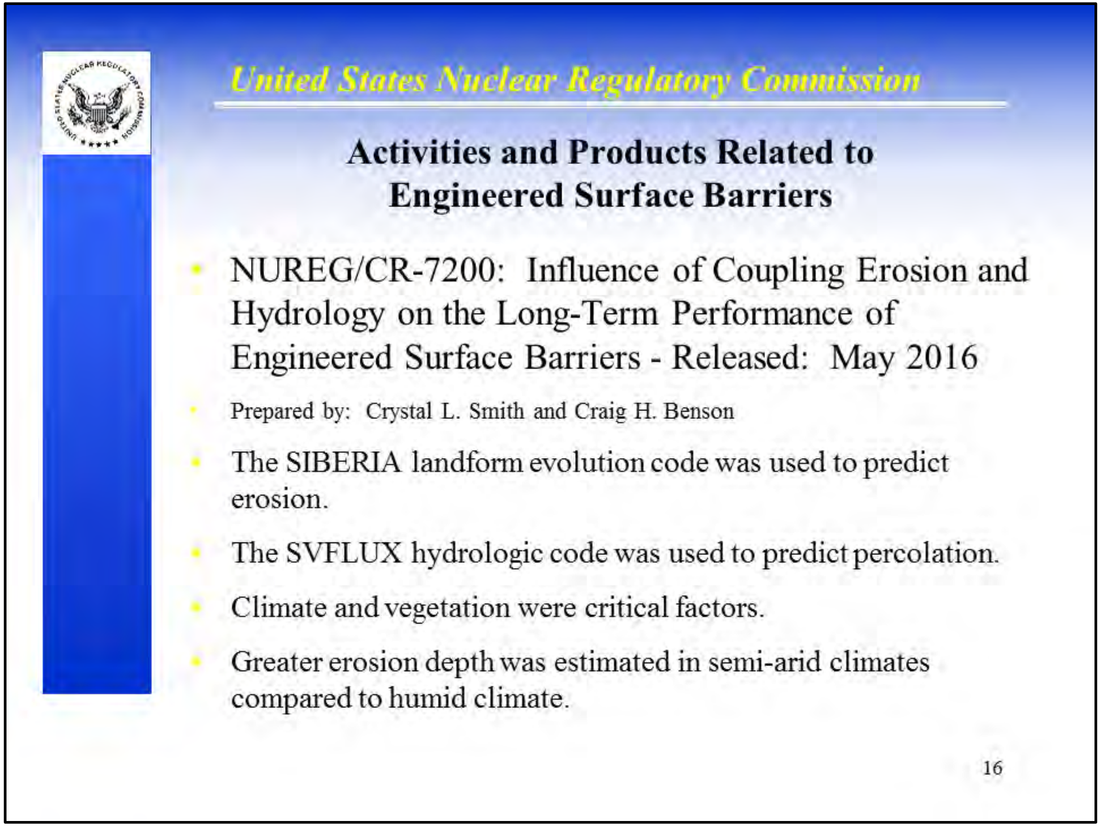
- CNWRA report: Methods for Monitoring Net Inflow Through Soil Covers of Uranium Mill Tailings Impoundments - Released: November 21, 2013
- In order to monitor seepage into and geochemistry within the tailings, applicability of the following was evaluated:
- (i) slant and directional drilling methods to depths immediately below tailings impoundments
- (ii) vertical drilling through uranium mill tailings
- (iii) borehole sensor systems and logging tools;
- (iv) in-situ single point sensors; and
- (v) surface-based geophysical monitoring methods.



United States Nuclear Regulatory Commission

Activities and Products Related to Engineered Surface Barriers

- CNWRA report: Uranium Tailings Impoundments - Bottom Liners and Their Performance
  Released: February 6, 2015
- Reviewed and documented findings on
- (i) leachate chemistry;
- (ii) identification of research results;
- (iii) bottom liner system failures;
- (iv) dewatering of tailings impoundments; and
- (v) long-term performance expectations of uranium tailings impoundments.



United States Nuclear Regulatory Commission

Activities and Products Related to Engineered Surface Barriers

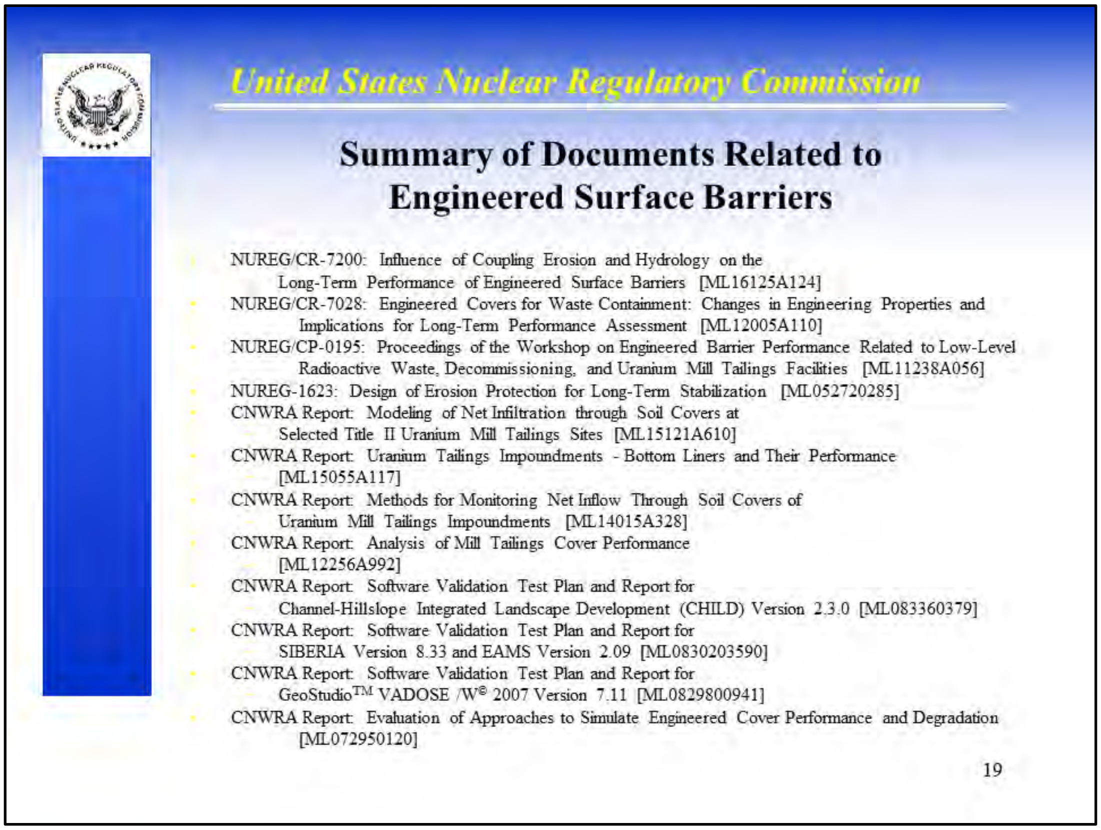
- NUREG/CR-7200: Influence of Coupling Erosion and Hydrology on the Long-Term Performance of Engineered Surface Barriers - Released: May 2016
- Prepared by: Crystal L. Smith and Craig H. Benson
- The SIBERIA landform evolution code was used to predict erosion.
- The SVFLUX hydrologic code was used to predict percolation.
- Climate and vegetation were critical factors.
- Greater erosion depth was estimated in semi-arid climates compared to humid climate.

Activities and Products Related to Engineered Surface Barriers

- NUREG/CR-7200 (continued)
- The humid climate had the least erosion when terraced slopes were utilized.
- Due to higher erosion rates in the semi-arid climate, natural and concave slopes that promote deposition produced the least erosion.
- Overall, a rip-rap surface layer prevented erosion most effectively for any type of topography, climate, or cover type.
- However, covers with a riprap surface had higher percolation rates.
- In contrast, a gravel admixture surface had slightly greater erosion, but was more effective in limited percolation.

Current Activity Related to Engineered Surface Barriers

- From the User Need Response for FSME 2013-001:
- Task Details for the “Effectiveness of Surface Covers for Controlling Fluxes of Water and Radon at Disposal Facilities for Uranium Mill Tailings” Project
  - Task 1. Site-wide Rn Concentrations
  - Task 2. Rn Flux Measurements
  - Task 3. Pedogenesis
  - Task 4. Evaluation of Processes Influencing Flux



Summary of Documents Related to Engineered Surface Barriers

- NUREG/CR-7200: Influence of Coupling Erosion and Hydrology on the Long-Term Performance of Engineered Surface Barriers [ML16125A124]
- NUREG/CR-7028: Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment [ML12005A110]
- NUREG/CP-0195: Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities [ML11238A056]
- NUREG-1623: Design of Erosion Protection for Long-Term Stabilization [ML052720285]
- CNWRA Report: Modeling of Net Infiltration through Soil Covers at Selected Title II Uranium Mill Tailings Sites [ML15121A610]
- CNWRA Report: Uranium Tailings Impoundments - Bottom Liners and Their Performance [ML15055A117]
- CNWRA Report: Methods for Monitoring Net Inflow Through Soil Covers of Uranium Mill Tailings Impoundments [ML14015A328]
- CNWRA Report: Analysis of Mill Tailings Cover Performance [ML12256A992]
- CNWRA Report: Software Validation Test Plan and Report for Channel-Hillslope Integrated Landscape Development (CHILD) Version 2.3.0 [ML083360379]
- CNWRA Report: Software Validation Test Plan and Report for SIBERIA Version 8.33 and EAMS Version 2.09 [ML0830203590]
- CNWRA Report: Software Validation Test Plan and Report for GeoStudio™ VADOSE /W© 2007 Version 7.11 [ML0829800941]
- CNWRA Report: Evaluation of Approaches to Simulate Engineered Cover Performance and Degradation [ML072950120]

2.3 Engineered Covers for UMTRCA Sites and DOE/LM's Projects

Presented by Jody Waugh
W.J. Waugh[1], C.H. Benson[2], W.H., Albright[3], C.N. Joseph[4]
[1]Navarro Research and Engineering, Inc., [2]University of Virginia,
[3]Desert Research Institute, [4]University of Arizona

2.3.1 Abstract

DOE/LM is responsible for long-term surveillance and maintenance (LTS&M) of disposal cells for uranium mill tailings throughout the United States. The long-term protectiveness of disposal cells relies on engineered earthen covers to limit radon flux, rainwater percolation flux, and erosion. Past LM studies have demonstrated how natural ecological and soil-forming processes are changing the as-built engineering properties of disposal cell covers. The LM Strategic Plan includes four strategies for improving the long-term sustainability of environmental remedies: (1) evaluate long-term performance, (2) collaborate with LTS&M experts, (3) explore innovations that improve and inform remedies, and (4) improve LTS&M plans as warranted to maintain compliance objectives while reducing costs. LM's execution of the Strategic Plan included a suite of studies designed to help answer several questions (see below) about the effects of natural processes acting on engineered covers. Collaboration with the NRC on the Radon Barrier Study is a key component of this effort. LM plans to use the results of these studies to inform LTS&M decisions, such as whether to discontinue herbicide spraying at selected sites.

Will soil formation increase permeability and percolation? During the 1990s and early 2000s, DOE/LM measured the field-saturated hydraulic conductivity (K_s) of radon barriers at five LM sites using air-entry permeameters. Sites selected for study encompassed ranges of climates, ecologies, and cover designs within the LM portfolio. In general, K_s was higher where plants were rooted in radon barriers compared to areas without vegetation, and higher near the tops than near the bottoms of radon barriers. Similar to the results reported in NUREG/CR-7028, geometric means of K_s for the five sites were generally between 1×10^{-7} and 1×10^{-5} meters per second (m/s), whereas the design target, according to UMTRCA cover design reports, was 1×10^{-9} m/s. A similar increase in radon barrier K_s led to an annual percolation flux of up to 17 percent of precipitation in an LM test of a rock-armored cover without vegetation near Grand Junction, CO.

Will plants take up and accumulate contamination? DOE/LM and the University of Arizona studied the uptake of elements of concern in plants growing on seven UMTRCA covers located at arid and semiarid sites near Native American communities. Concentrations in current-year leaf and stem tissues harvested from plants growing on disposal cell covers and in reference areas near the disposal cells were compared with maximum tolerance levels set for animal diets by the National Research Council (2005). For 14 of 46 comparisons, levels of uranium and other elements of concern were higher in plants growing on engineered disposal cells covers compared to reference area plants, indicating possible mobilization of these elements from the tailings into plant tissues. However, with one exception, all concentrations in plants were well below maximum tolerance levels (MTLs). Selenium, the only element that exceeded its MTL, likely originated in local seleniferous soil used to construct disposal cell covers.

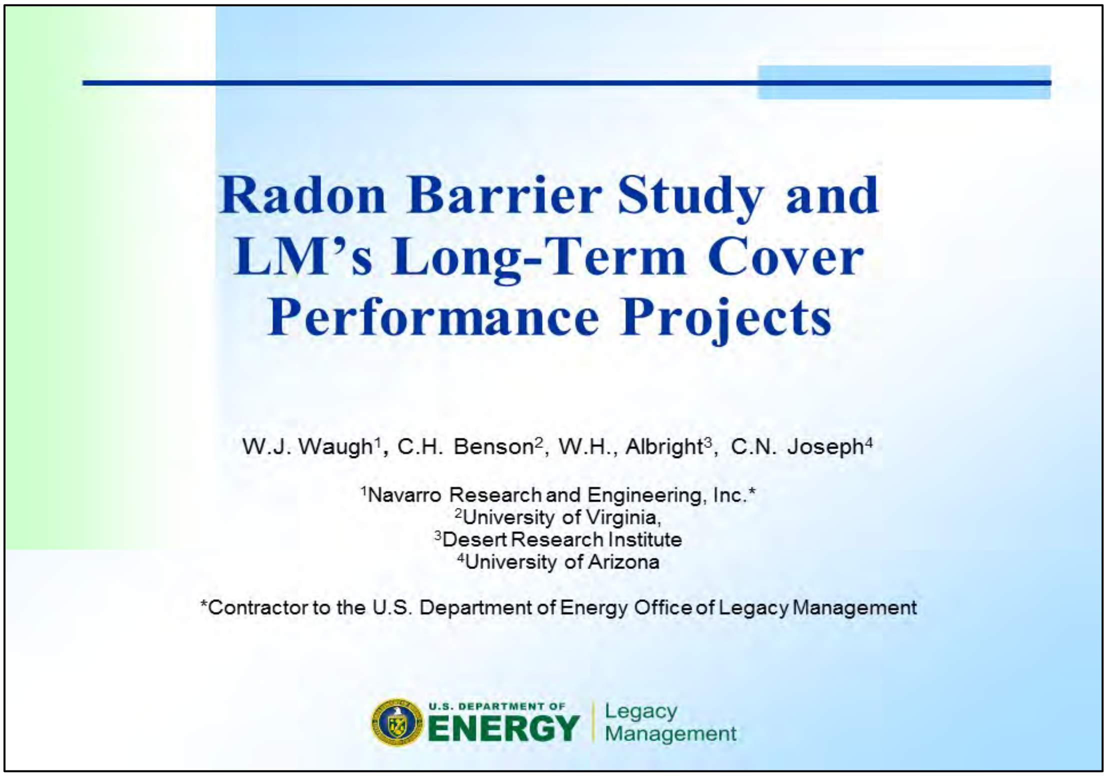
Will soil formation and ecological succession increase radon diffusion and flux? Results of the LM/NRC Radon Barrier Study addressed this question and are presented by Dr. Craig Benson (Section 2.6) and Dr. Mark Fuhrmann (section 2.7).

Will dust deposition influence erosion and ecological succession? At many arid and semiarid UMTRCA sites, aeolian dust is filling the interstitial spaces in rock riprap layers that were designed to control wind and water erosion. Dust accumulation in these layers may influence the long-term protectiveness of disposal cell covers in both positive and negative ways. DOE/LM plans to begin a study in 2019 to address several LTS&M questions: What are the rates of soil infilling rock layers? What are the chemical, physical (engineering), biological, and morphological properties of these emerging rock-soil matrixes? How will soil formation in this layer influence ecological succession, radon attenuation, water percolation, and erosion of rock-armored covers?

Are evapotranspiration (ET) covers a sustainable alternative? DOE/LM is investigating alternatives to conventional resistive cover designs for uranium mill tailings. A cover constructed in 2000 near Monticello, UT, was designed to mimic the natural soil-water balance as measured in nearby undisturbed native soils and vegetation. To limit percolation, the alternative (water balance or ET) cover relies on a thick sandy clay loam soil overlying a coarse sand capillary barrier for water storage, and a planting of native sagebrush steppe vegetation to seasonally release soil water through ET. Water balance monitoring within a 3.0-ha drainage lysimeter embedded in the cover during construction provides convincing evidence that the cover has performed well. Mean annual percolation was 0.1 percent of precipitation (range of 0.0 to 0.8 percent of precipitation) over 18 years. Plant species diversity, percent cover, and leaf area increased over the 18-year period.

Are natural processes effectively transforming conventional covers into ET covers, and if they are, should we enhance this process? DOE/LM studies are weighing the environmental tradeoffs of natural and enhanced (managed) transformation of conventional UMTRCA covers into ET covers. Past and current studies show that ecological and soil-forming processes have already changed as-built engineering properties of conventional covers. Results so far suggest that if vegetation is allowed to establish or is planted on disposal cells, conventional covers may begin to function more like ET covers without undue increases in environmental or regulatory risk. Soil-forming processes may have increased radon flux, but mean fluxes remain below the regulatory standard. Contaminant concentrations in plants growing on covers also remain well below risk thresholds. In an LM test cover without plants, soil-forming processes increased percolation flux from near 0 percent to 17 percent of precipitation within 5 years. However, in a second test cover, ET reduced percolation flux from 12.0 percent to 0.1 percent of precipitation 3 years after planting during three dry years. LM will continue to evaluate natural and enhanced conversion of conventional covers into ET covers to help inform LTS&M decisions.

2.3.2 Presentation



Radon Barrier Study and LM's Long-Term Cover Performance Projects

W.J. Waugh[1], C.H. Benson[2], W.H., Albright[3], C.N. Joseph[4]

[1]Navarro Research and Engineering, Inc.*
[2]University of Virginia,
[3]Desert Research Institute
[4]University of Arizona

*Contractor to the U.S. Department of Energy Office of Legacy Management

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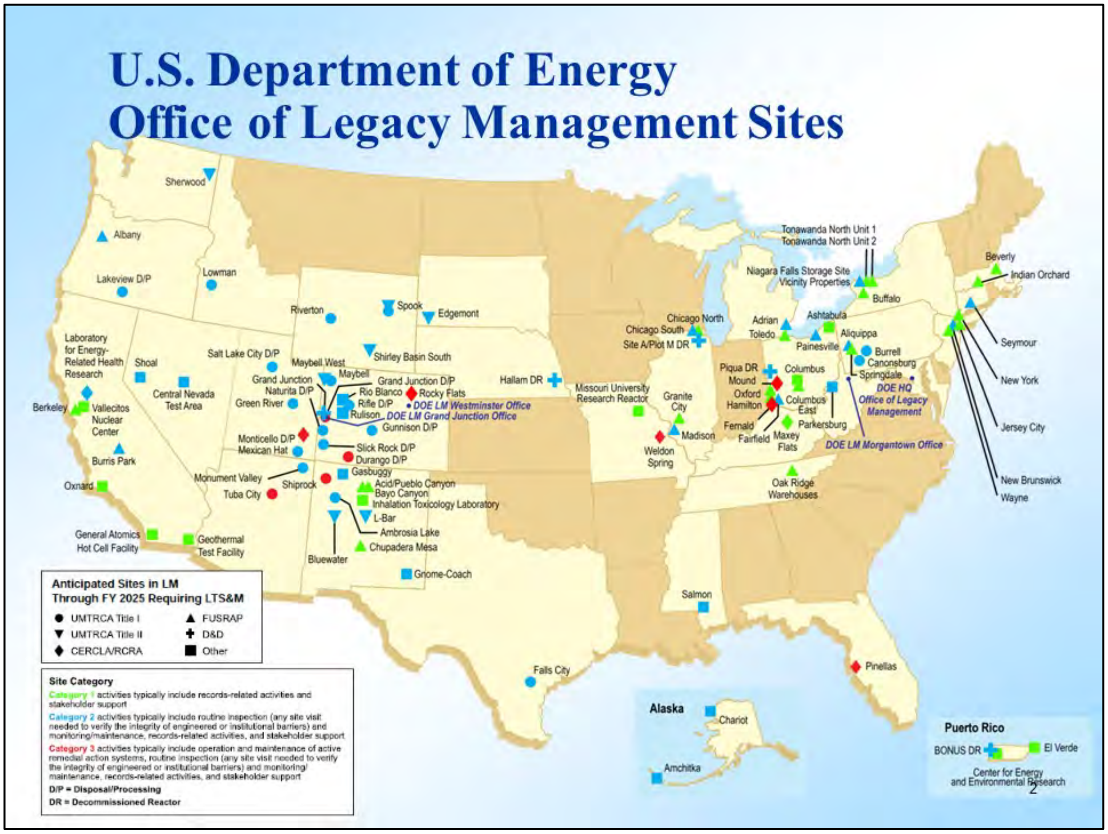


U.S. Department of Energy
Office of Legacy Management Sites

Anticipated Sites in LM Through FY 2025 Requiring LTS&M

● UMTRCA Title I
▼ UMTRCA Title II
◆ CERCLA/RCRA
▲ FUSRAP
✚ D&D
■ Other

Site Category

Category 1 activities typically include records-related activities and stakeholder support

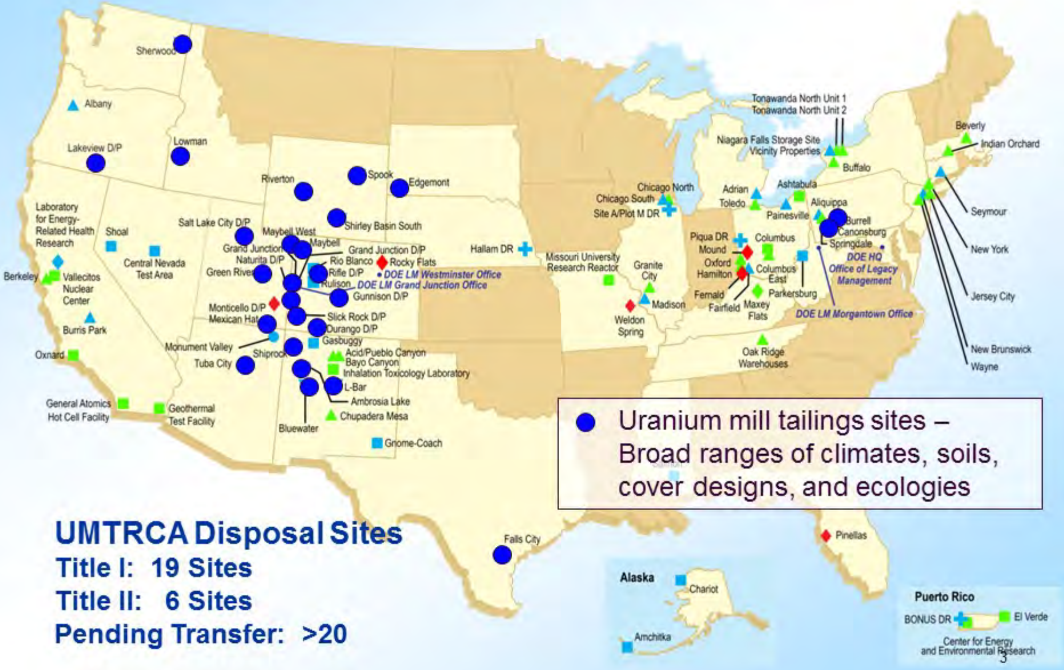
Category 2 activities typically include routine inspection (any site visit needed to verify the integrity of engineered or institutional barriers) and monitoring/maintenance, records-related activities, and stakeholder support

Category 3 activities typically include operation and maintenance of active remedial action systems, routine inspection (any site visit needed to verify the integrity of engineered or institutional barriers) and monitoring/maintenance, records-related activities, and stakeholder support

D/P = Disposal/Processing

DR = Decommissioned Reactor

Uranium Mill Tailings Sites



● Uranium mill tailings sites – Broad ranges of climates, soils, cover designs, and ecologies

UMTRCA Disposal Sites

Title I: 19 Sites

Title II: 6 Sites

Pending Transfer: >20

Presentation Topics

Part I

- Engineered Covers for Uranium Mill Tailings
- Horror Vacui (Mother Nature Abhors a Vacuum)
- Long-Term Surveillance and Maintenance Questions
- LM Strategic Plan
- Radon Barrier Study and LM's Long-Term Cover Performance Projects
- Summary

Part II

- Radon Barrier Study Objectives and Site Selection
- Test Conditions and Plant Ecology
- Summary

Presentation Topics

Part I

- **Engineered Covers for Uranium Mill Tailings**
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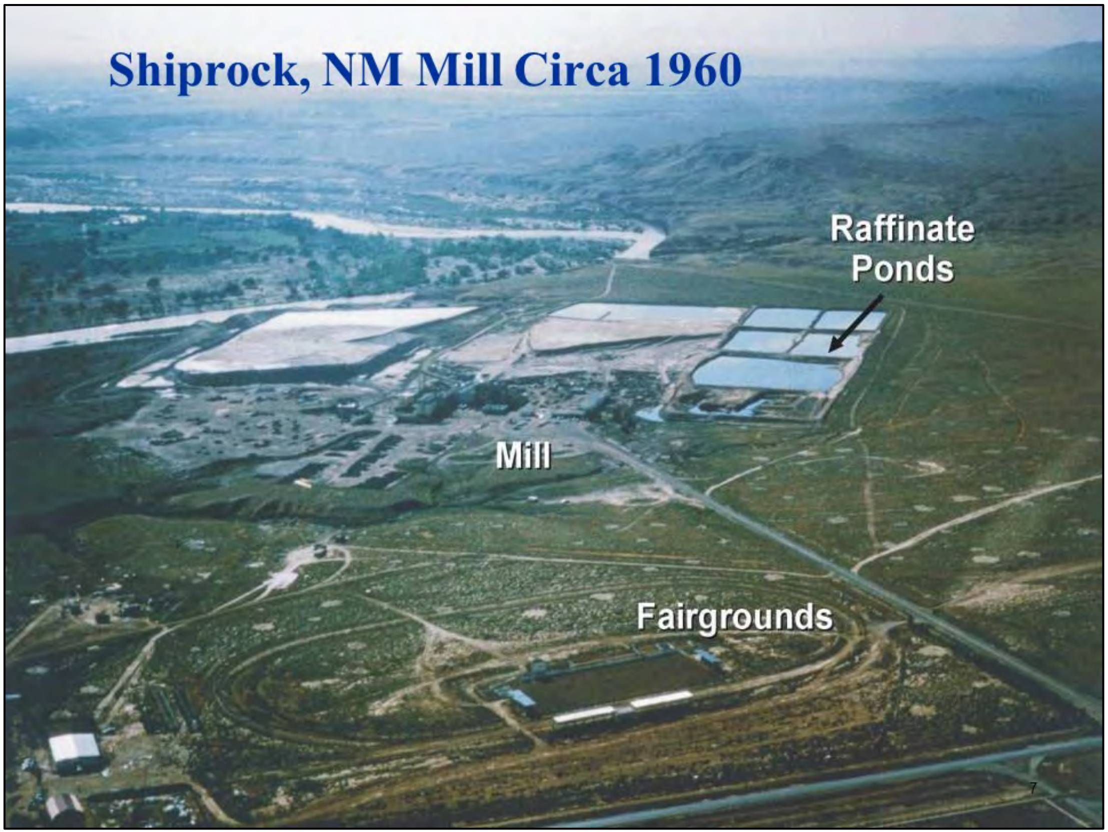
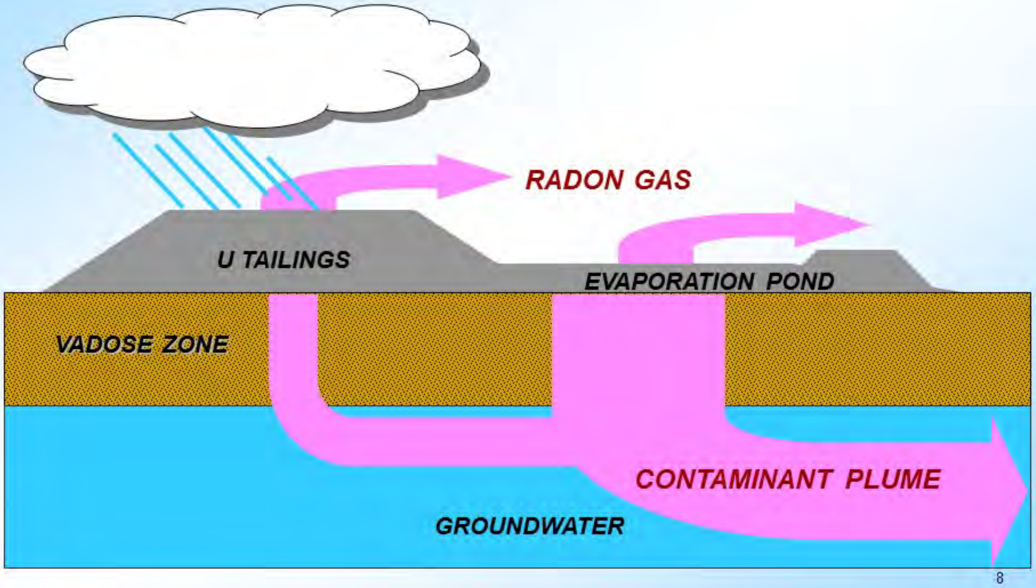
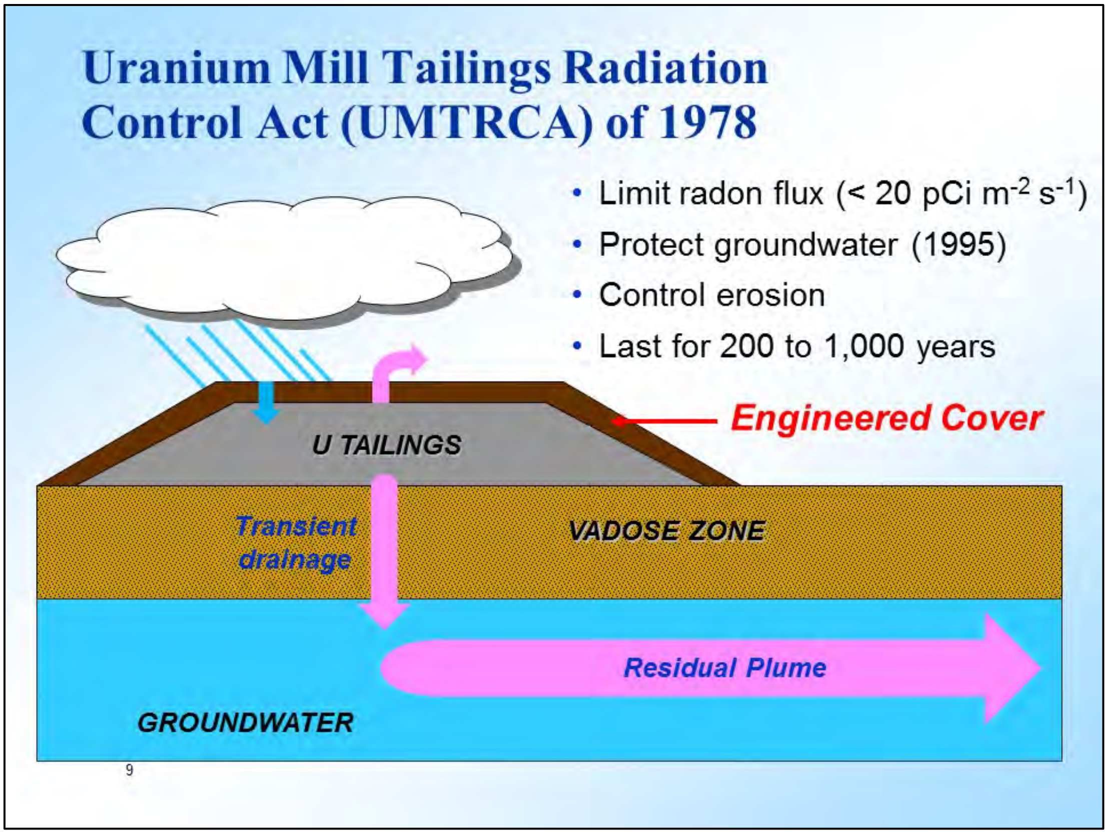
Example: Shiprock, New Mexico

Shiprock, NM Mill Circa 1960



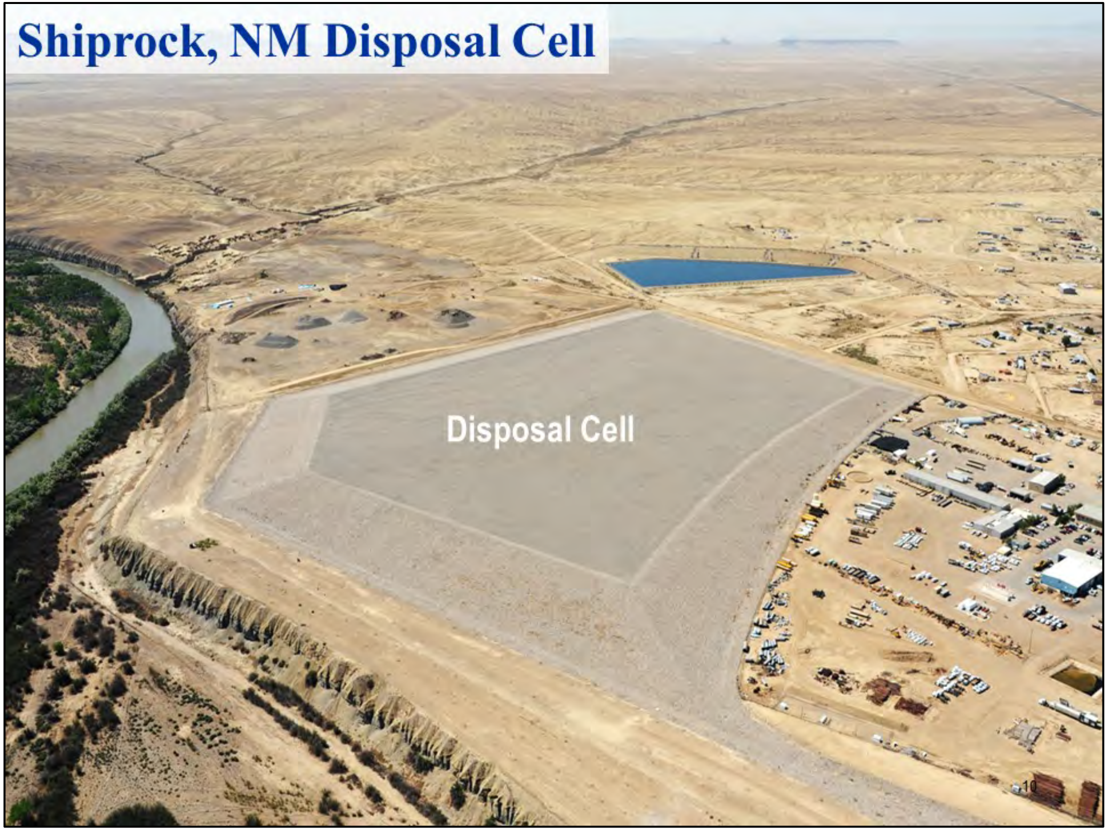
Uranium Mill Tailings (Before Remediation)





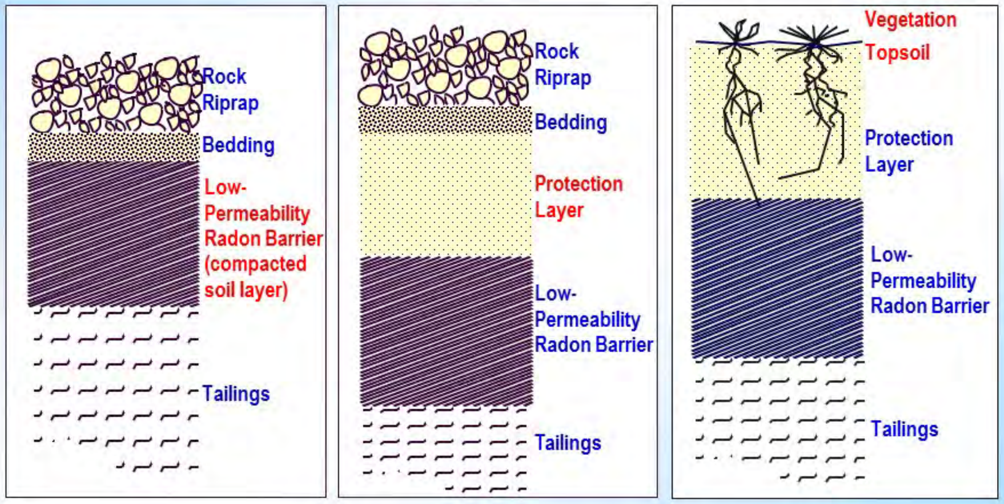
Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978

- Limit radon flux (< 20 pCi m^{-2} s^{-1})
- Protect groundwater (1995)
- Control erosion
- Last for 200 to 1,000 years



Shiprock, NM Disposal Cell

Generalized UMTRCA Cover Designs



Presentation Topics

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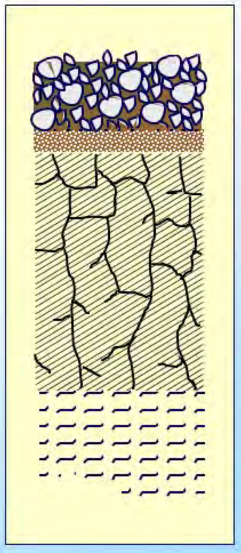
Natural Processes are Changing Engineered Covers

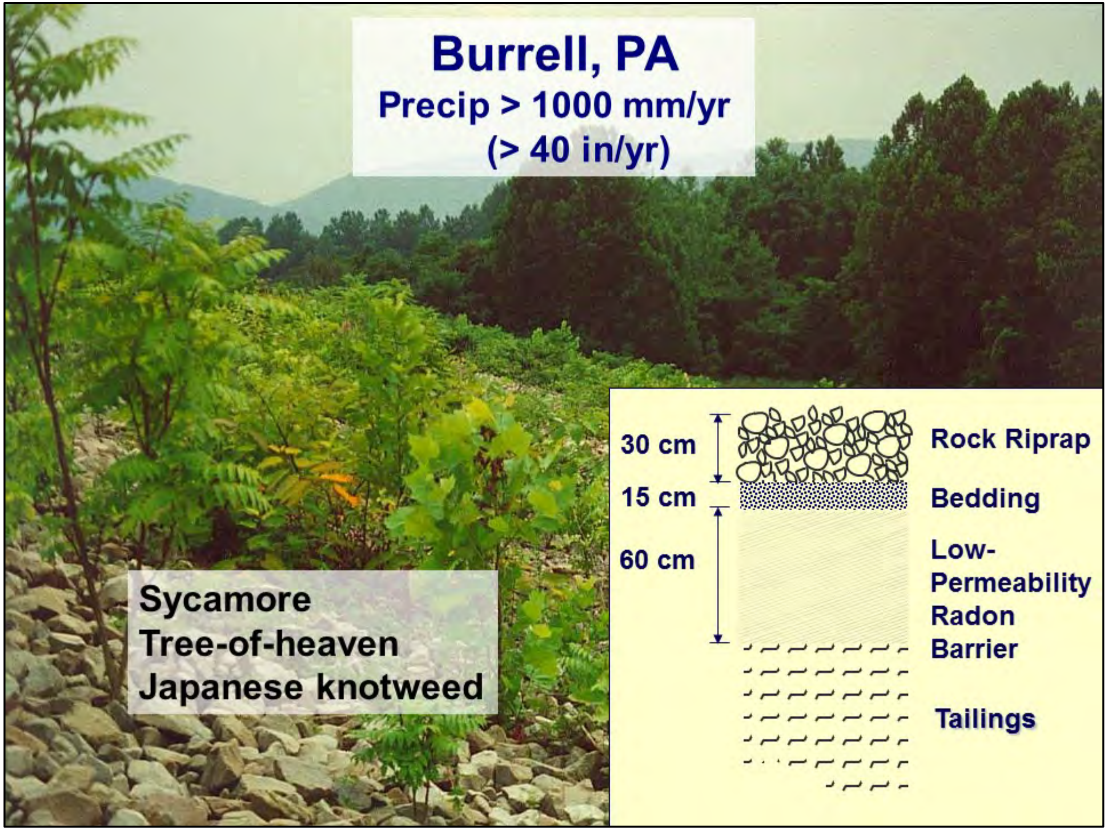
Ecological Succession:

- Rock layers reduce evaporation, increase soil moisture, and create habitat for woody plants
- Roots penetrate compacted soil barriers

Soil Forming Processes:

- Soil structure is the aggregation of particles into peds (clods) separated by planes of weakness.
- Freeze-thaw and wet-dry cycling, roots, secondary minerals, organic acids, and microorganisms promote aggregation and formation of soil structure
- Soil is filling the voids in the rock layer

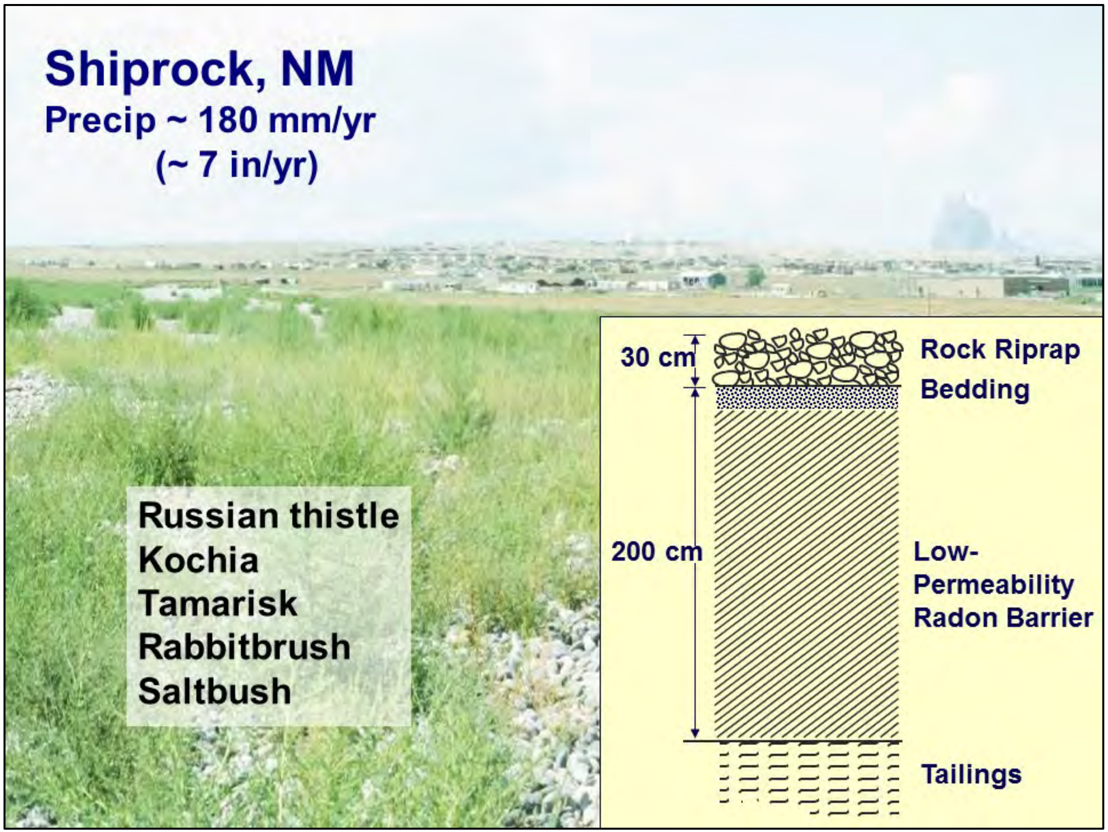




Burrell, PA

Precip > 1000 mm/yr
(> 40 in/yr)

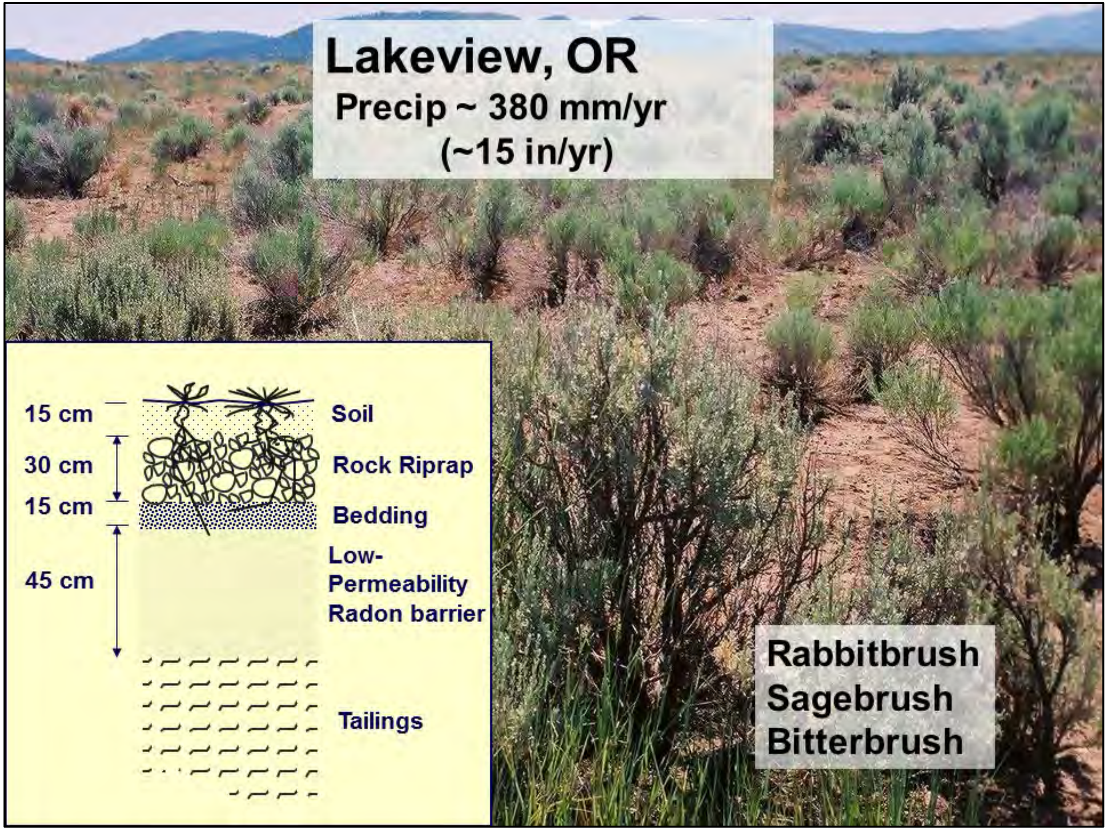
Sycamore
Tree-of-heaven
Japanese knotweed



Shiprock, NM

Precip ~ 180 mm/yr
(~ 7 in/yr)

Russian thistle
Kochia
Tamarisk
Rabbitbrush
Saltbush

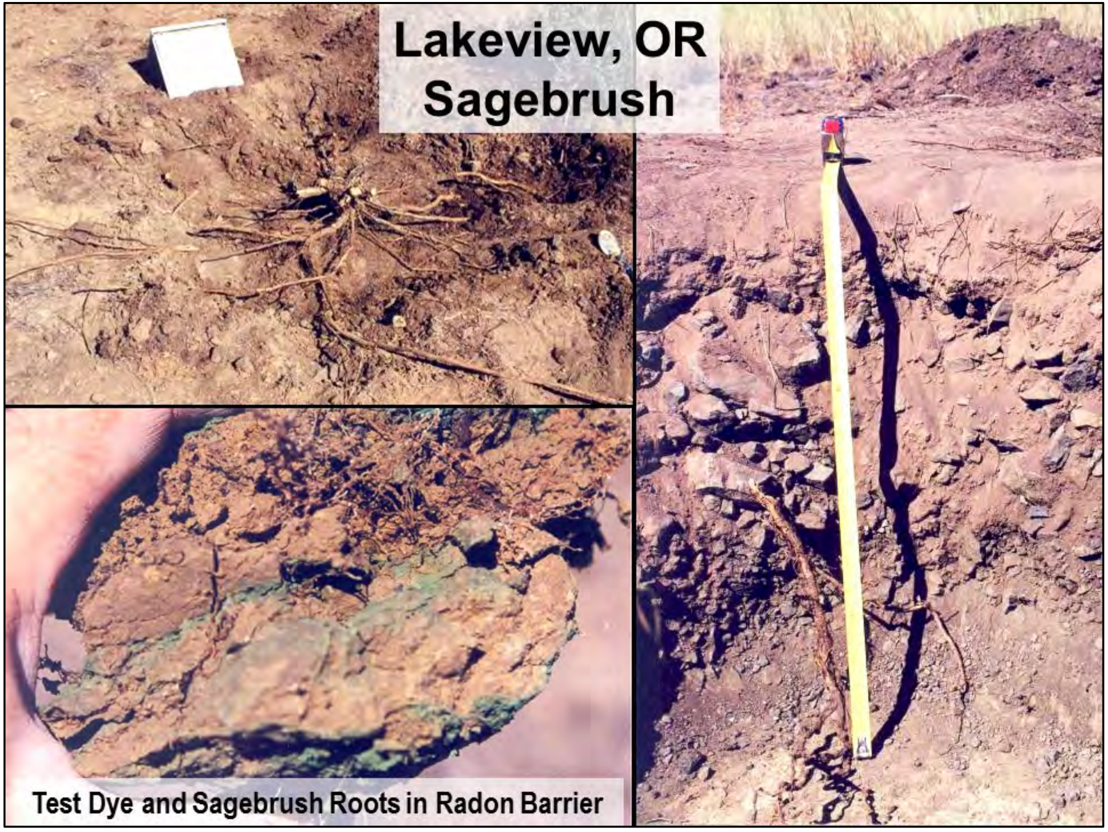


Lakeview, OR

Precip ~ 380 mm/yr
(~15 in/yr)

Rabbitbrush
Sagebrush
Bitterbrush

Lakeview, OR
Sagebrush



Lakeview, OR
Sagebrush

Test Dye and Sagebrush Roots in Radon Barrier

Grand Junction, CO

Fourwing saltbush (*Atriplex canescens*) and soil structure

Saltbush roots following soil structure plane

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LTS&M Questions

- Herbicides are currently used to control vegetation on many engineered covers. Under what conditions should vegetation be allowed to grow on covers?
- Have natural ecological and soil-forming processes changed cover engineering properties leading to increased radon flux and soil water percolation?
- If so, what are the HH&E (human health & environment), regulatory, and perceived risks, and are covers *currently* protective of HH&E?
- Could natural processes continue to increase radon flux, soil water percolation, or erosion over the design life of a cover—will covers be protective in the long term?

LTS&M Questions (cont.)

- Counterintuitively, could natural processes transform *low-permeability covers* into *evapotranspiration (ET) covers*, improving hydraulic performance? Can we we enhance favorable processes (ecological engineering)?
- Are existing technologies adequate to evaluate and screen the portfolio of UMTRCA covers for possible long-term management as ET covers?
- Will disposal cell covers at UMTRCA Title II transition sites satisfy long-term performance and risk expectations, or will they require modification before or after transfer to LM?
- How would water percolation and radon flux through in-service covers be monitored if regulatory requirements change, placing greater emphasis on performance monitoring and risk management?

Presentation Topics

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2016–2025
STRATEGIC PLAN

Goal 1. Protect Human Health and the Environment

Objective 3. Improve the long-term sustainability of environmental remedies.

Strategies

- Record and analyze data on long-term performance…
- Collaborate with organizations that conduct scientific R&D in support of LTS&M (Long-Term Surveillance and Maintenance).
- Explore and advance innovative technical approaches that improve LTS&M and inform remediation strategies.
- Develop changes to LTS&M plans that maintain compliance objectives (**manage risks**) and **reduce costs**.

Presentation Topics

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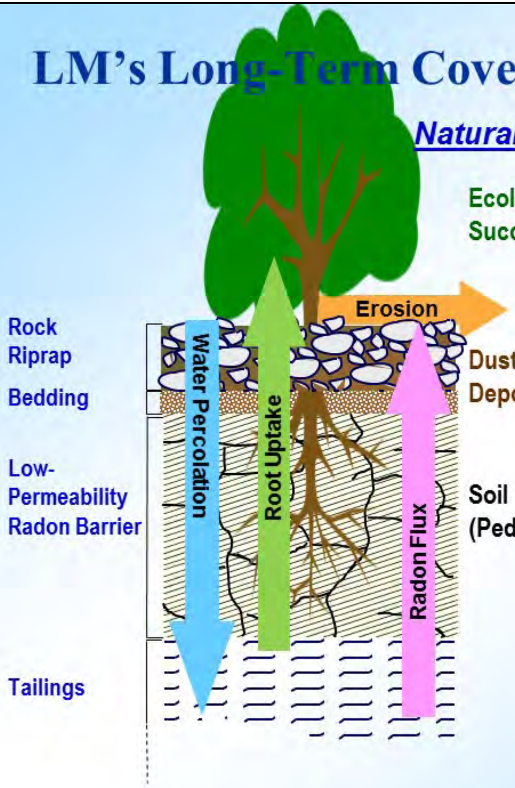
LM's Long-Term Cover Performance Projects



Natural Changes

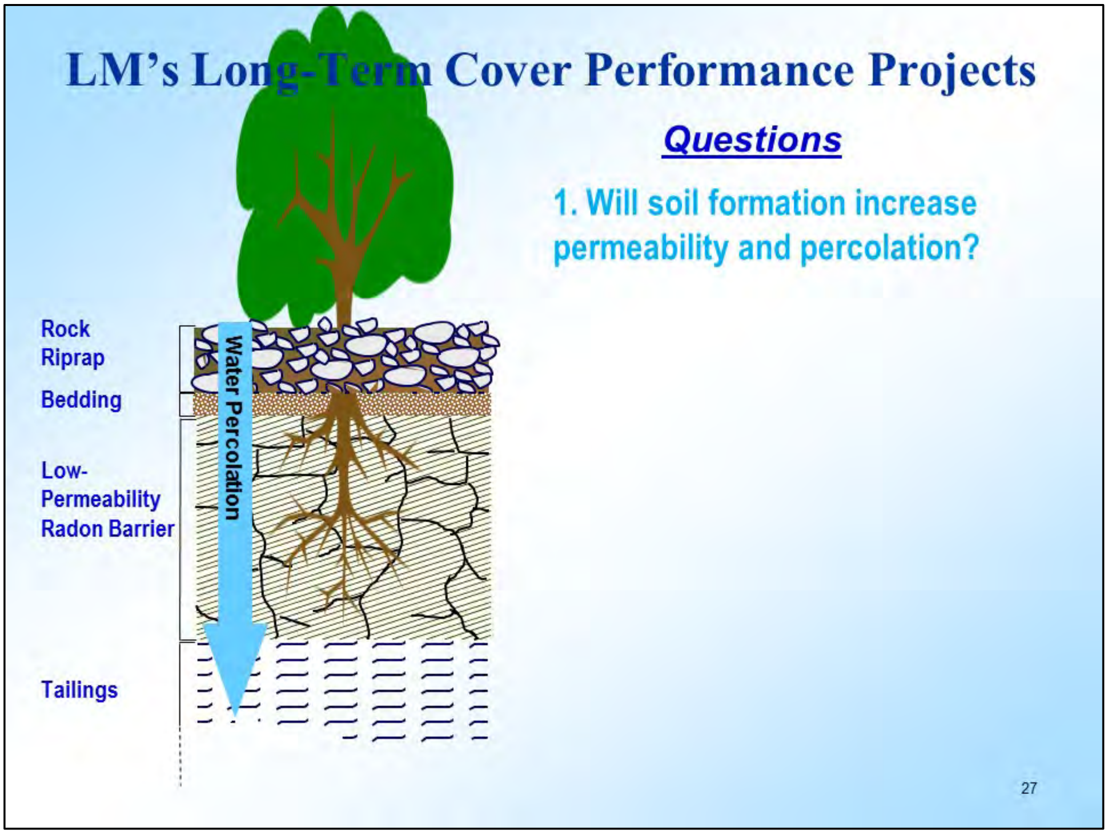
Ecological Succession

Dust Deposition

Soil Formation (Pedogenesis)

Questions

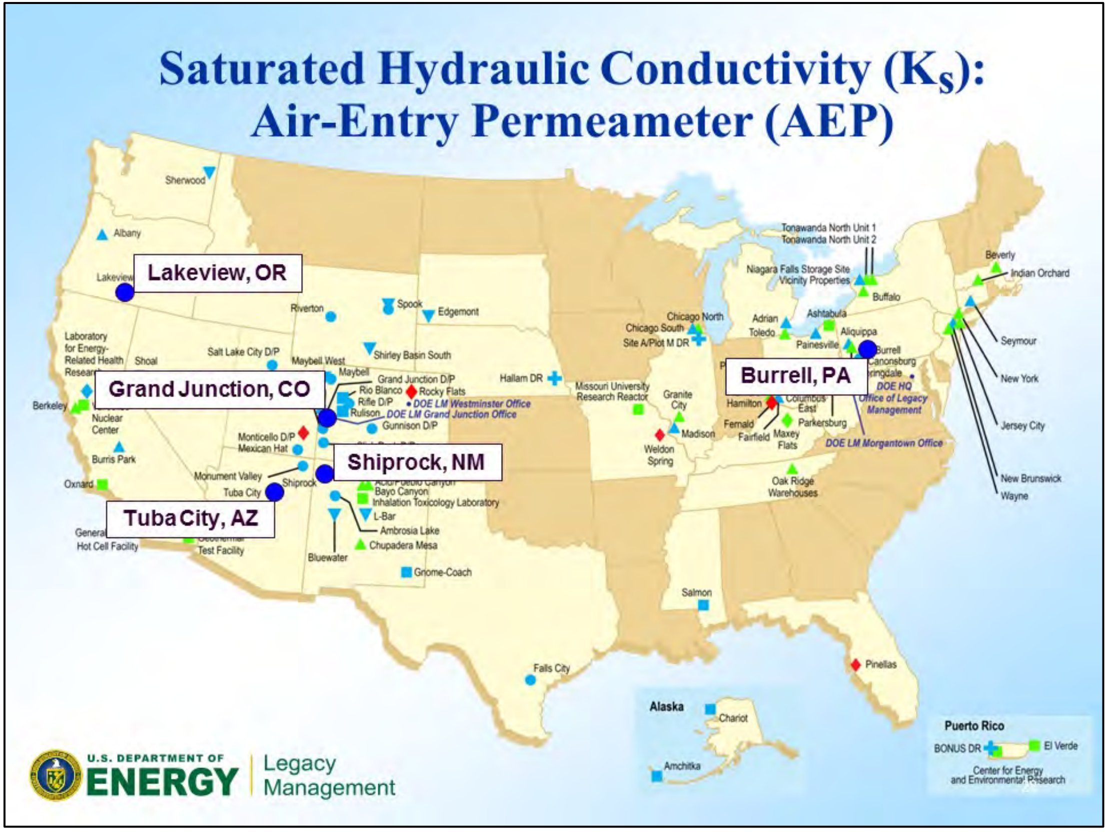
1. Will soil formation increase permeability and percolation?
2. Will plants take up and accumulate contamination?
3. Will soil formation and ecological succession increase radon diffusion and flux?
4. Will dust deposition influence erosion and ecological succession?
5. Are evapotranspiration (ET) covers a sustainable alternative?
6. Is Mother Nature transforming conventional covers into ET covers? Should we enhance this?



LM's Long-Term Cover Performance Projects

Questions

1. Will soil formation increase permeability and percolation?



Saturated Hydraulic Conductivity (K_S): Air-Entry Permeameter (AEP)

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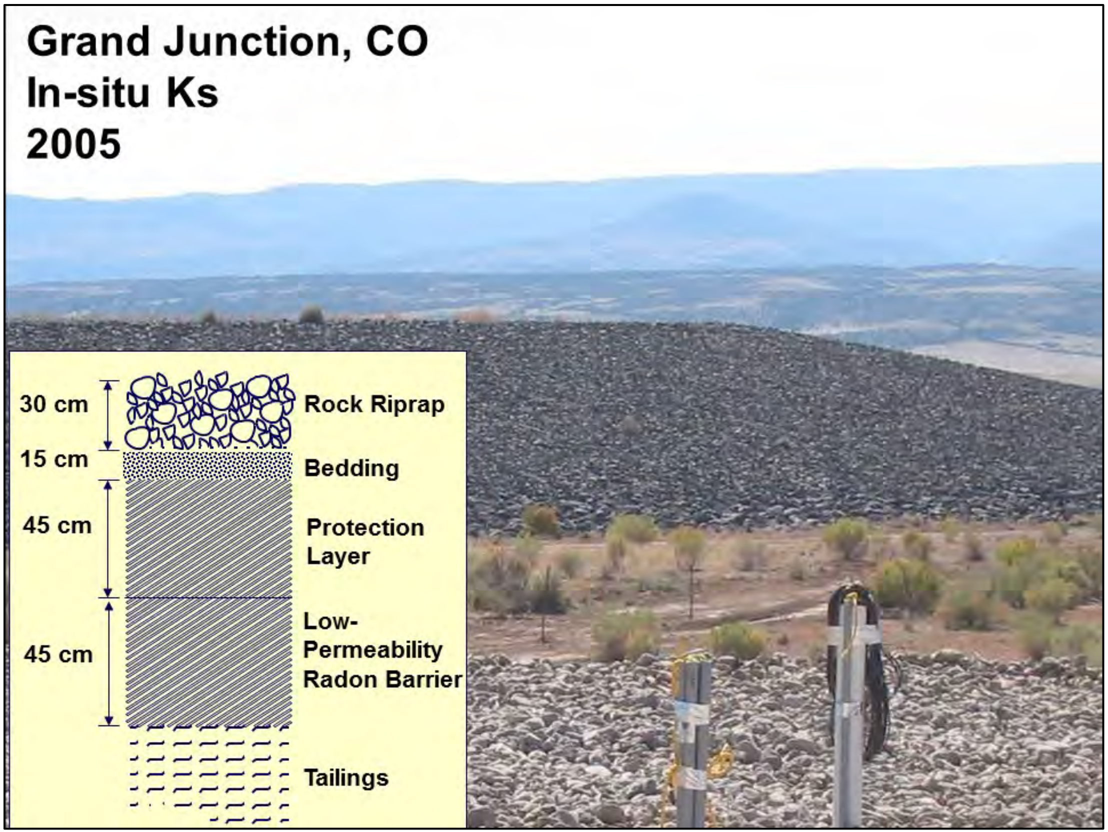
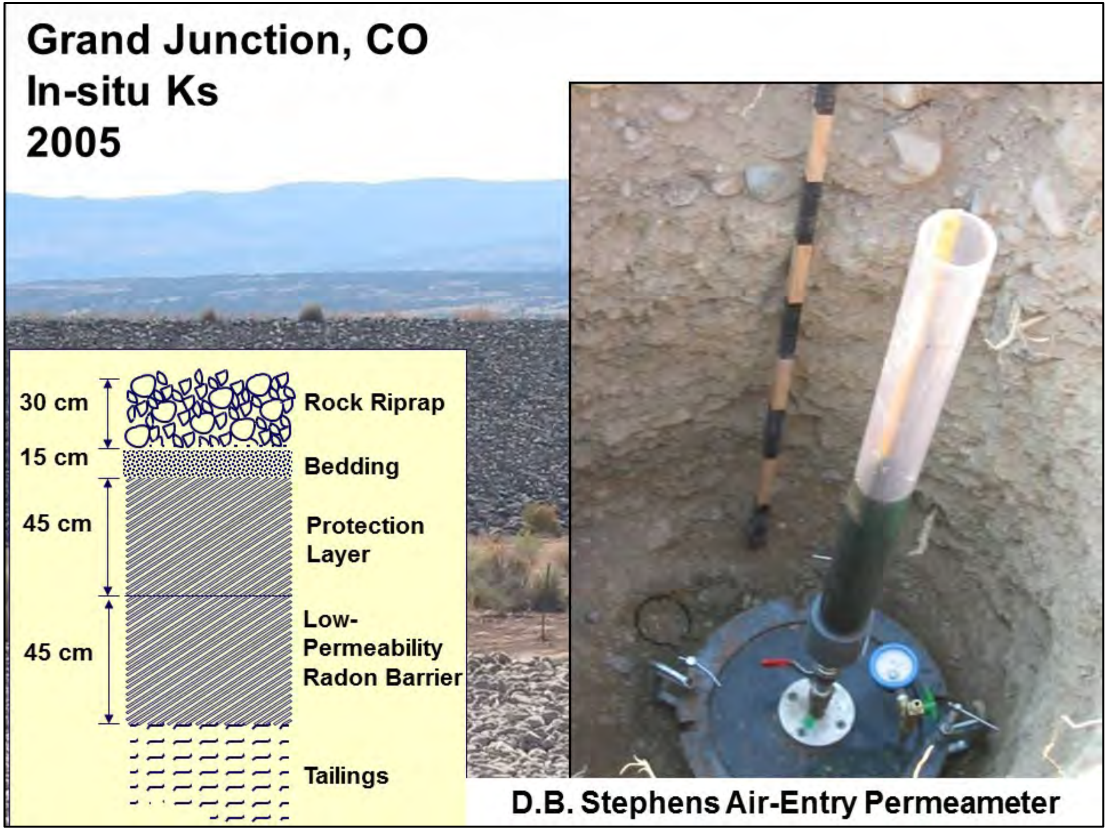


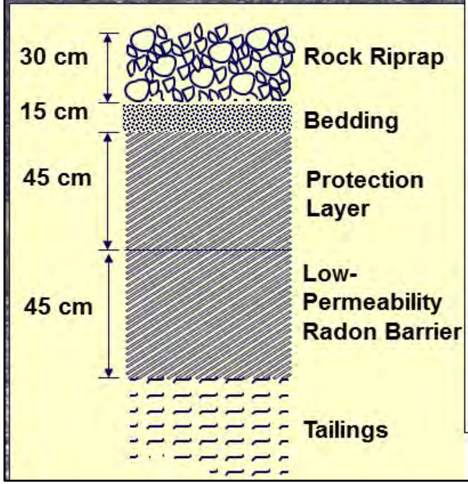
Grand Junction, CO
In-situ Ks
2005

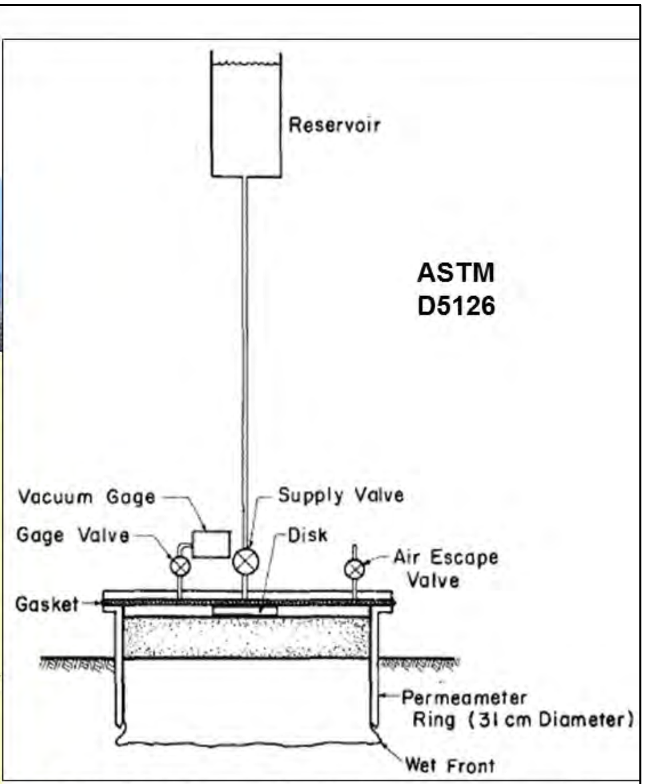


Grand Junction, CO
In-situ Ks
2005

D.B. Stephens Air-Entry Permeameter

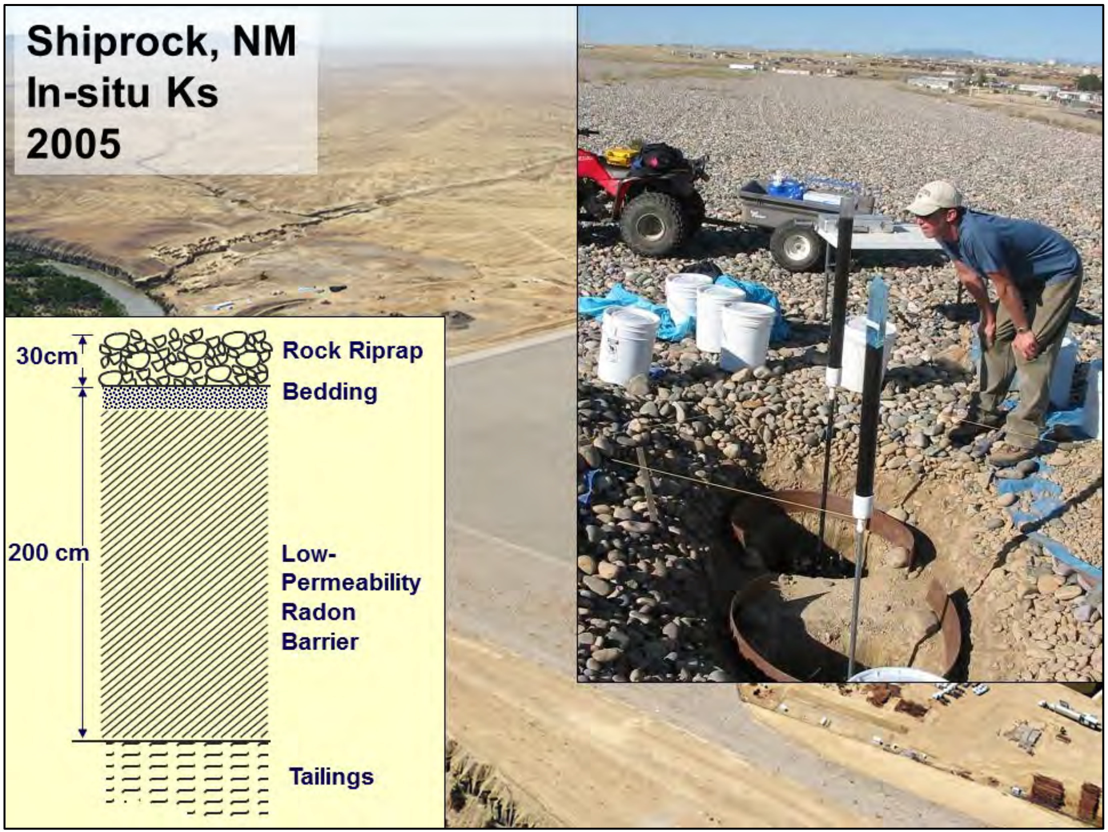
Grand Junction, CO
In-situ Ks
2005





D.B. Stephens Air-Entry Permeameter

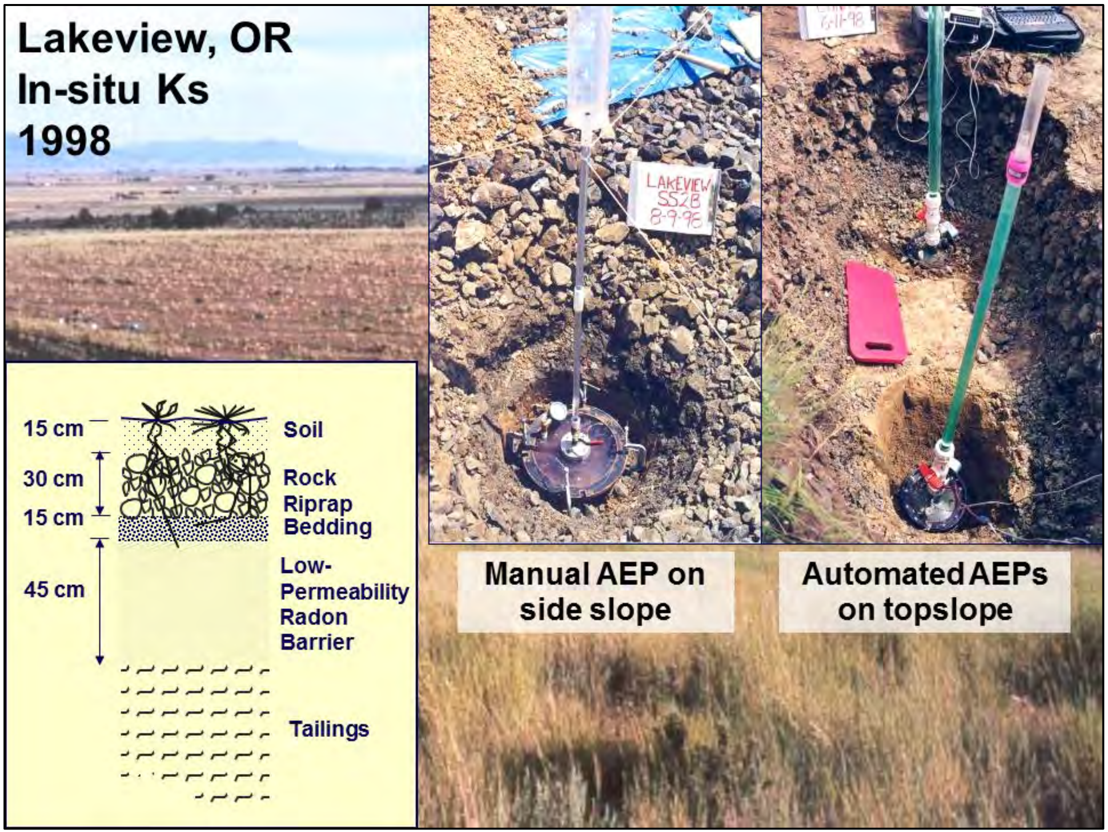
Shiprock, NM
In-situ Ks
2005



Shiprock, NM
In-situ Ks
2005

Lakeview, OR
In-situ Ks
1998

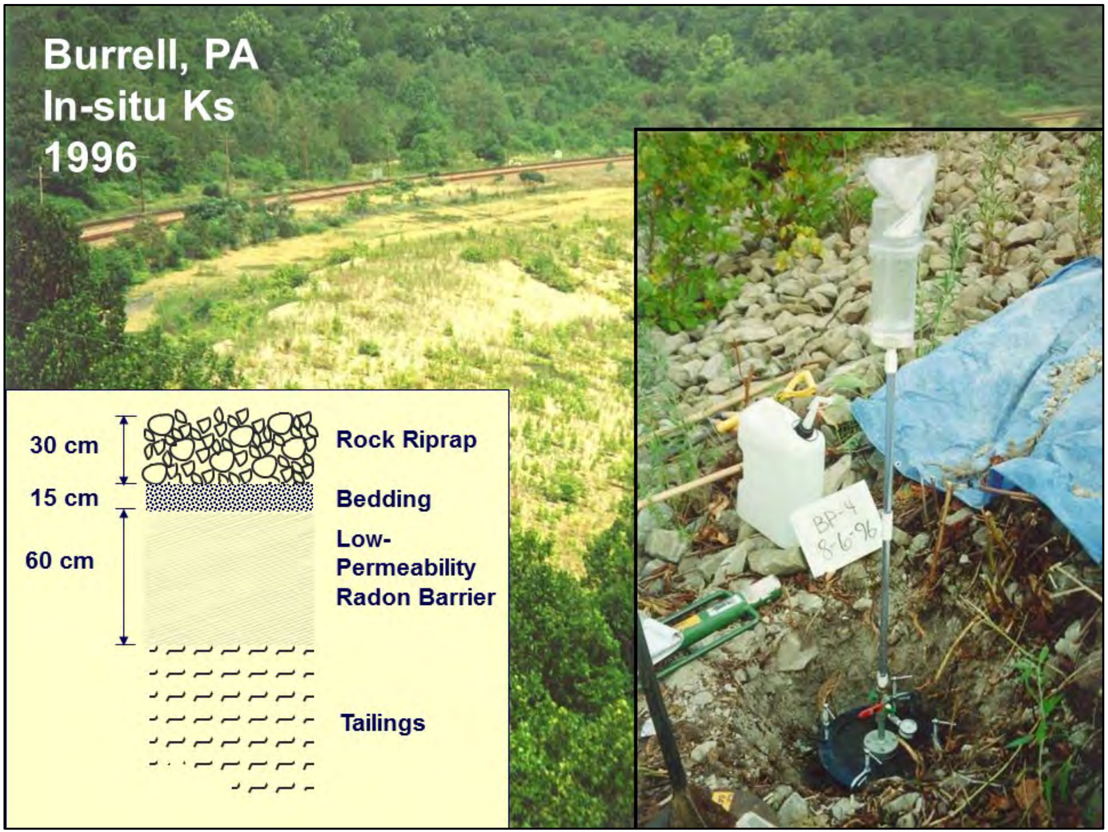
Lakeview, OR
In-situ Ks
1998



Manual AEP on side slope

Automated AEPs on topslope

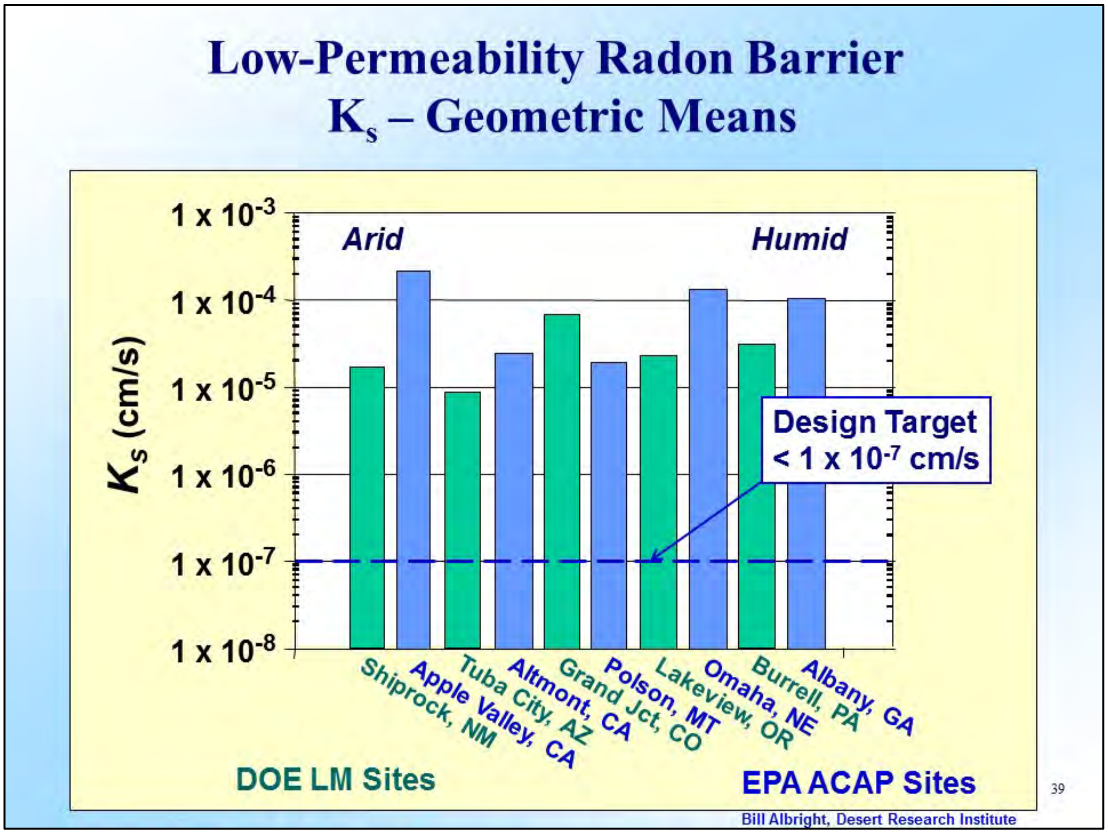
Burrell, PA
In-situ Ks
1996



Burrell, PA
In-situ Ks
1996

Burrell, PA
In-situ Ks
1996

AEP at analog site:
Same soil series as cover

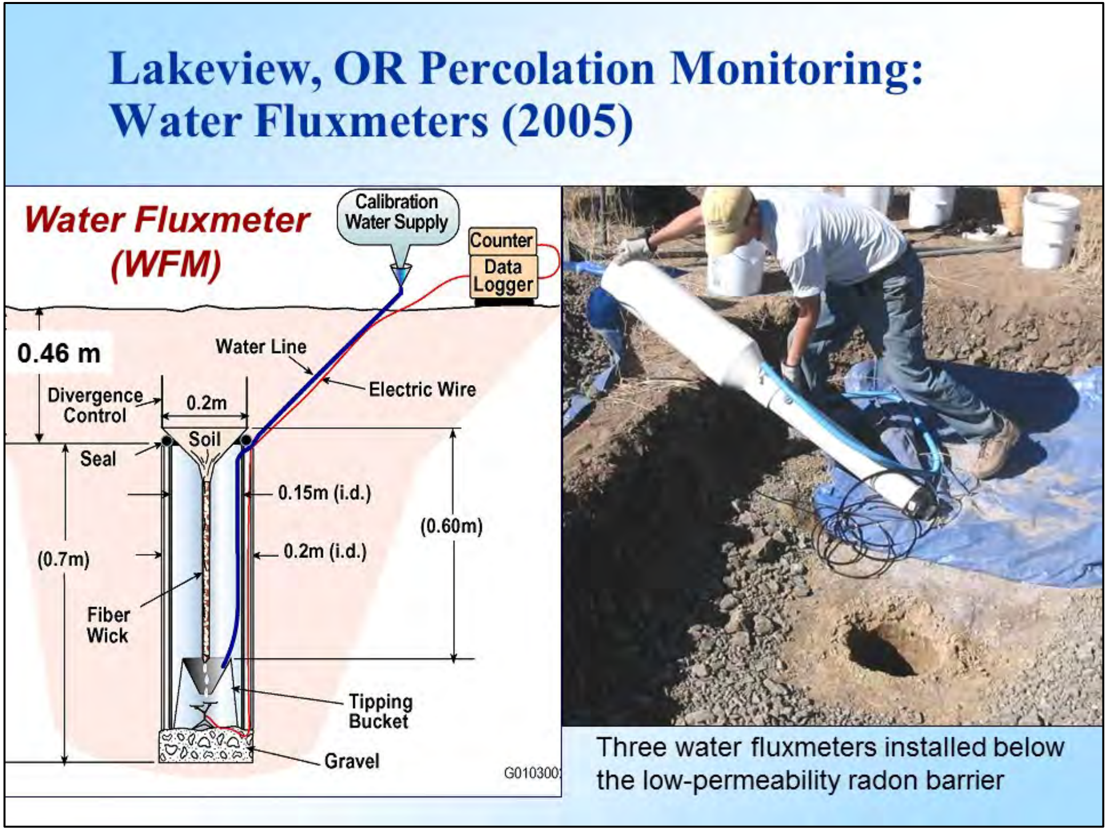


Low-Permeability Radon Barrier K_s – Geometric Means

DOE LM Sites

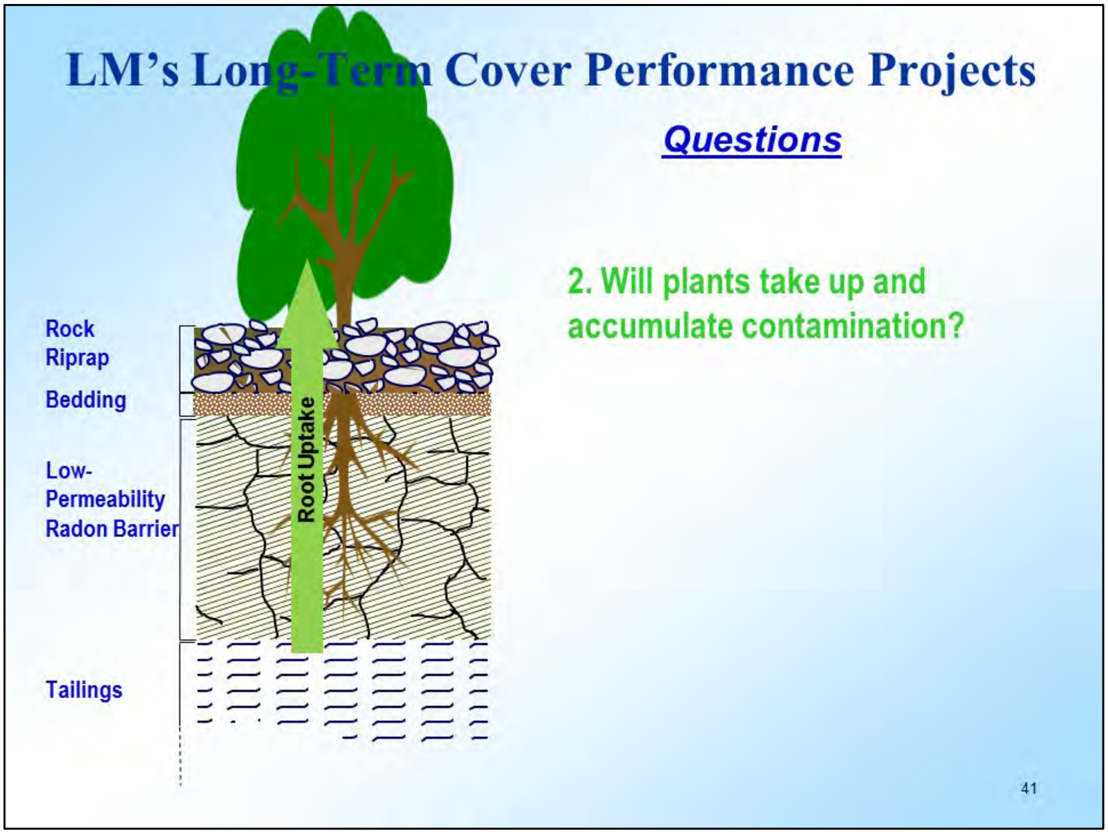
EPA ACAP Sites

Bill Albright, Desert Research Institute



Lakeview, OR Percolation Monitoring: Water Fluxmeters (2005)

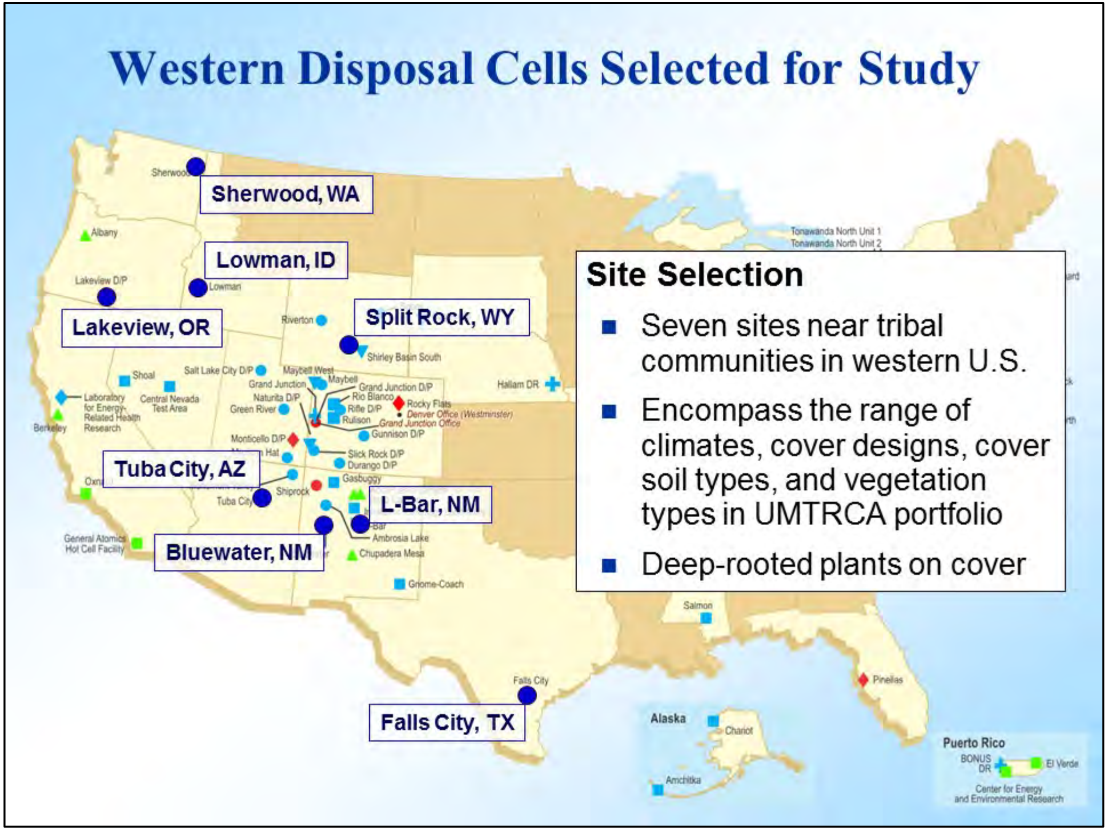
Three water fluxmeters installed below the low-permeability radon barrier



LM's Long-Term Cover Performance Projects

Questions

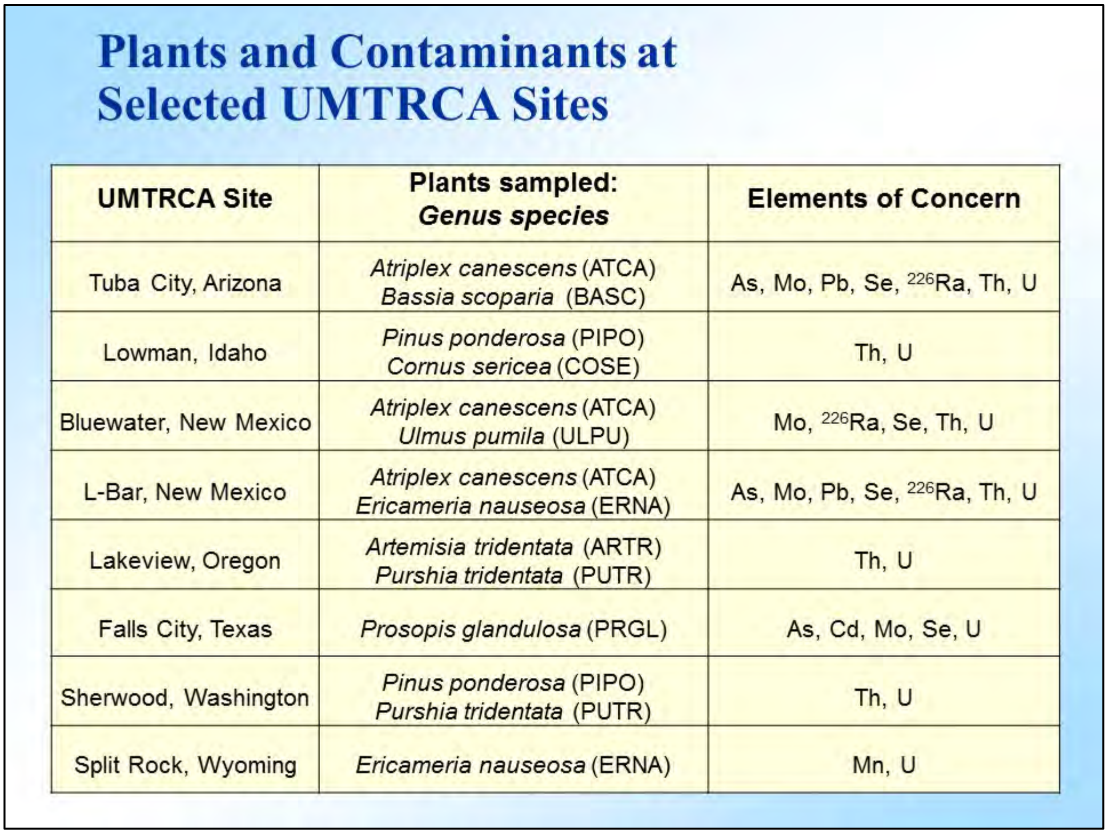
2. Will plants take up and accumulate contamination?



Western Disposal Cells Selected for Study

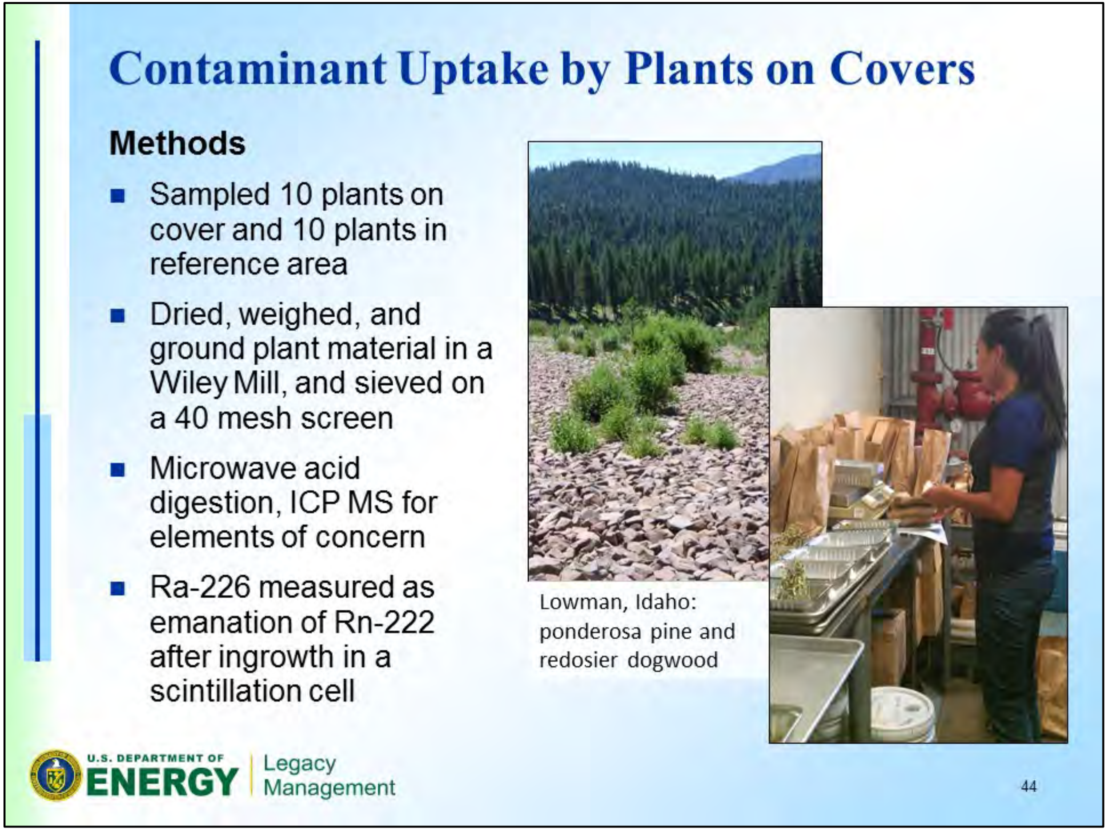
Site Selection

- Seven sites near tribal communities in western U.S.
- Encompass the range of climates, cover designs, cover soil types, and vegetation types in UMTRCA portfolio
- Deep-rooted plants on cover



Plants and Contaminants at Selected UMTRCA Sites

UMTRCA Site	**Plants sampled:** ***Genus species***	Elements of Concern
Tuba City, Arizona	*Atriplex canescens* (ATCA) *Bassia scoparia* (BASC)	As, Mo, Pb, Se, ^{226}Ra, Th, U
Lowman, Idaho	*Pinus ponderosa* (PIPO) *Cornus sericea* (COSE)	Th, U
Bluewater, New Mexico	*Atriplex canescens* (ATCA) *Ulmus pumila* (ULPU)	Mo, ^{226}Ra, Se, Th, U
L-Bar, New Mexico	*Atriplex canescens* (ATCA) *Ericameria nauseosa* (ERNA)	As, Mo, Pb, Se, ^{226}Ra, Th, U
Lakeview, Oregon	*Artemisia tridentata* (ARTR) *Purshia tridentata* (PUTR)	Th, U
Falls City, Texas	*Prosopis glandulosa* (PRGL)	As, Cd, Mo, Se, U
Sherwood, Washington	*Pinus ponderosa* (PIPO) *Purshia tridentata* (PUTR)	Th, U
Split Rock, Wyoming	*Ericameria nauseosa* (ERNA)	Mn, U

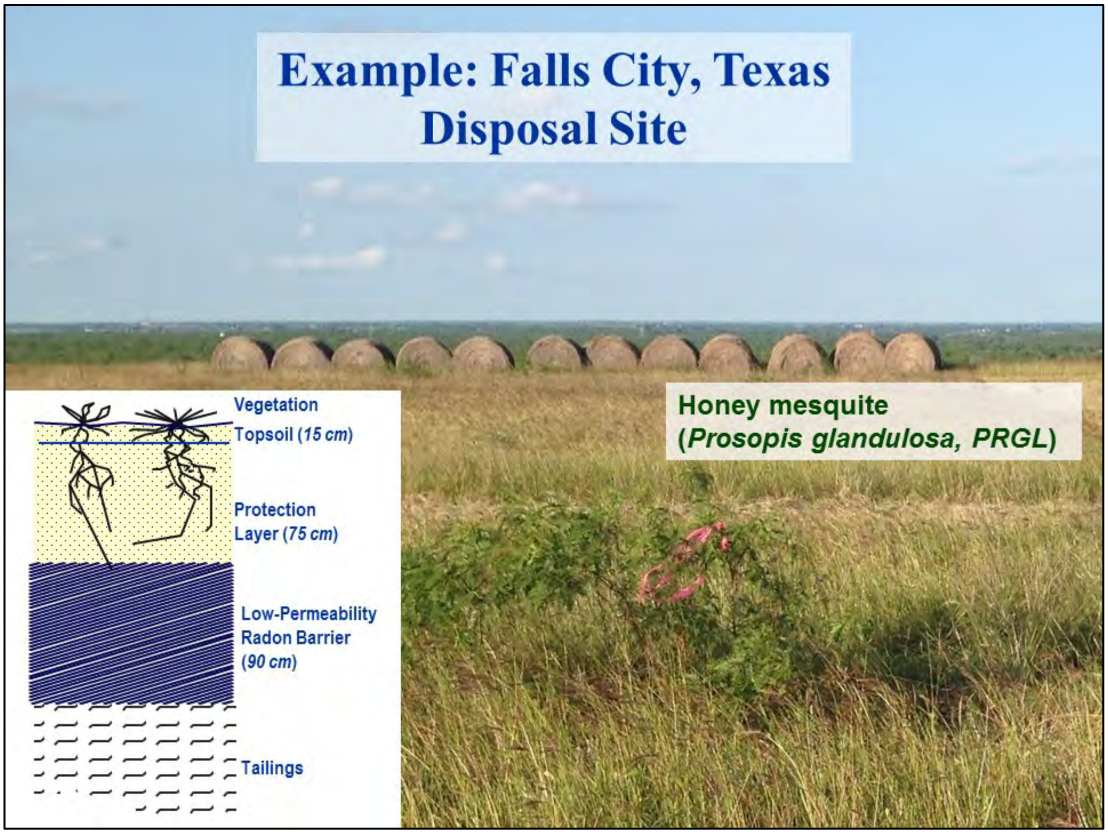


Contaminant Uptake by Plants on Covers

Methods

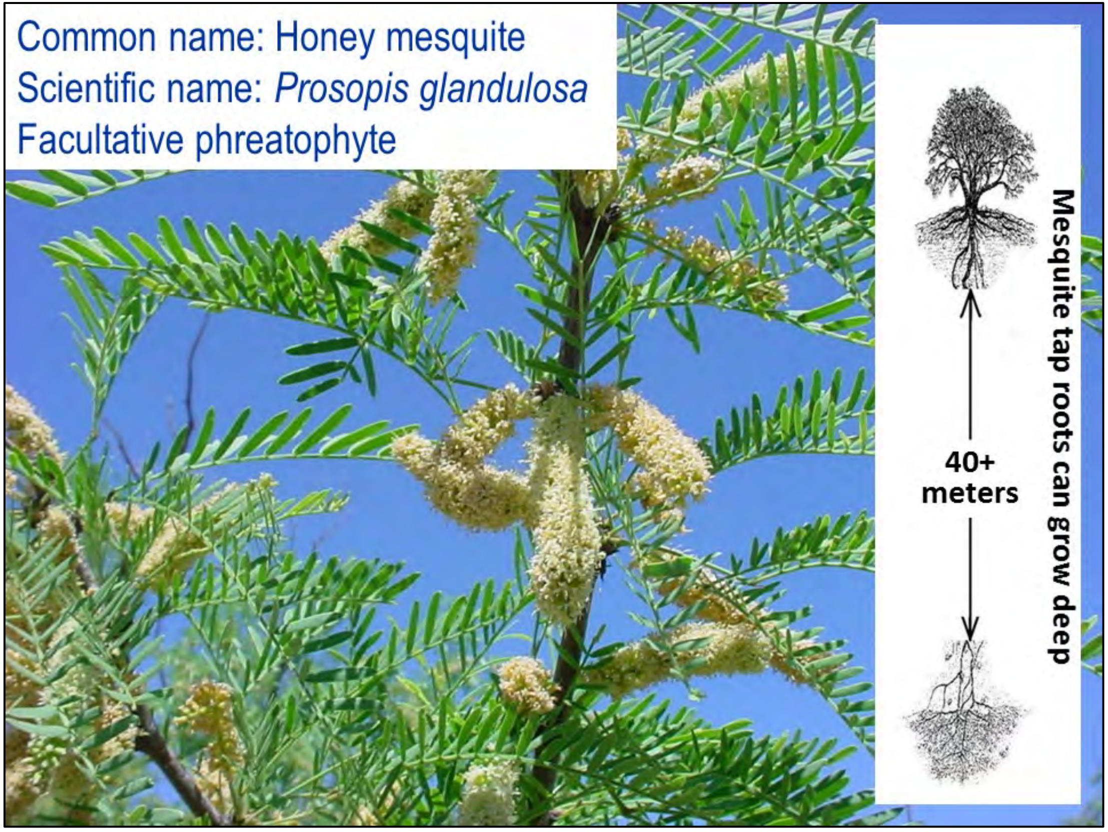
- Sampled 10 plants on cover and 10 plants in reference area
- Dried, weighed, and ground plant material in a Wiley Mill, and sieved on a 40 mesh screen
- Microwave acid digestion, ICP MS for elements of concern
- Ra-226 measured as emanation of Rn-222 after ingrowth in a scintillation cell

Lowman, Idaho: ponderosa pine and redosier dogwood



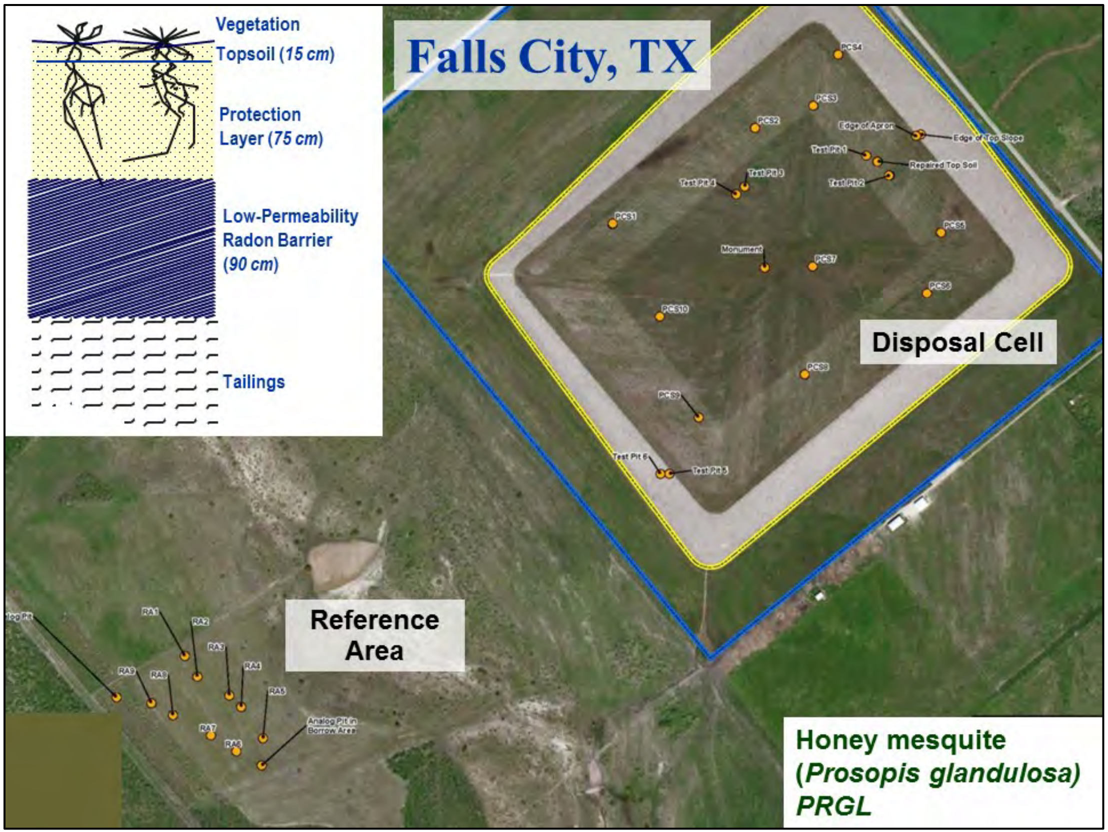
Example: Falls City, Texas Disposal Site

Honey mesquite (*Prosopis glandulosa, PRGL*)



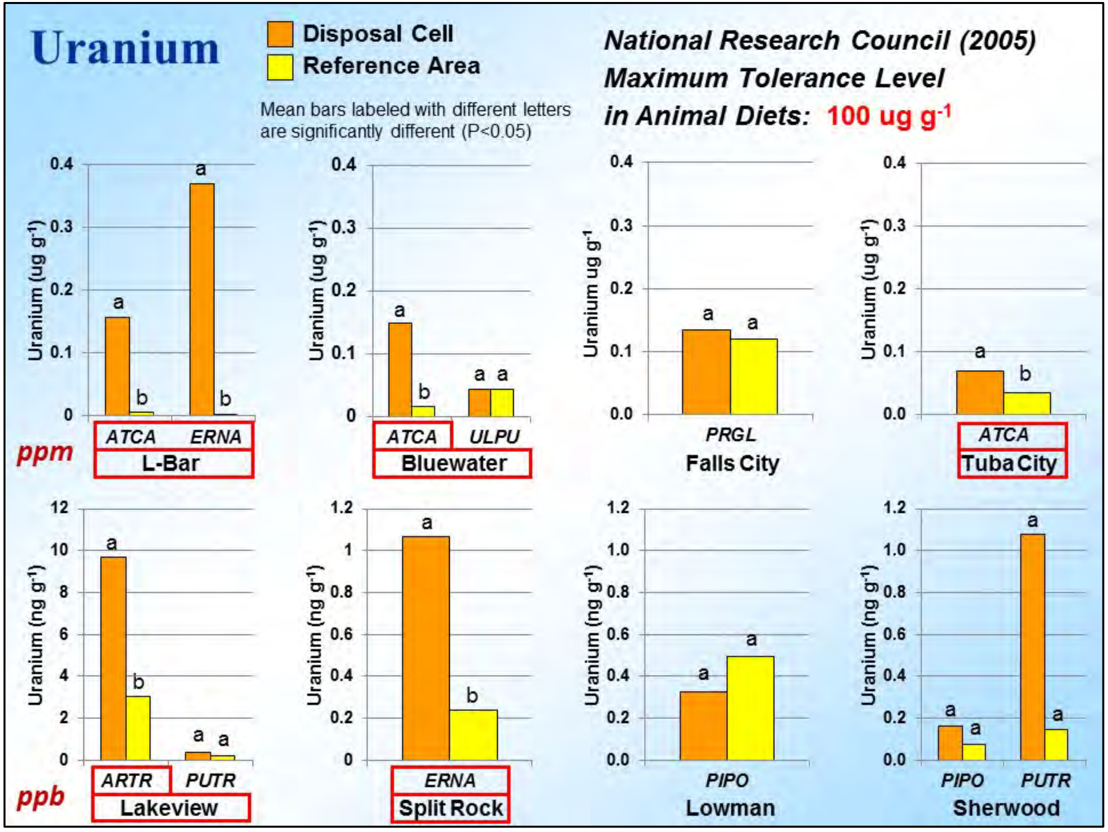
Common name: Honey mesquite
Scientific name: *Prosopis glandulosa*
Facultative phreatophyte

Falls City, TX



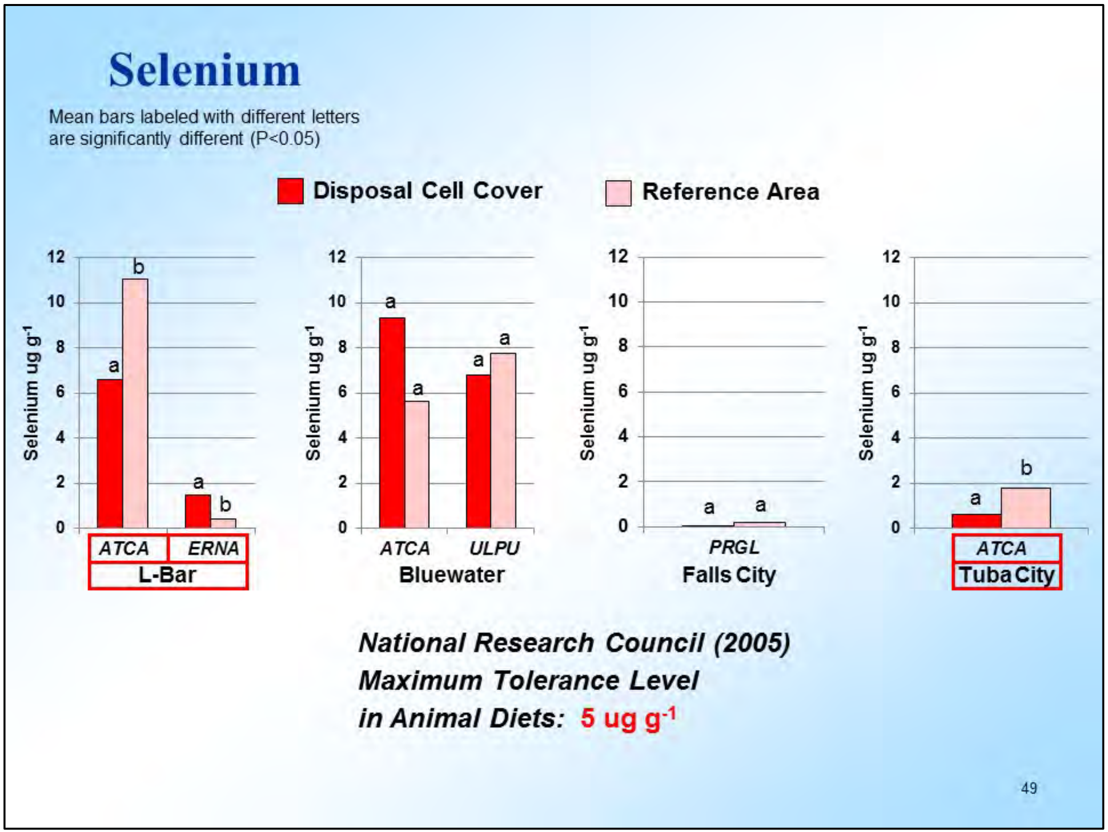
Honey mesquite
(*Prosopis glandulosa*)
PRGL

Uranium



Mean bars labeled with different letters are significantly different (P<0.05)

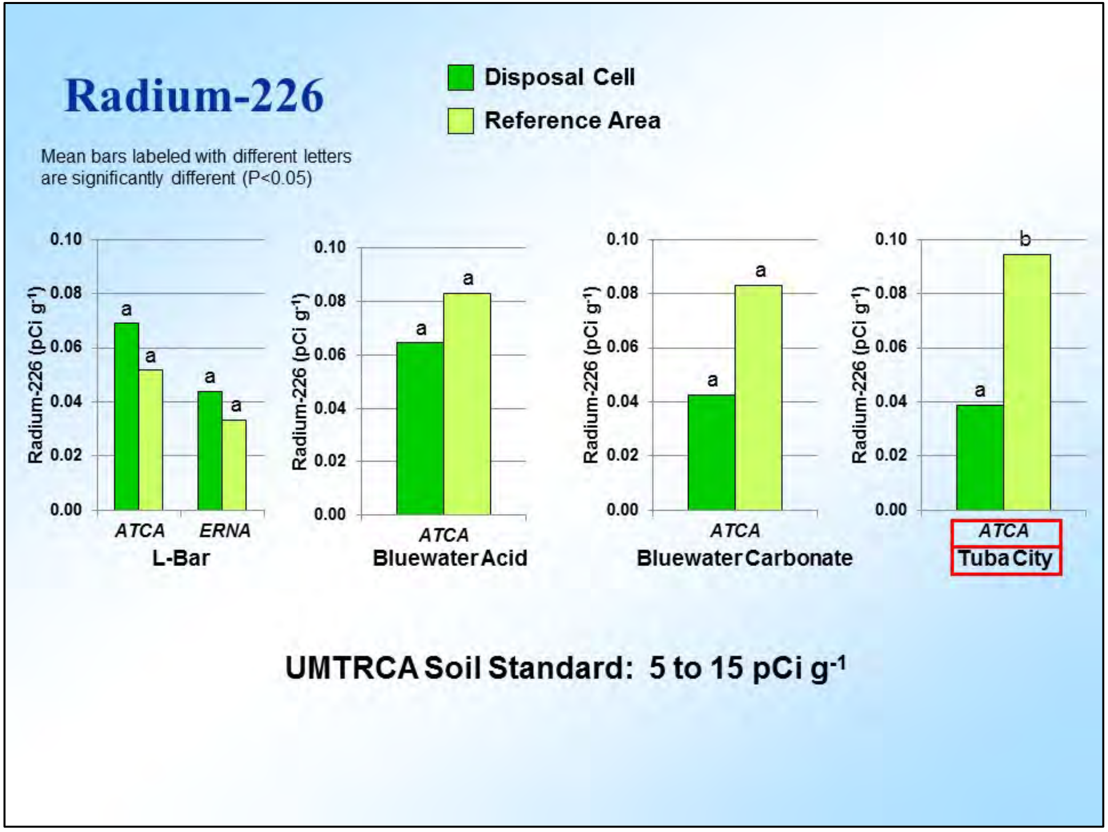
National Research Council (2005)
Maximum Tolerance Level
***in Animal Diets:* 100 ug g^{-1}**



Selenium

Mean bars labeled with different letters are significantly different (P<0.05)

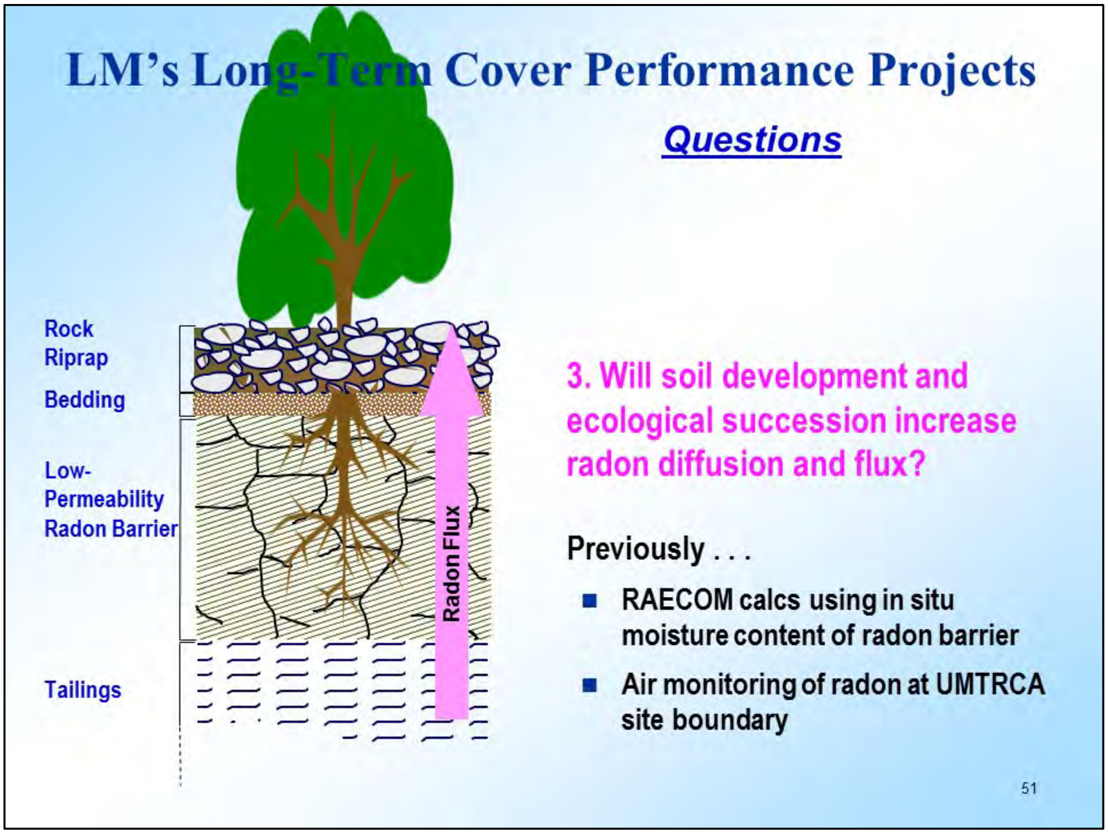
National Research Council (2005)
Maximum Tolerance Level
in Animal Diets: **5 ug g^{-1}**



Radium-226

Mean bars labeled with different letters are significantly different (P<0.05)

UMTRCA Soil Standard: 5 to 15 pCi g^{-1}



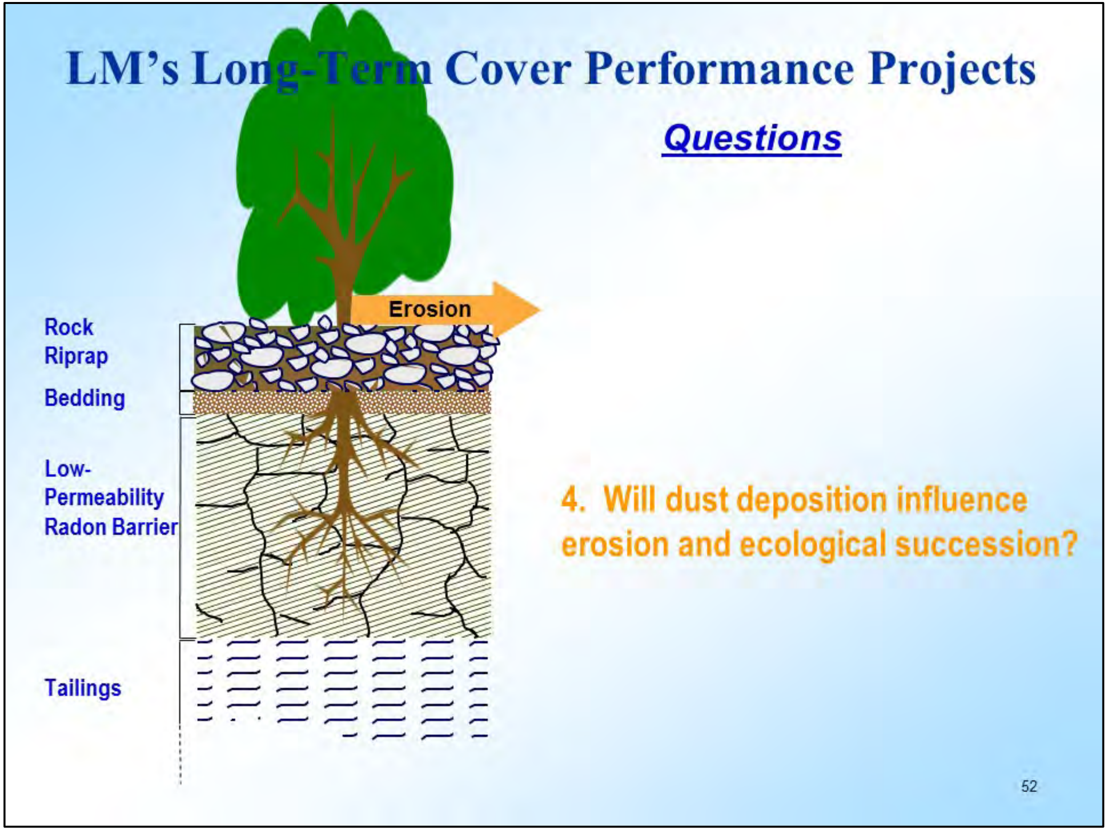
LM's Long-Term Cover Performance Projects

Questions

3. Will soil development and ecological succession increase radon diffusion and flux?

Previously . . .

- **RAECOM calcs using in situ moisture content of radon barrier**
- **Air monitoring of radon at UMTRCA site boundary**



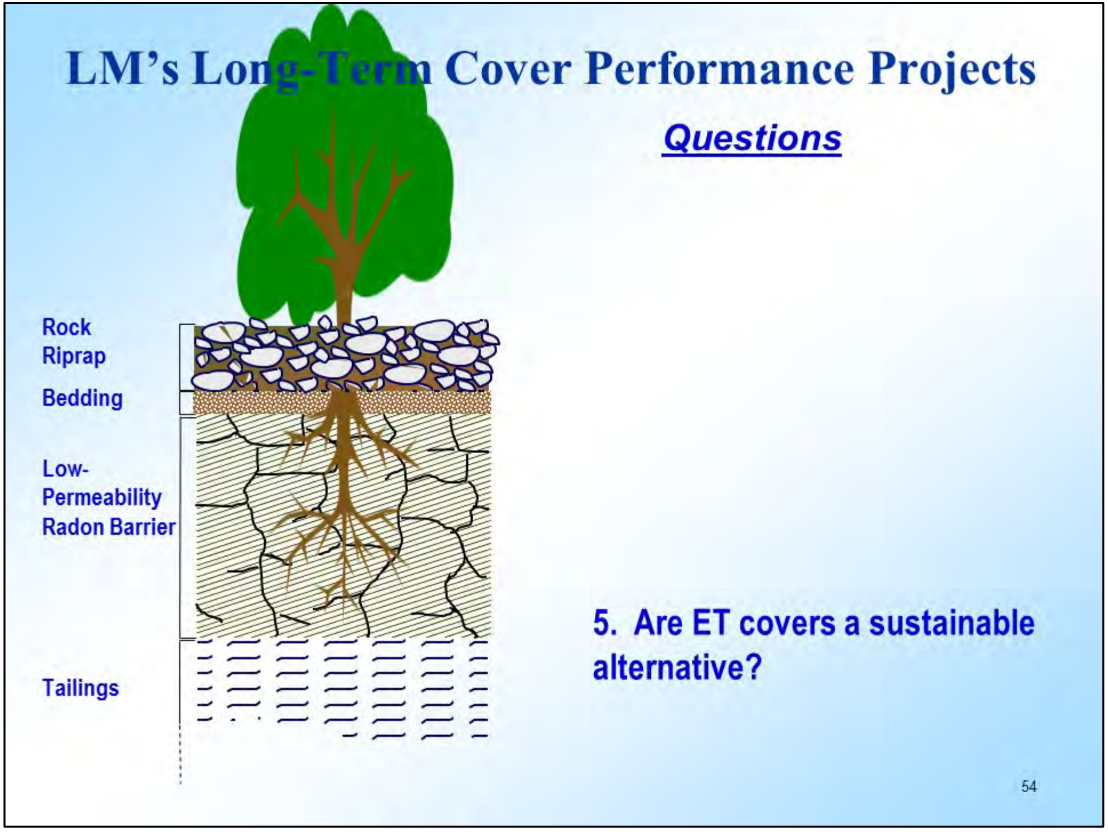
LM's Long-Term Cover Performance Projects

Questions

4. Will dust deposition influence erosion and ecological succession?

New Project: Aeolian Deposition on UMTRCA Covers

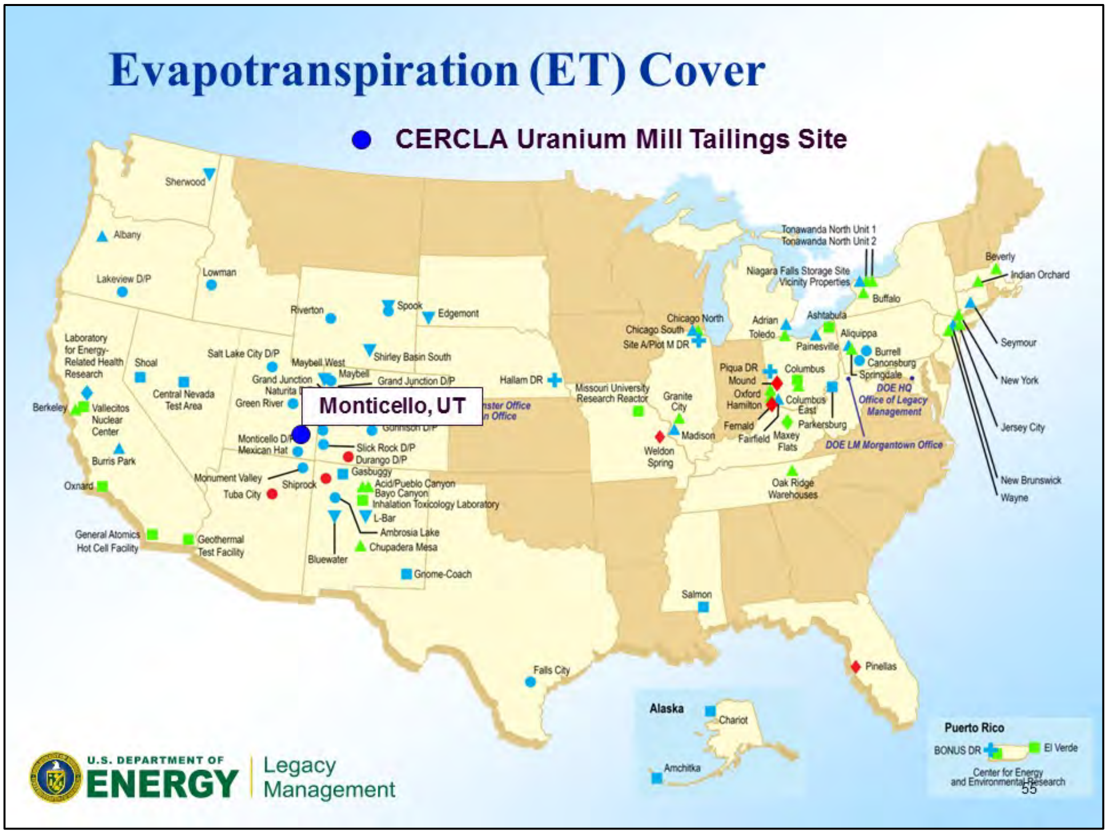
Grand Junction Disposal Cell



LM's Long-Term Cover Performance Projects

Questions

5. Are ET covers a sustainable alternative?



Evapotranspiration (ET) Cover

● CERCLA Uranium Mill Tailings Site

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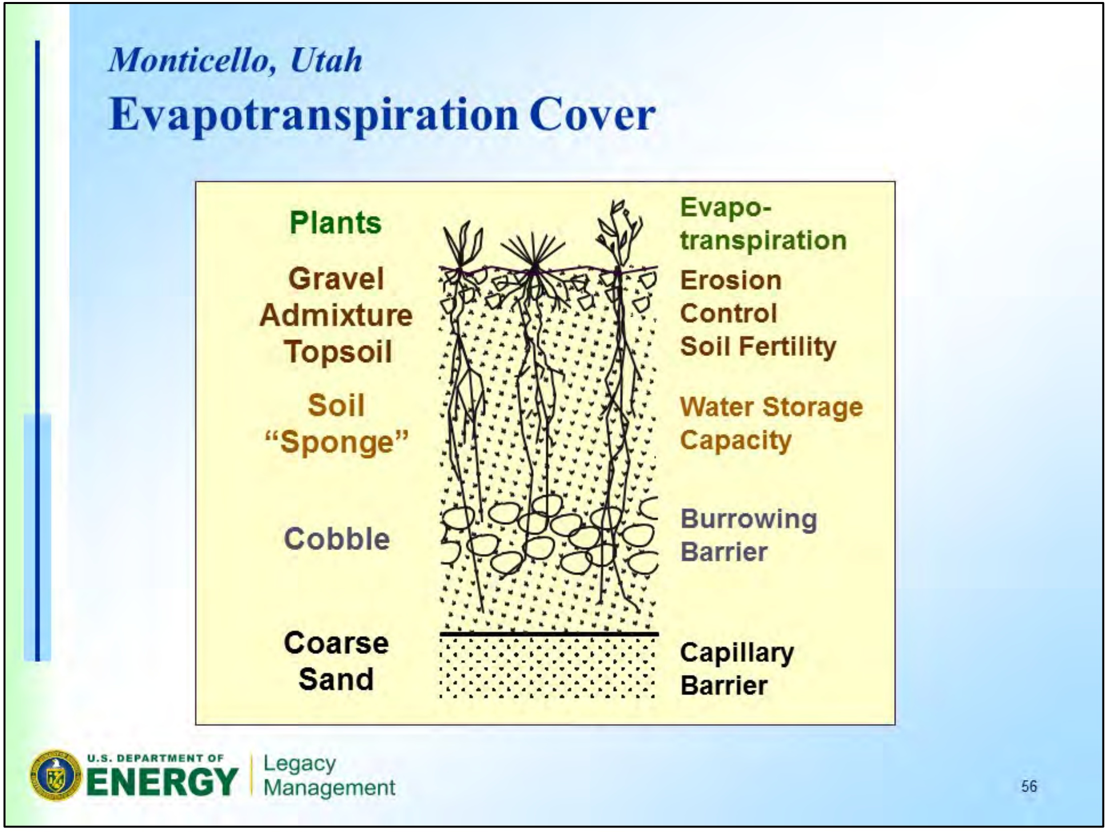

Monticello, Utah

Evapotranspiration Cover

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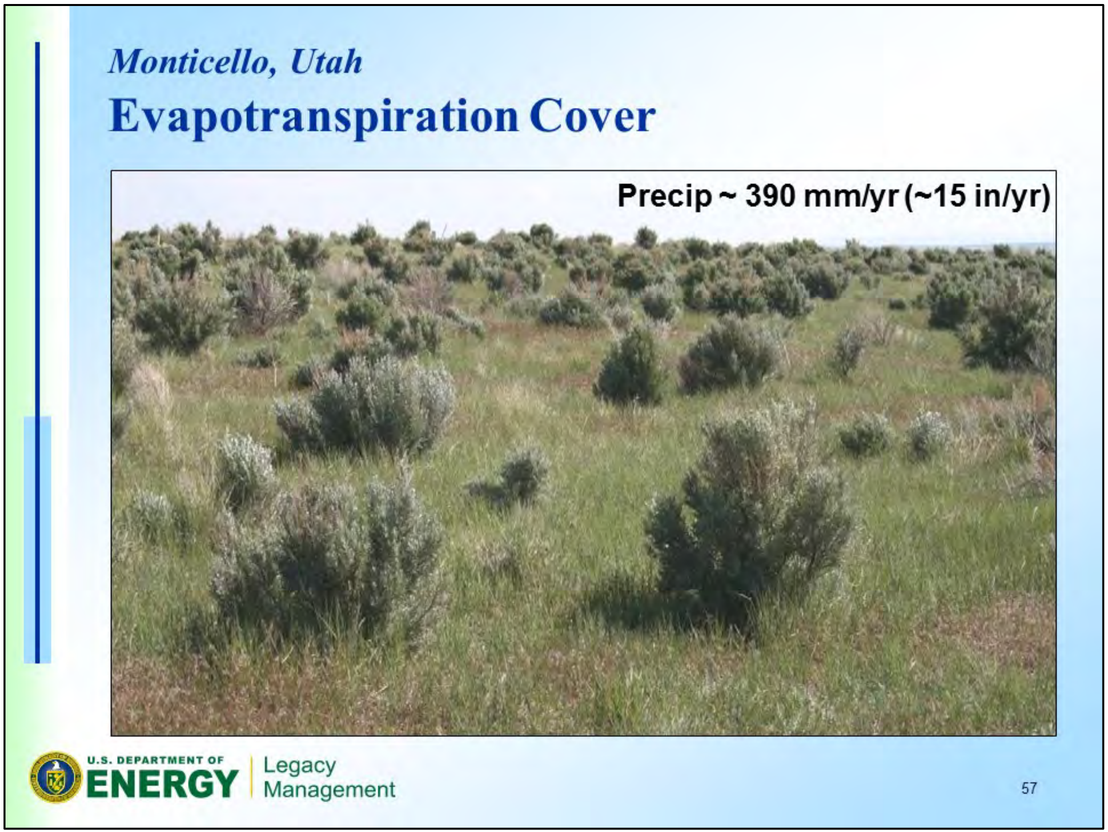

Monticello, Utah

Evapotranspiration Cover

Precip ~ 390 mm/yr (~15 in/yr)

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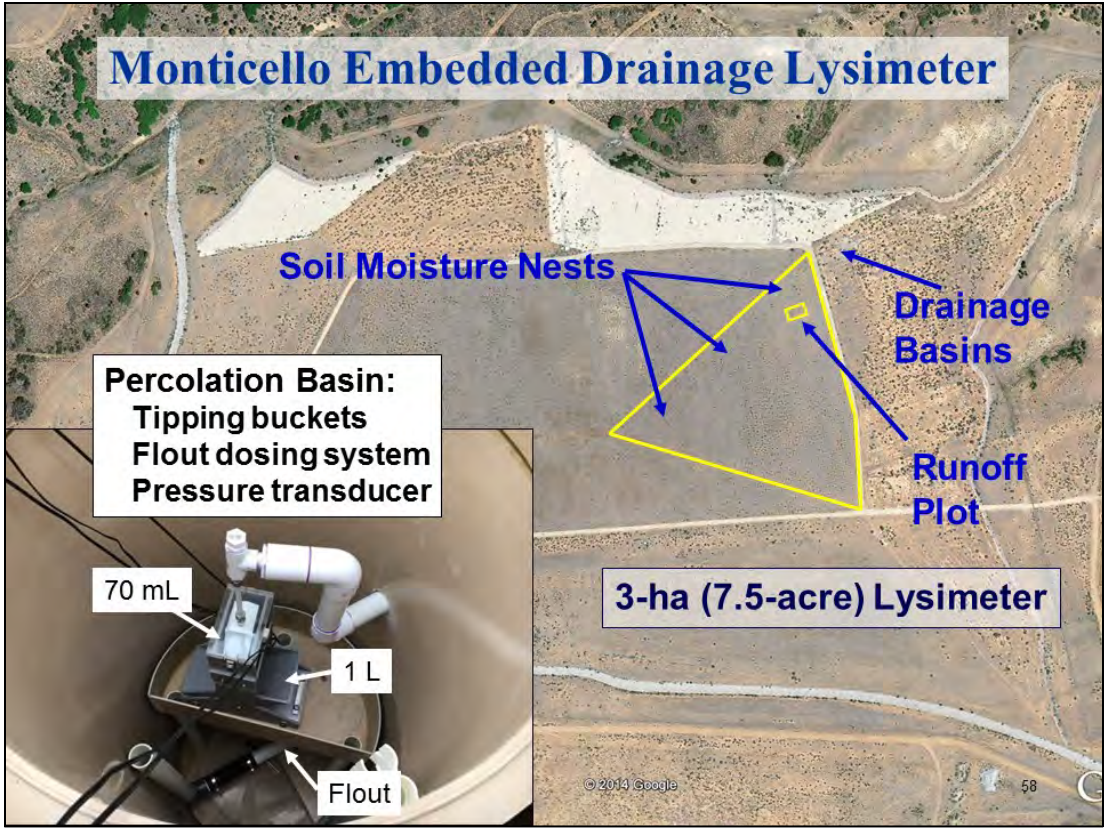


Monticello Embedded Drainage Lysimeter

Soil Moisture Nests

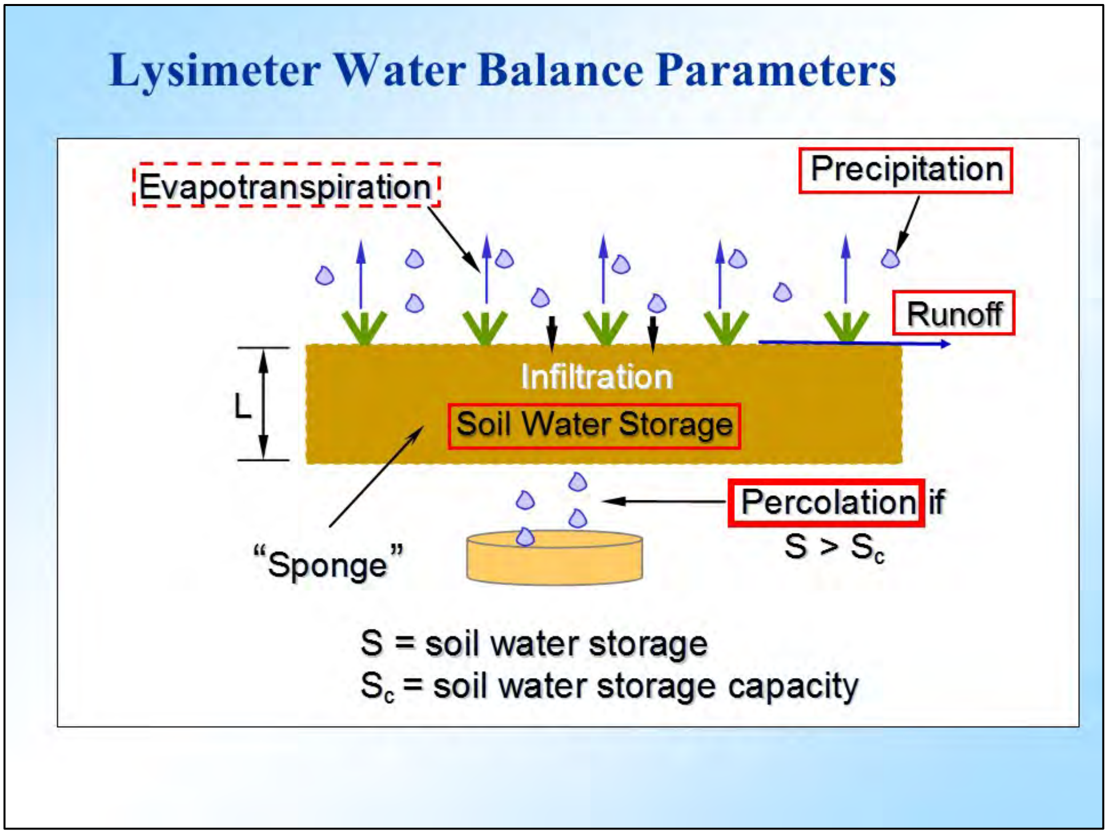
Drainage Basins

Runoff Plot

3-ha (7.5-acre) Lysimeter

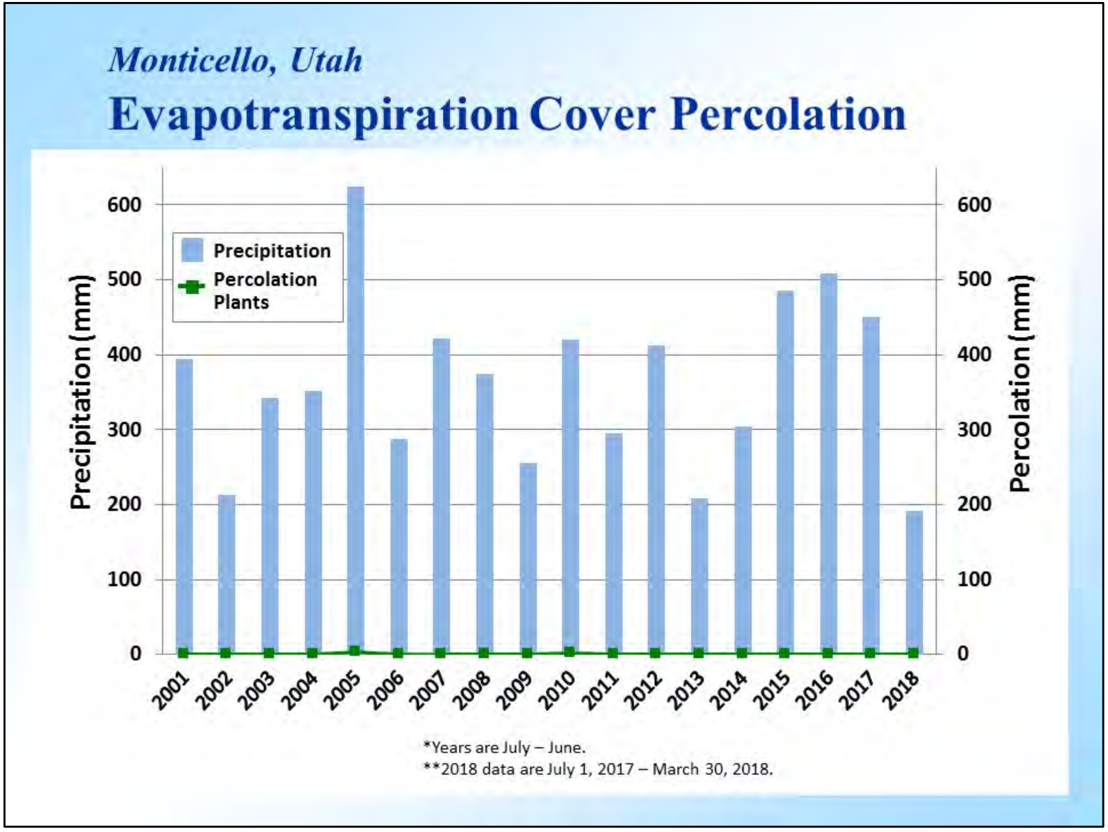
Percolation Basin:

- **Tipping buckets**
- **Flout dosing system**
- **Pressure transducer**



Lysimeter Water Balance Parameters

S = soil water storage
S_c = soil water storage capacity



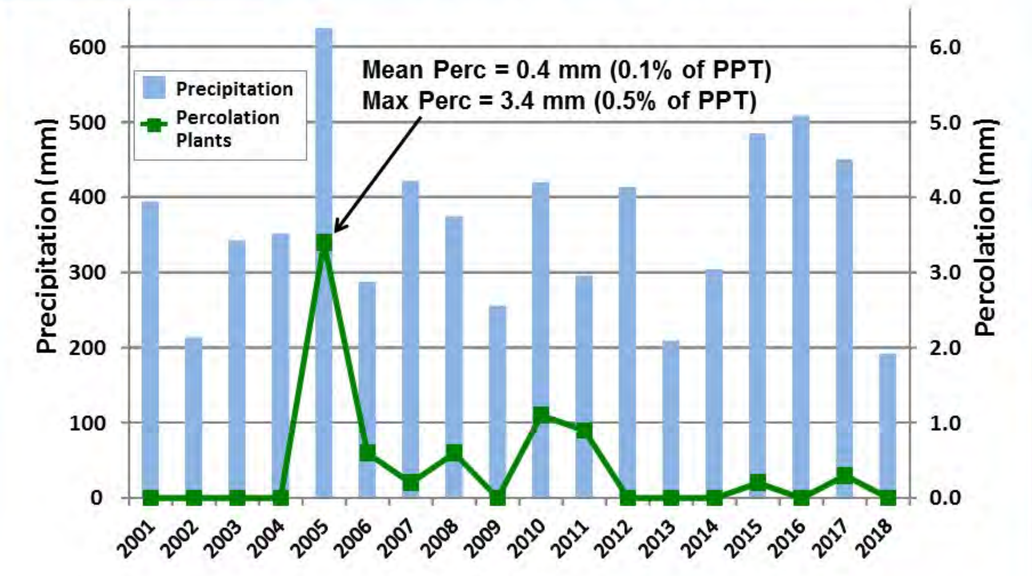
Monticello, Utah

Evapotranspiration Cover Percolation

*Years are July – June.
**2018 data are July 1, 2017 – March 30, 2018.

Monticello, Utah

Evapotranspiration Cover Percolation



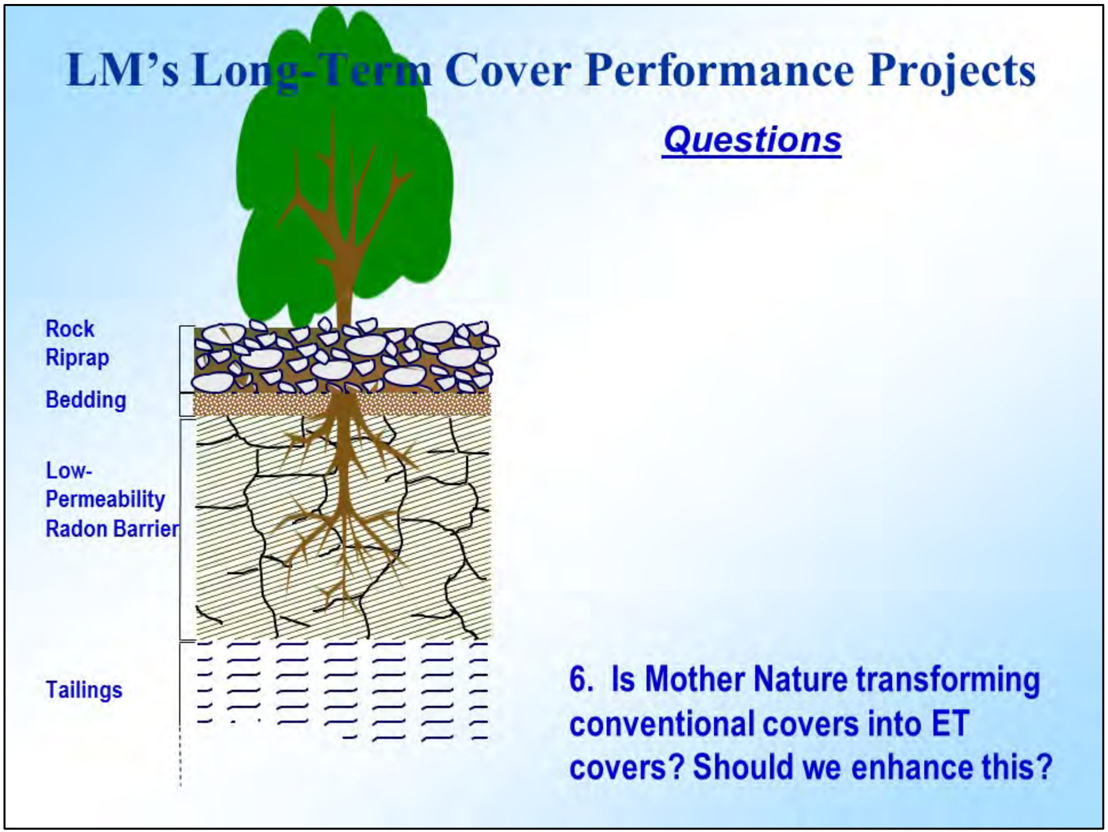
Mean Perc = 0.4 mm (0.1% of PPT)
Max Perc = 3.4 mm (0.5% of PPT)

*Years are July – June.
**2018 data are July 1, 2017 – March 30, 2018.

Cover Percolation Comparison

Cover Type	Site EPA ACAP DOE LM	Average Precipitation (mm/yr)	Average Percolation (mm/yr)	Percolation as % of Precipitation
Low-Permeability Cover Design	Albany, GA[2]	849	265.0	26.0
	Apple Valley, CA[2]	61	2.5	4.1
	Cedar Rapids, IA[2]	449	39.5	8.8
	Lakeview, OR[1]	319	30.1	9.4
Water Balance (ET) Cover Design	Apple Valley, CA[2]	167	0.5	0.3
	Boardman, OR[2]	181	0	0.0
	Polson, MT[2]	349	0.2	0.1
	Monticello, UT[2]	387	0.4	0.1

[1] Water Fluxmeter
[2] Drainage Lysimeter



LM's Long-Term Cover Performance Projects

Questions

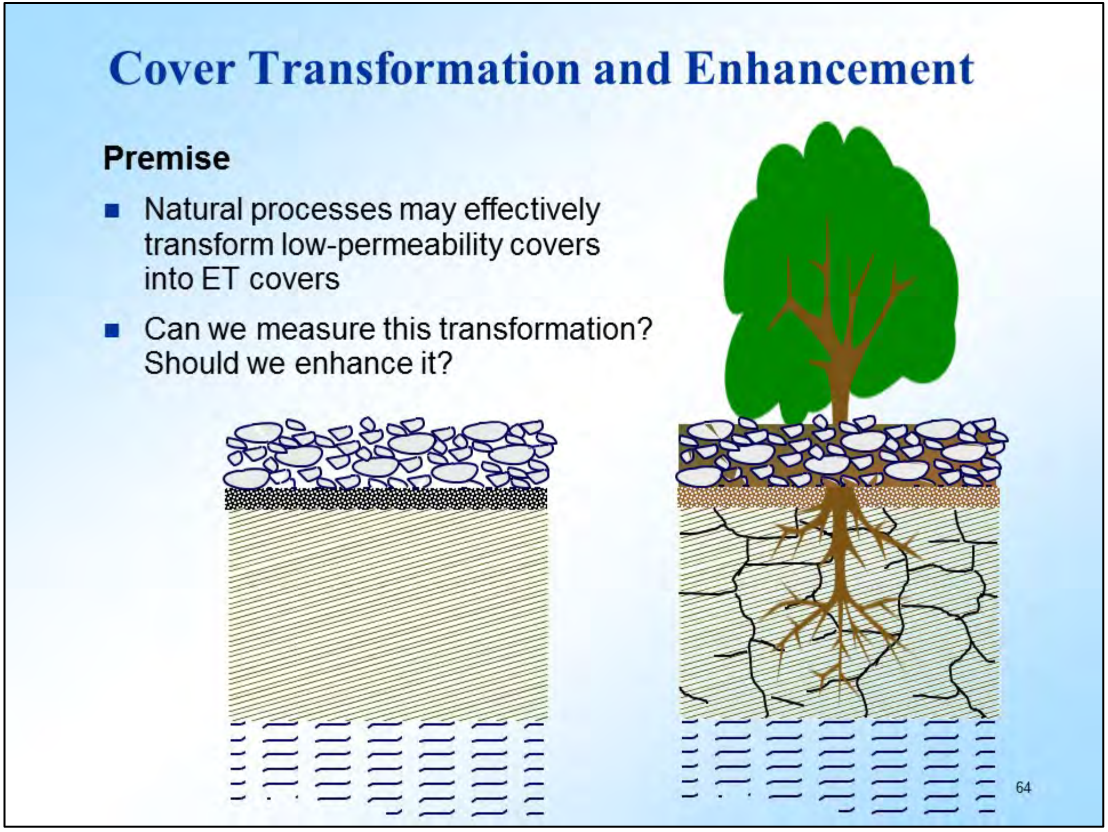
Rock
Riprap

Bedding

Low-
Permeability
Radon Barrier

Tailings

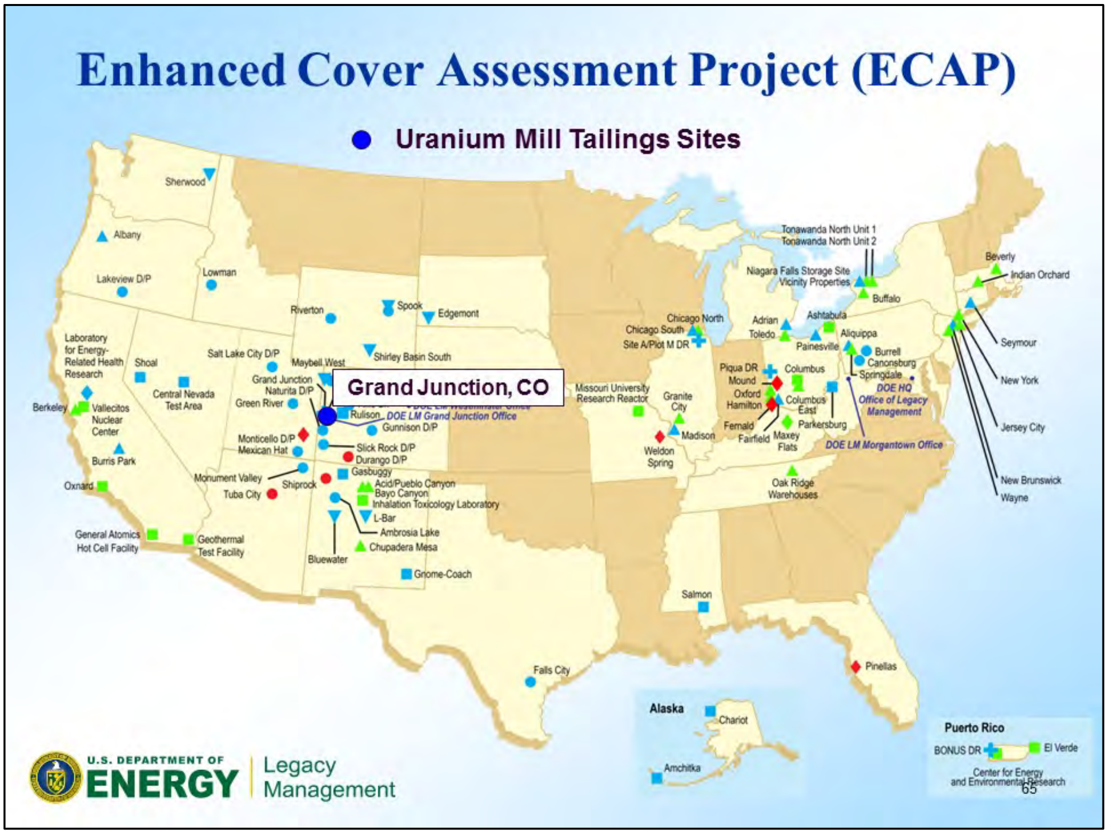
6. Is Mother Nature transforming conventional covers into ET covers? Should we enhance this?



Cover Transformation and Enhancement

Premise

- Natural processes may effectively transform low-permeability covers into ET covers
- Can we measure this transformation? Should we enhance it?



Enhanced Cover Assessment Project (ECAP)

● Uranium Mill Tailings Sites

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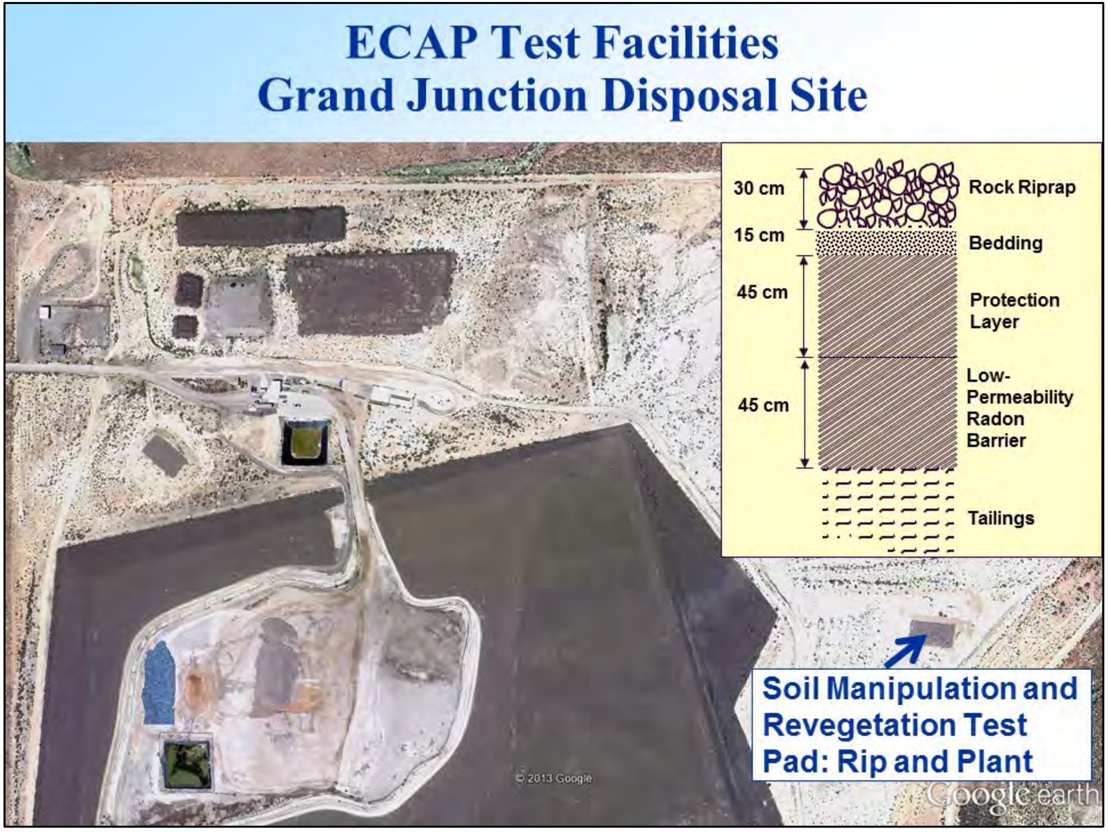
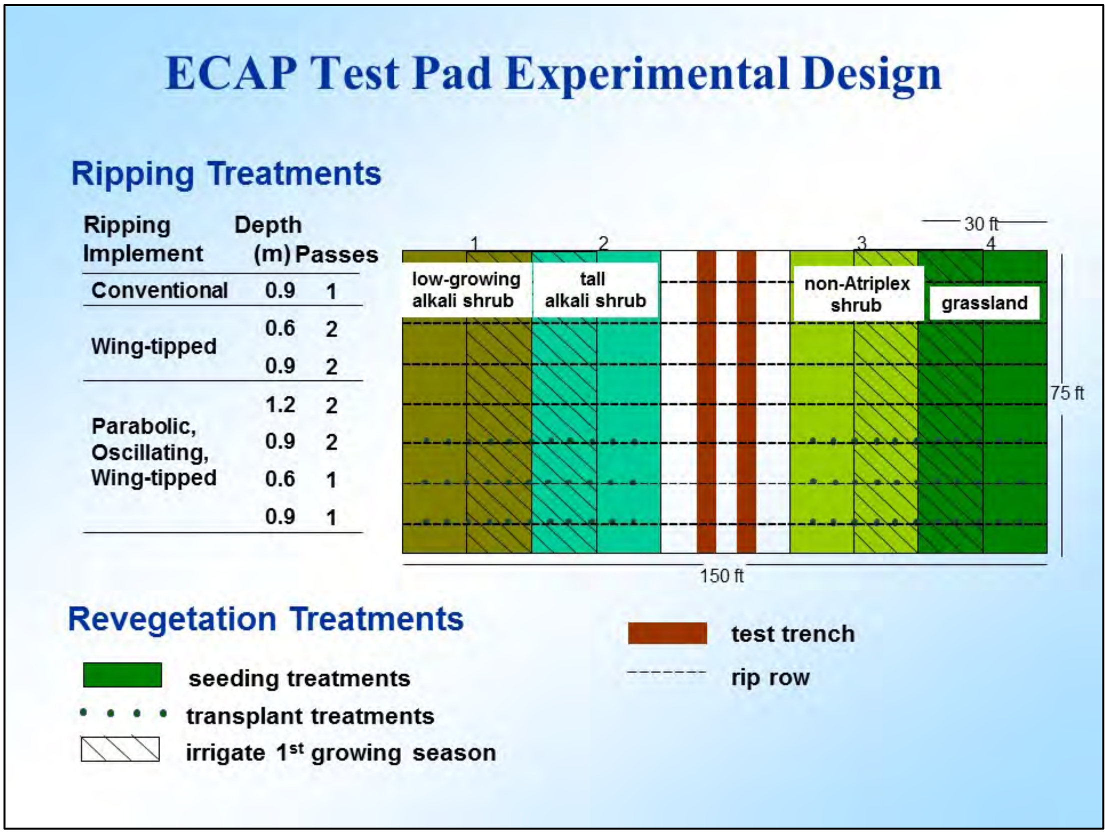


ECAP Test Facilities
Grand Junction Disposal Site

Soil Manipulation and Revegetation Test Pad: Rip and Plant



ECAP Test Pad Experimental Design

Ripping Treatments

Ripping Implement	Depth (m)	Passes
Conventional	0.9	1
Wing-tipped	0.6	2
	0.9	2
Parabolic, Oscillating, Wing-tipped	1.2	2
	0.9	2
	0.6	1
	0.9	1

Revegetation Treatments

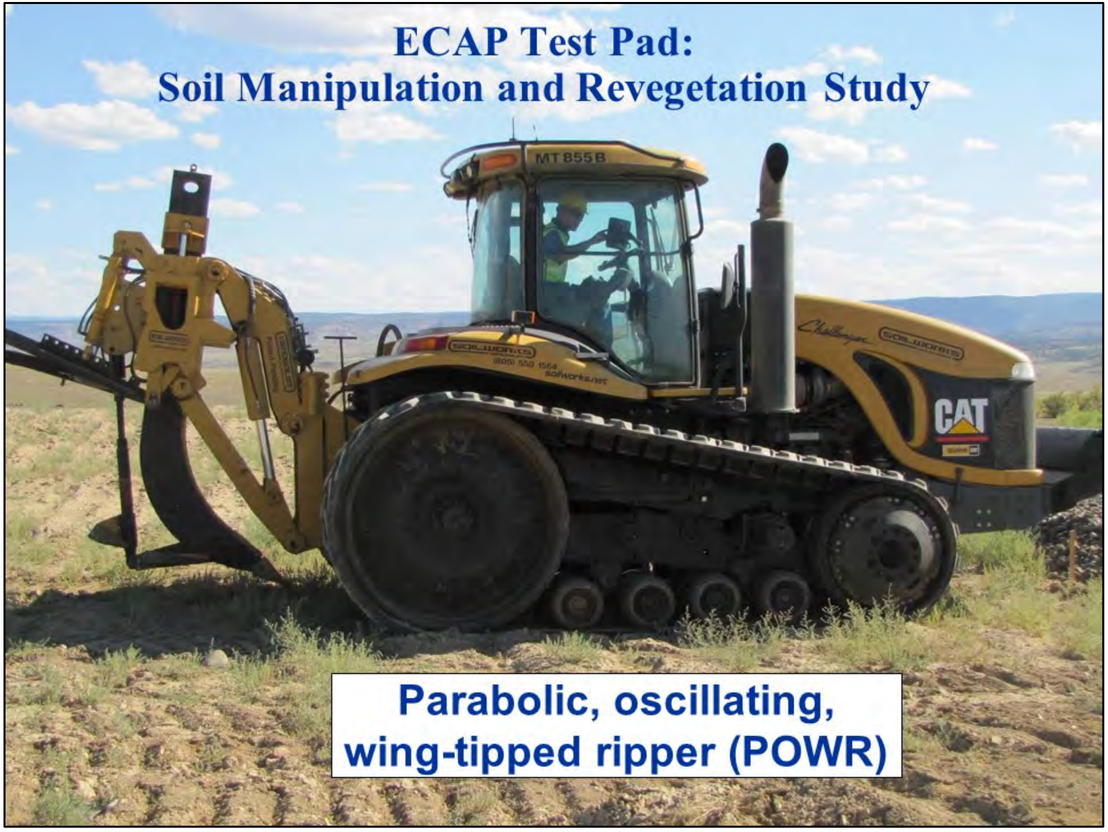
🟩 seeding treatments

• • • • transplant treatments

▨ irrigate 1st growing season

🟥 test trench

------- rip row



ECAP Test Pad:
Soil Manipulation and Revegetation Study

Parabolic, oscillating, wing-tipped ripper (POWR)

ECAP Test Pad: Soil Manipulation and Revegetation Study

ECAP Test Pad: Soil Manipulation and Revegetation Study

ECAP Test Pad Results Summary

Ripping

- All 7 treatments lifted fines into the bedding layer and moved gravel and cobble down into protection layer
- Ripping created large soil aggregates and voids
- Water content increased in the bedding layer and decreased in the protection layer after ripping
- The POWR at 1.2-m depth and two passes created the largest disturbance zone with a low dry density and a more favorable seedbed soil texture

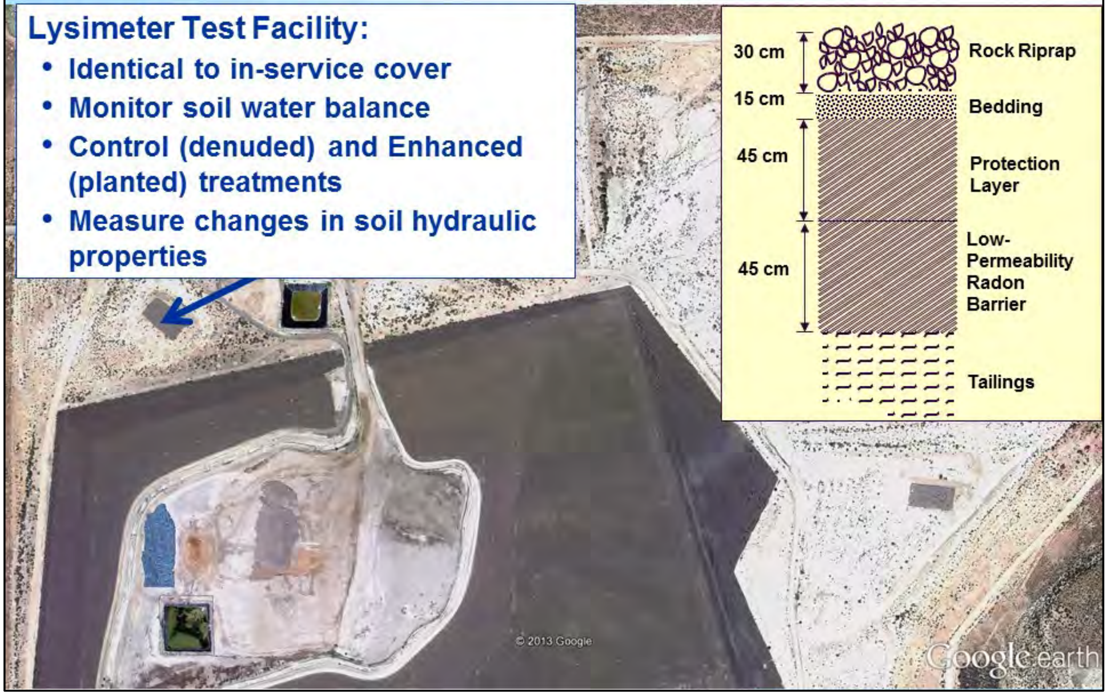
Revegetation

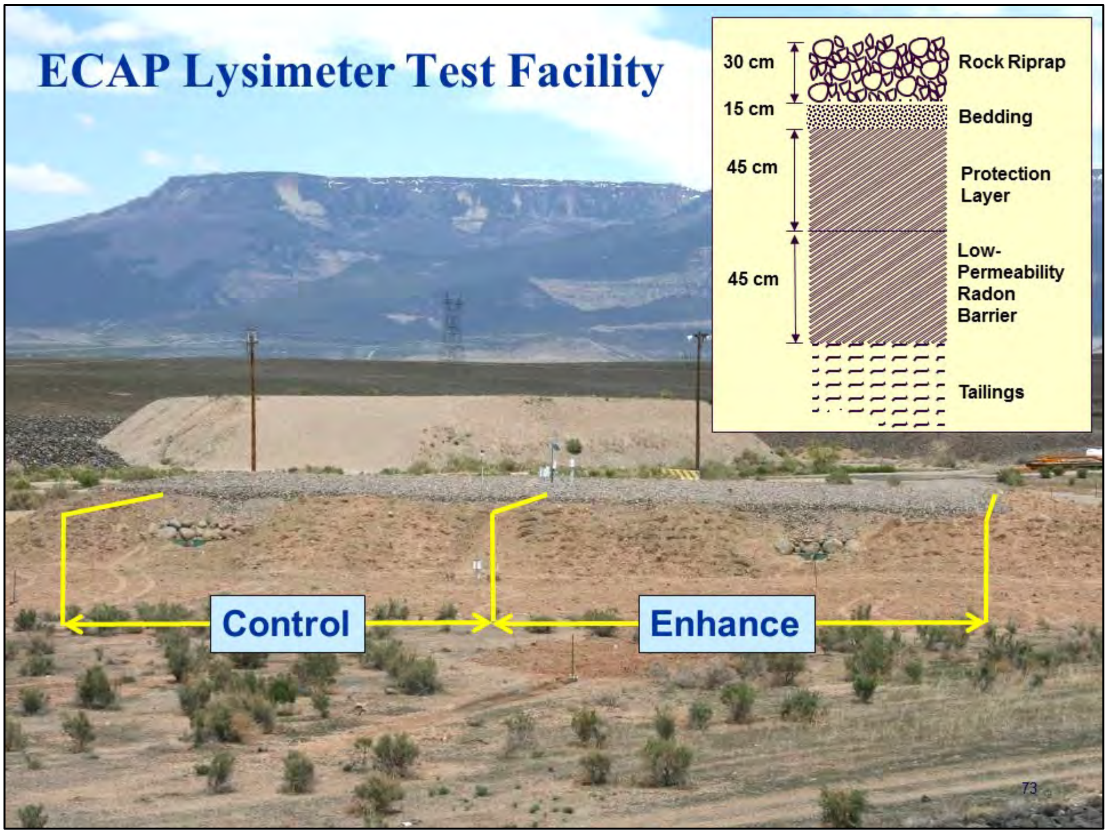
- Transplanting in POWR rows was superior to seeding
- Highest survival and growth: Fourwing saltbush (*Atriplex canescens*) and rabbitbrush (*Ericameria nauseosa*), with and without irrigation

ECAP Test Facilities
Grand Junction Disposal Site

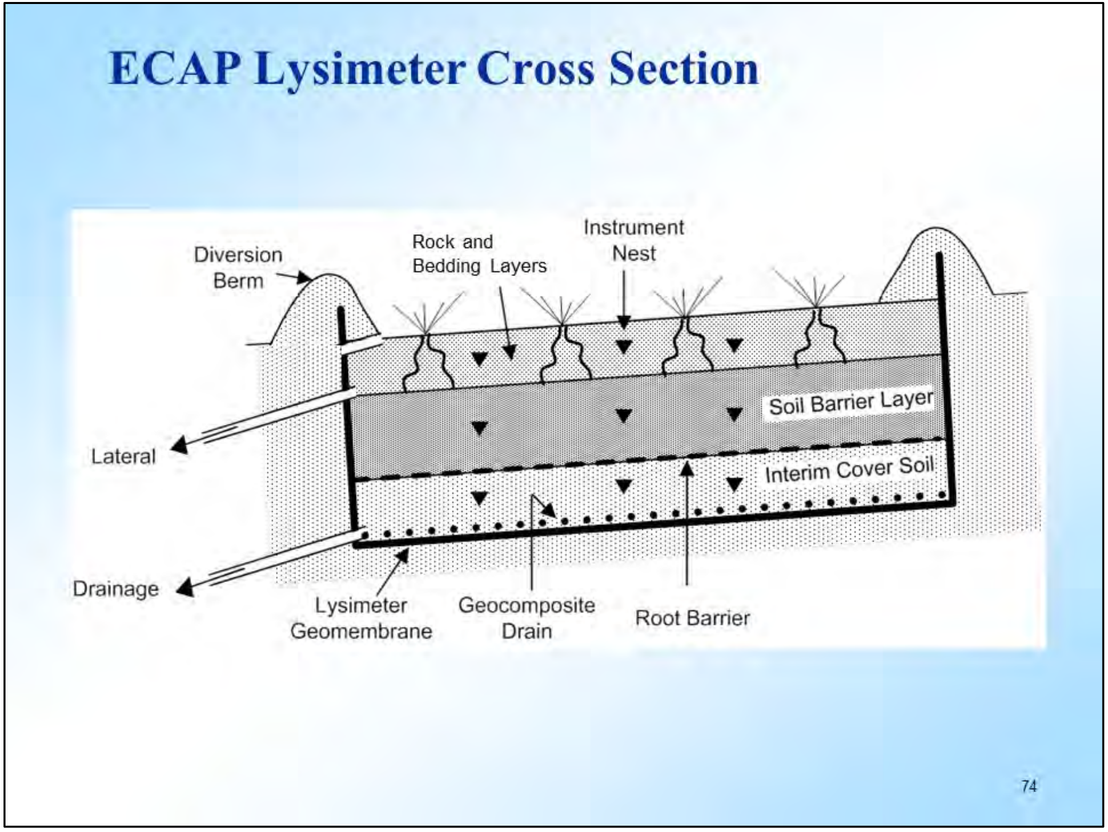
Lysimeter Test Facility:

- **Identical to in-service cover**
- **Monitor soil water balance**
- **Control (denuded) and Enhanced (planted) treatments**
- **Measure changes in soil hydraulic properties**

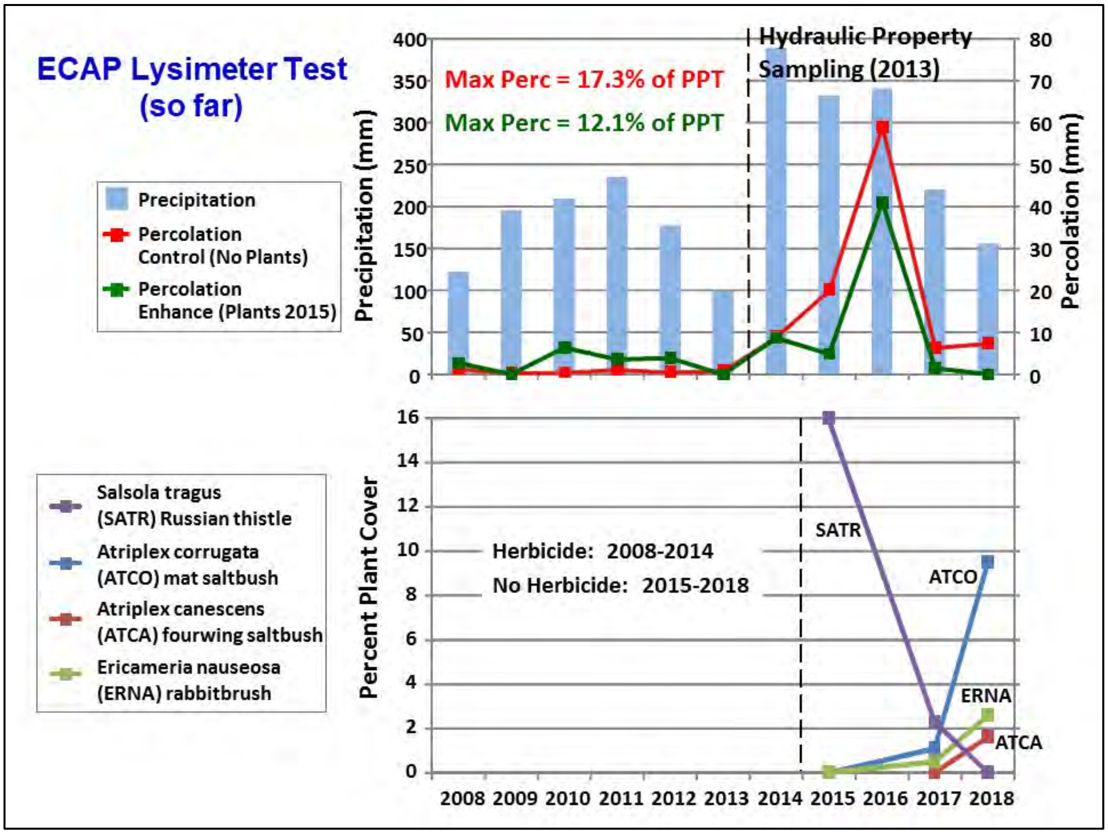


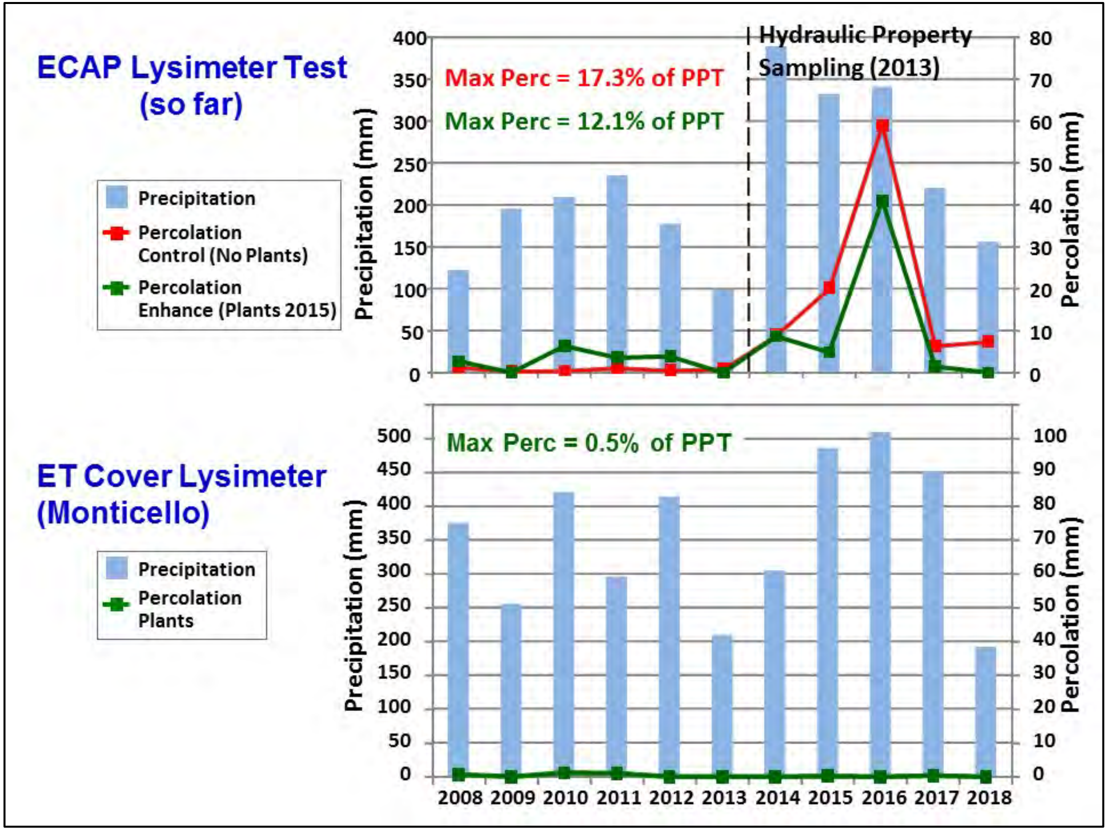


ECAP Lysimeter Test Facility



ECAP Lysimeter Cross Section


ECAP Lysimeter Test (so far)
Precipitation
Percolation Control (No Plants)
Percolation Enhance (Plants 2015)
Max Perc = 17.3% of PPT
Max Perc = 12.1% of PPT
Hydraulic Property Sampling (2013)
Precipitation (mm)
Percolation (mm)
400
350
300
250
200
150
100
50
0
80
70
60
50
40
30
20
10
0
Salsola tragus (SATR) Russian thistle
Atriplex corrugata (ATCO) mat saltbush
Atriplex canescens (ATCA) fourwing saltbush
Ericameria nauseosa (ERNA) rabbitbrush
Percent Plant Cover
16
14
12
10
8
6
4
2
0
Herbicide: 2008-2014
No Herbicide: 2015-2018
SATR
ATCO
ERNA
ATCA
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018


ECAP Lysimeter Test (so far)
Precipitation
Percolation Control (No Plants)
Percolation Enhance (Plants 2015)
Max Perc = 17.3% of PPT
Max Perc = 12.1% of PPT
Hydraulic Property Sampling (2013)
Precipitation (mm)
Percolation (mm)
400
350
300
250
200
150
100
50
0
80
70
60
50
40
30
20
10
0
ET Cover Lysimeter (Monticello)
Precipitation
Percolation Plants
Max Perc = 0.5% of PPT
Precipitation (mm)
Percolation (mm)
500
450
400
350
300
250
200
150
100
50
0
100
90
80
70
60
50
40
30
20
10
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2008
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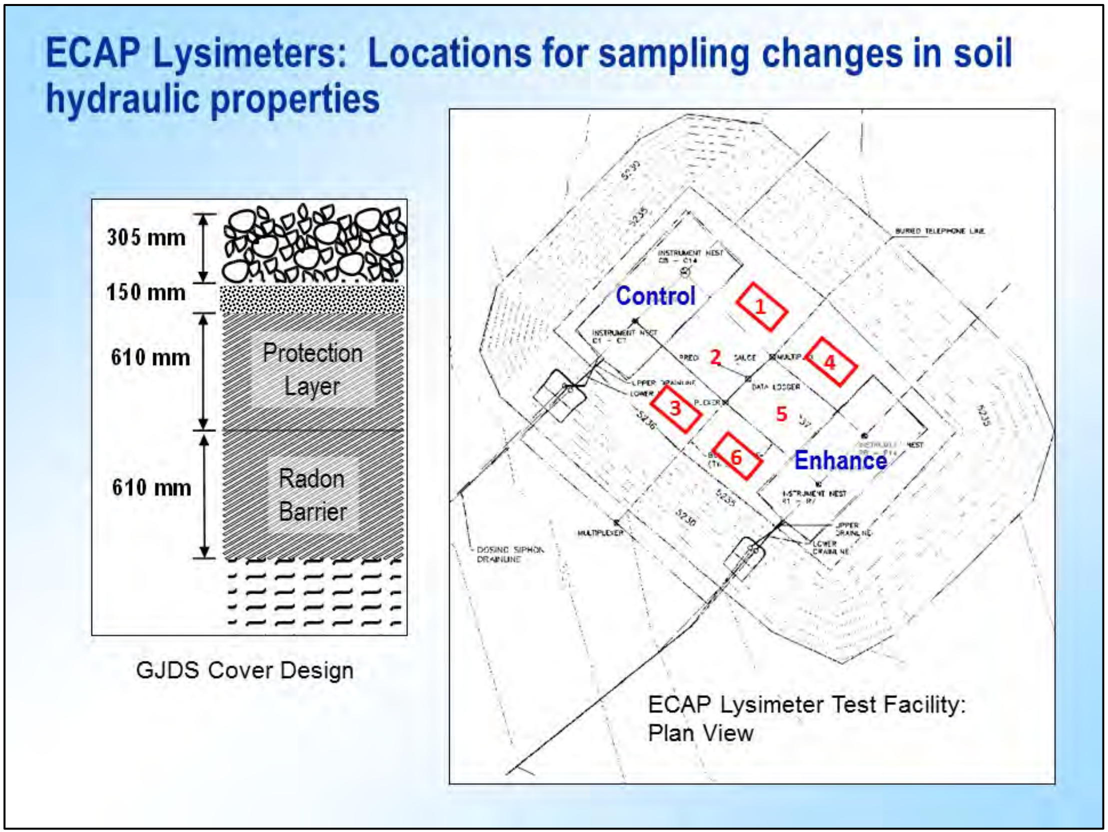
2013
2014
2015
2016
2017
2018



ECAP Lysimeters: Locations for sampling changes in soil hydraulic properties

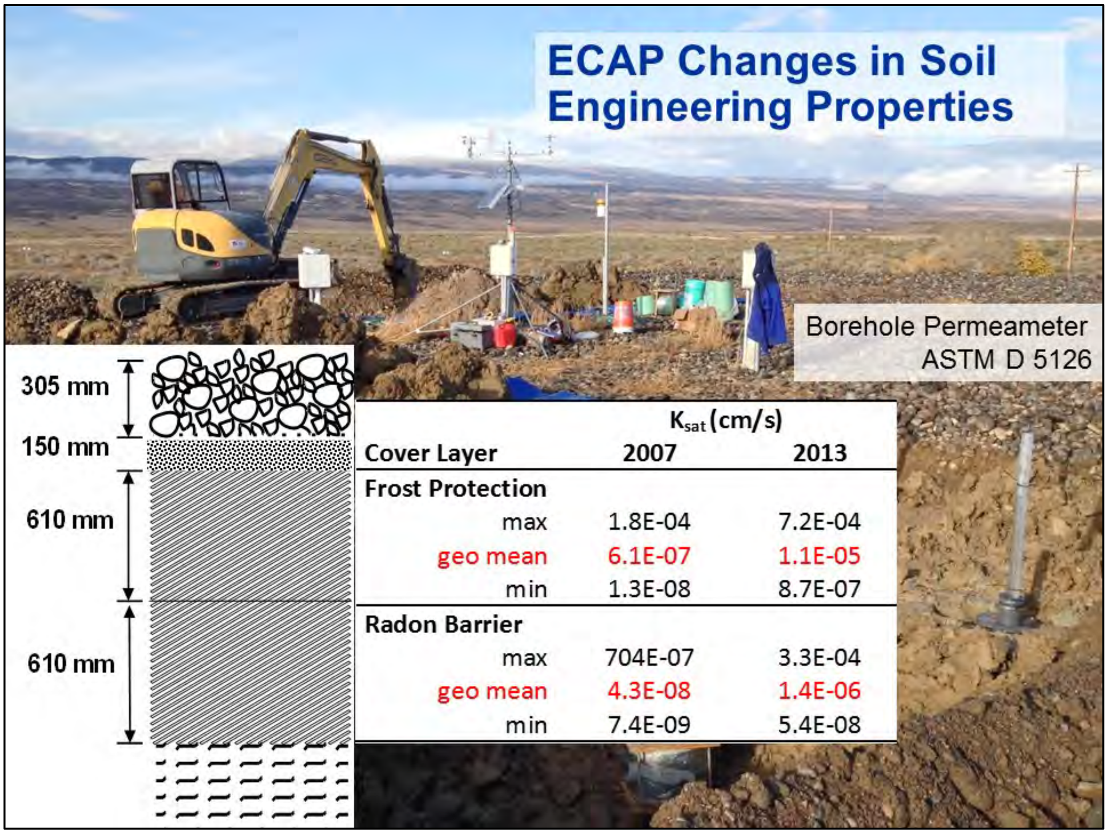
GJDS Cover Design

ECAP Lysimeter Test Facility: Plan View

ECAP Changes in Soil Engineering Properties

Borehole Permeameter
ASTM D 5126

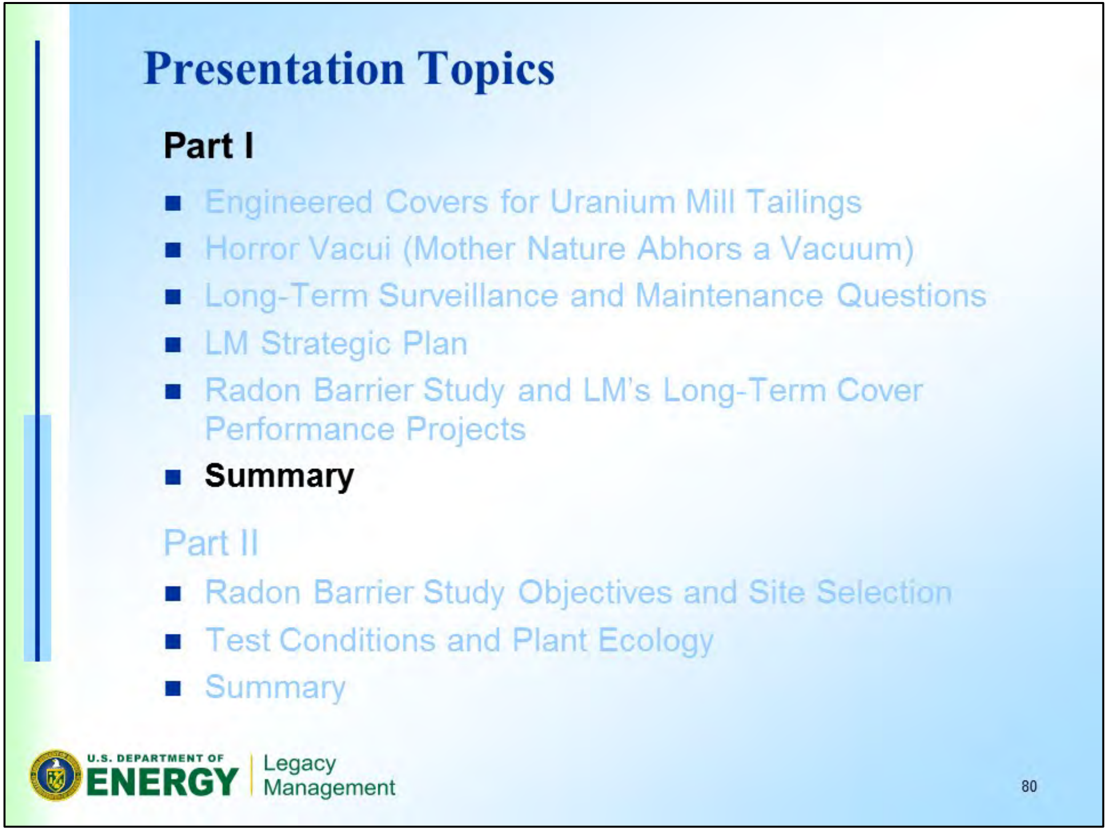
Block Monolith and
Flexible-Wall Permeameter
ASTM D 5084



ECAP Changes in Soil Engineering Properties

Borehole Permeameter
ASTM D 5126

Cover Layer	K_{sat} (cm/s) 2007	2013
Frost Protection		
max	1.8E-04	7.2E-04
geo mean	6.1E-07	1.1E-05
min	1.3E-08	8.7E-07
Radon Barrier		
max	704E-07	3.3E-04
geo mean	4.3E-08	1.4E-06
min	7.4E-09	5.4E-08



Presentation Topics

Part I

- Engineered Covers for Uranium Mill Tailings
- Horror Vacui (Mother Nature Abhors a Vacuum)
- Long-Term Surveillance and Maintenance Questions
- LM Strategic Plan
- Radon Barrier Study and LM's Long-Term Cover Performance Projects
- **Summary**

Part II

- Radon Barrier Study Objectives and Site Selection
- Test Conditions and Plant Ecology
- Summary

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Summary

- Engineered covers were designed to satisfy UMTRCA requirements for radon attenuation, groundwater protection, erosion control, and longevity (200-1000 years)
- LM's Strategic Plan advocates continuous remedy evaluations and LTS&M improvements
- LM has been evaluating effects of natural processes on cover performance and sustainability since the 1990s
- The Radon Barrier Study is one of several projects under the LM's Long-Term Cover Performance (LTCP) program
- Collectively, LTCP studies are (1) weighing the pros and cons of natural processes acting on covers, and (2) evaluating methods to enhance beneficial processes
- Results will inform LTS&M options and plans

What's Next?

- Continue monitoring the large embedded lysimeter at Monticello to capture water balance responses to ecological and climatic variability
- Continue monitoring soil water balance in Control and Enhance test lysimeters at Grand Junction
- Evaluate aeolian deposition and effects on cover ecology, erosion, and performance (radon flux and water balance)
- Evaluate and refine remote sensing ET algorithms to be able to monitor effects of plant succession on cover water balance
- Evaluate site-specific risks of changes in covers as components of greater disposal cell/groundwater systems

2.3.3 Question and Answer Session for: Engineered Covers for UMTRCA Sites and DOE/LM's Projects.

Question. Considering conversion of rock armored resistive covers to ET covers, you spoke about aeolian transport of fines and you talked about plowing the rock cover.... "ripping" it.....did you consider just adding soil to the cover?
Reply. Yes we have also considered adding soil as an option. At some sites, Mother Nature is already doing that for us with aeolian deposition of fine textured soil in the rock riprap. Morgan Williams will be working with us on an aeolian deposition study next year. Regarding adding soil, the cost of ripping is actually cheaper but it may be more disruptive. The ripping process did not mix the rock and soil very well. It left large clods and voids that created channels for preferential flow. However, for mine land reclamation, ripping is often done on the contour to provide furrows to capture runoff water. This can reduce erosion and promote plant growth and higher ET.

Question. What about contaminant uptake in the plants?
Reply. Plants are grown on covers not for uptake of contaminants or phytoremediation, but for controlling the soil water balance. However at some sites we have studied the use of desert plants for phytoremediation: uptake of uranium, ammonium, and nitrate. For example, we published on phytoremediation of ammonium and nitrate in groundwater at Monument Valley. We have graduate students continuing to work on uptake of contaminants by deep-rooted plants growing on disposal cell covers. [editor's note: a more detailed talk about plant uptake of metals at some UMTRCA sites was given by the presenter at the DOE Long-Term Stewardship Conference, Grand Junction CO, August 20-23, 2018].

Question. You mentioned plant uptake studies on mill tailing sites. What would be most useful would be analyzing for Pb-210. It ought to show up in plants as an indicator of radon. Concentrations would be low but might be measurable. There would be two pathways; one from radon decay in the plant and the other from Pb-210 uptake from the soil, if the plant takes up Pb. If the student has samples left it might be something to look at.
Reply. Years ago we adapted a leaf porometer to measure radon transport in plants through the transpiration stream. It was very low, but that was a single point in time. Lead-210 would be more time averaged.

2.4 The Radon Barriers Project Objectives, Test Conditions, and Plant Ecology

Presented by Jody Waugh
W.J. Waugh[1], W.H. Albright[2], C.H. Benson[3], M. Fuhrmann[4], W.J. Likos[5], and M.M. Williams[6]
[1]Navarro Research and Engineering, Inc., [2]Desert Research Institute, [3]University of Virginia,
[4]U.S. Nuclear Regulatory Commission, [5]University of Wisconsin—Madison,
[6]University of California–Berkeley

2.4.1 Abstract

DOE/LM, the NRC, and university partners are collaborating on a study of the effects of ecological and soil-forming processes on the engineering properties and long-term performance of radon barriers. Here we present the overall objectives of the study, the process for selecting study sites and test conditions on disposal cell covers, the purpose and selection of analog sites, and results of an early characterization of plant succession on engineered covers and at analog sites.

Radon Barrier Study Objectives. The objectives of the study can be summarized as a set of general questions:

- Soil morphology: Can we identify and quantify soil-forming processes that are changing as-built engineering properties of UMTRCA covers? How does soil formation vary for ranges of cover thicknesses, soil types, ecological conditions, and climates? Is soil formation in covers systematic, predictable, and depth dependent?

- Soil engineering: Can we measure depth-dependent effects of soil formation on radon diffusion, radon flux, and hydraulic properties of radon barriers? Can we improve field monitoring and modeling of radon flux and water percolation in covers that have been altered by soil-forming processes?

- Long-term performance: Can we project the *long-term* effects of ecological and soil-forming processes on radon flux and water percolation in radon barriers?

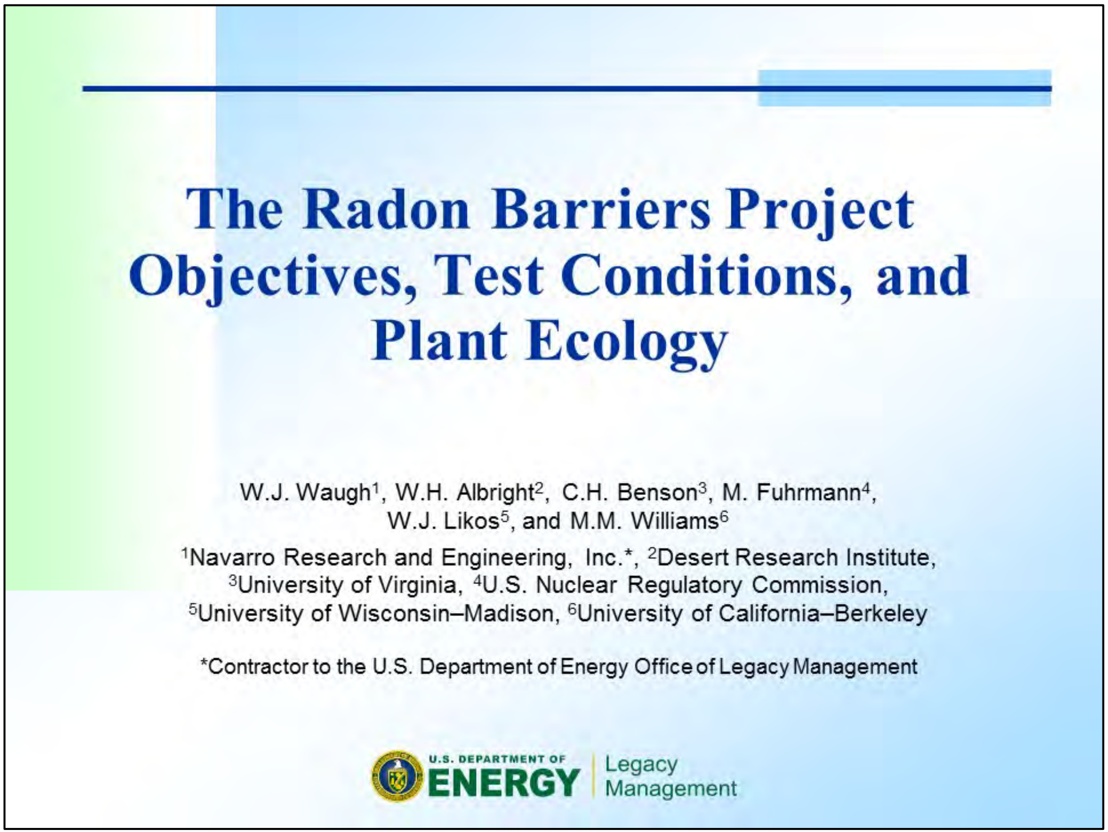
Study Site Selection, Test Conditions, and Analog Sites. The selection of study sites was intentionally biased. Our site selection process identified disposal sites and test locations on covers where we anticipated the greatest increases in radon flux and hydraulic conductivity—the worst case conditions, not the average condition. Selection of sites involved a ranking of Title I and II sites based on attributes such as design vulnerability, climatic influence, vegetation, source activity, and regulatory priority. The four sites selected for study encompassed a range of cover designs, climates, and ecological conditions within DOE/LM's portfolio: Falls City, TX; Bluewater, NM; Shirley Basin South, WY; and Lakeview, OR. We included test locations on covers where deep-rooted plants grew and where as-built radon flux values were highest. We sampled each site at the end of a period of high ET following a season of historically low precipitation—when radon barriers would likely be seasonally driest. Soil morphology, soil engineering properties, and plant ecology were also characterized at analog sites. Analog sites had undisturbed profiles of the same soil type as that used to construct the radon barrier. Analog soil profiles represent a possible long-term condition or end state of the radon barrier.

Plant Ecology. Plant succession is a driver of pedogenic changes in radon barrier engineering properties. We compared plant community composition and abundance on the four disposal cells

with their analog sites using a Relevé method. We used plant ecology data to infer effects of land use practices, current seral stages, and trajectories of plant succession, while recognizing the inherent uncertainty in these inferences related to climate change, future invasive species, and future land use.

The top-deck vegetation at Falls City is dominated by planted hay grasses that are considered to be invasive. The vegetation at the Falls City analog site consists of mid-seral native plants but is a poor late-succession reference area because of heavy grazing. A relatively sparse mix of early seral grasses and annual weeds grows on the Bluewater cover. The two Bluewater analog sites are relatively undisturbed with late seral species and are good late-succession reference areas for the disposal cell cover. Similar to Falls City, the top-deck terraces at Shirley Basin South were planted with both introduced and native forage species that are currently managed for livestock grazing. Mostly early seral and weedy species grow on the rock slope, and wetland species at the base of the slope indicate ephemeral saturation. The mid to late seral shrub steppe at the Shirley Basin South analog site is a poor late-succession reference area because of historical grazing. The top deck at Lakeview was planted with grasses but is dominated by mid to late seral shrubs, likely because of poor water storage in the thin soil layer covering the rock riprap layer. The analog site, with diverse mid to late seral vegetation protected from grazing, is a good late-succession reference area.

2.4.2 Presentation

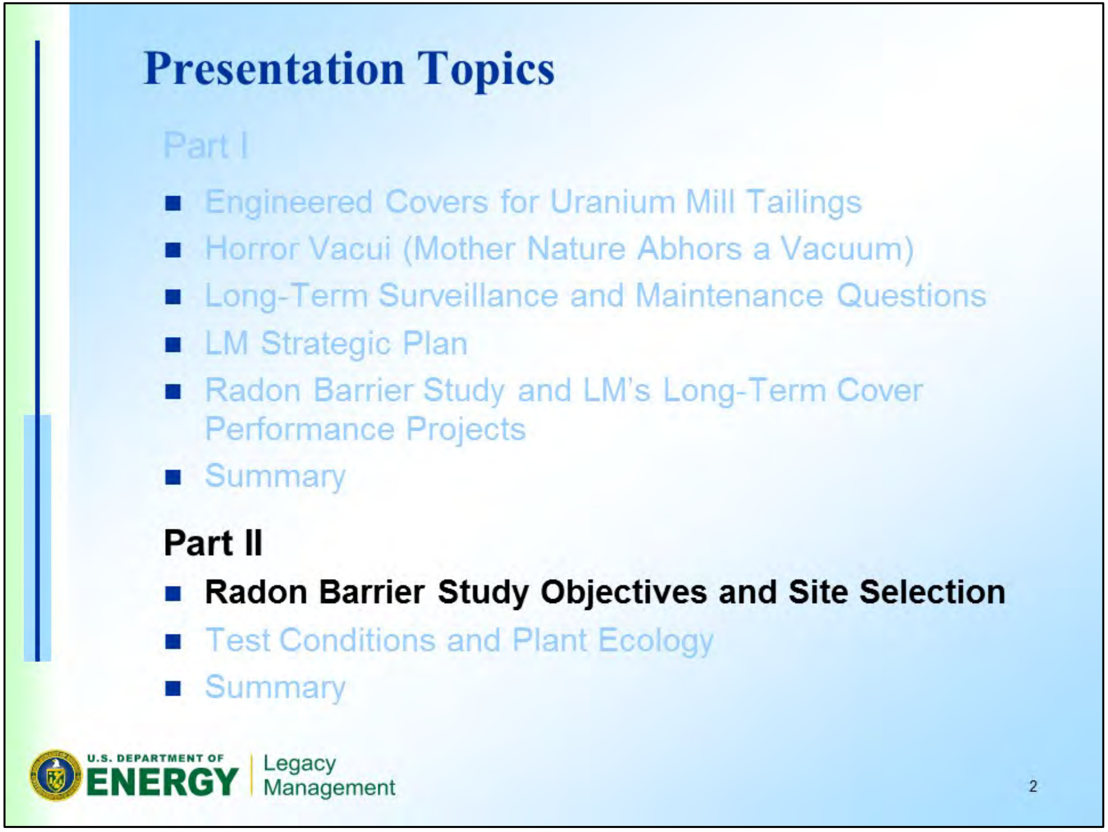


The Radon Barriers Project Objectives, Test Conditions, and Plant Ecology

W.J. Waugh[1], W.H. Albright[2], C.H. Benson[3], M. Fuhrmann[4],
W.J. Likos[5], and M.M. Williams[6]

[1]Navarro Research and Engineering, Inc.*, [2]Desert Research Institute,
[3]University of Virginia, [4]U.S. Nuclear Regulatory Commission,
[5]University of Wisconsin–Madison, [6]University of California–Berkeley

*Contractor to the U.S. Department of Energy Office of Legacy Management



Presentation Topics

Part I

- Engineered Covers for Uranium Mill Tailings
- Horror Vacui (Mother Nature Abhors a Vacuum)
- Long-Term Surveillance and Maintenance Questions
- LM Strategic Plan
- Radon Barrier Study and LM's Long-Term Cover Performance Projects
- Summary

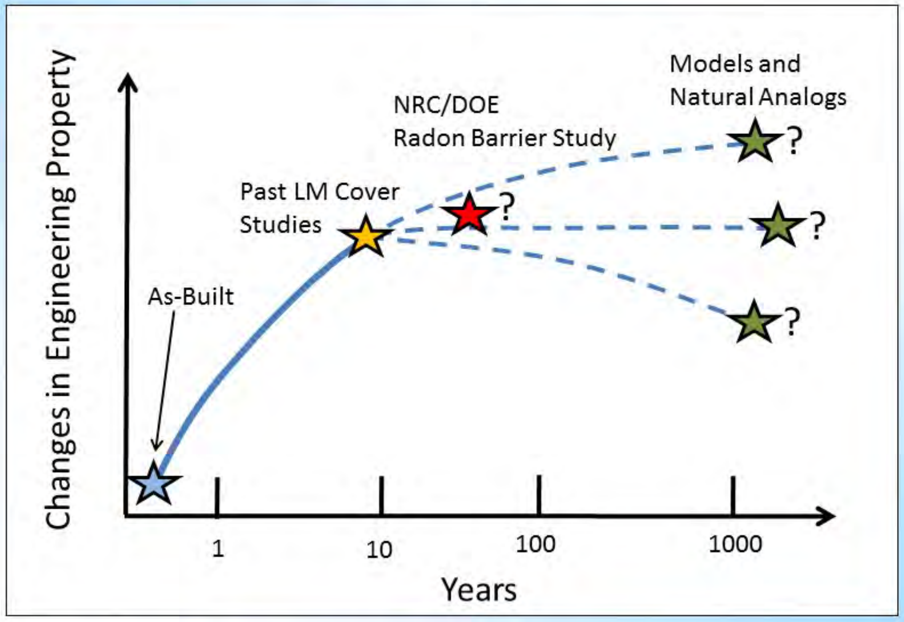
Part II

- **Radon Barrier Study Objectives and Site Selection**
- Test Conditions and Plant Ecology
- Summary

Field Crews

Bill Albright, Desert Research Institute
Craig Benson, University of Virginia
David Dander, Navarro Research and Engineering
Mark Fuhrmann, Nuclear Regulatory Commission
Bill Likos, University of Wisconsin-Madison
Anthony Martinez, Navarro Research and Engineering
Alex Michaud, University of Wisconsin-Madison
Nick Stefani, University of Wisconsin-Madison
Kuo Tian, George Mason University
Aaron Tigar, Navarro Research and Engineering
Xiaodong Wang, University of Wisconsin-Madison
Jody Waugh, Navarro Research and Engineering
Morgan Williams, University of California-Berkeley

Challenge: Predicting the Future



Adapted from Craig Benson, University of Virginia

General Study Questions

Soil morphology

- Can we identify and quantify soil-forming processes that are changing as-built engineering properties of UMTRCA covers?
- How does soil formation vary for ranges of cover thicknesses, soil types, ecological conditions, and climates?
- Is soil formation in covers systematic, predictable, and depth dependent?

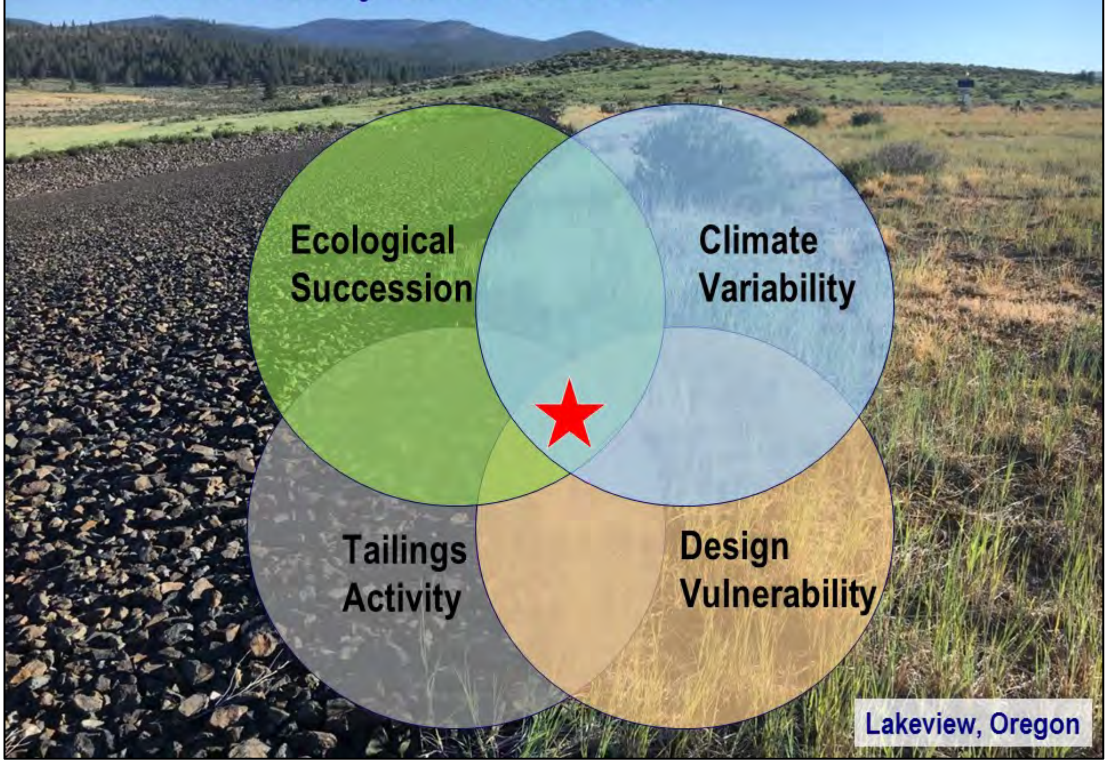
Soil engineering

- Can we measure depth-dependent effects of soil formation on radon diffusion, radon flux, and hydraulic properties of radon barriers?
- Can we improve field monitoring and modeling of radon flux and water percolation in covers that have been altered by soil-forming processes?

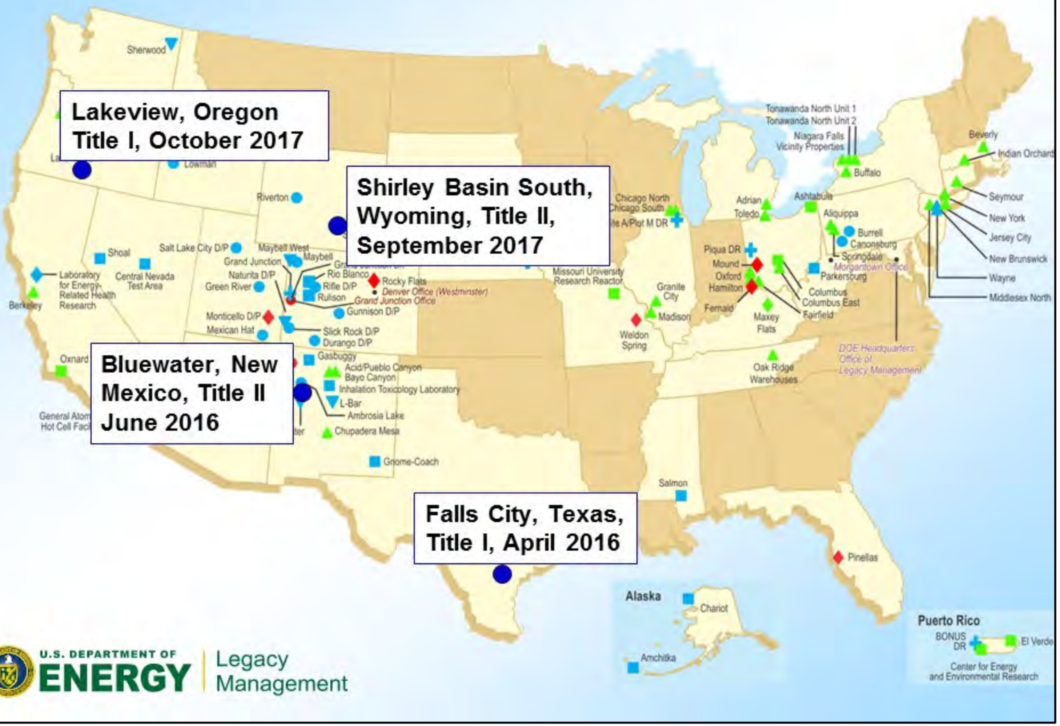
Long-term protectiveness

- Can we project the *long-term* effects of ecological and soil-forming processes on radon flux and water percolation?

Biased Study Site Selection



UMTRCA Sites Selected



Lakeview, Oregon Title I, October 2017

Shirley Basin South, Wyoming, Title II, September 2017

Bluewater, New Mexico, Title II June 2016

Falls City, Texas, Title I, April 2016

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Falls City, Texas

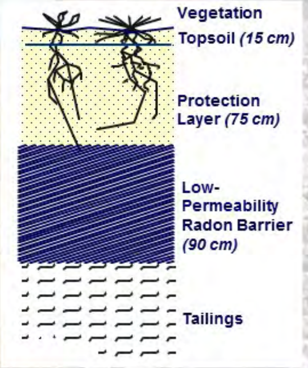

Bluewater, New Mexico


Shirley Basin, Wyoming


Lakeview, Oregon

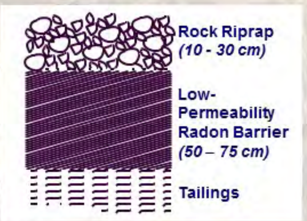
Falls City, Texas

- warm/wet
- thick protected cover



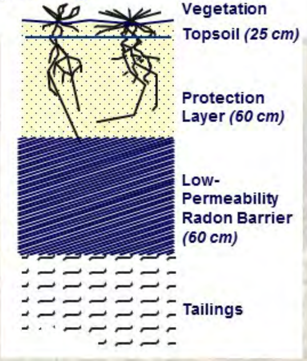
Bluewater, New Mexico

- warm/dry
- thin vulnerable cover



Shirley Basin, Wyoming

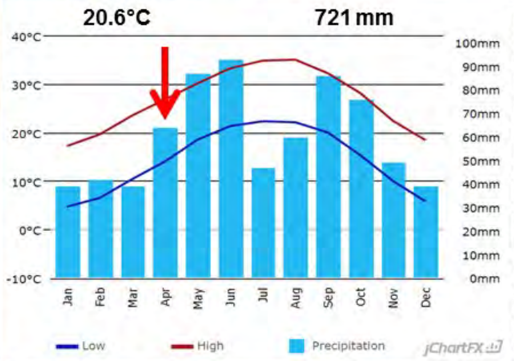
- cold/dry
- thick protected cover



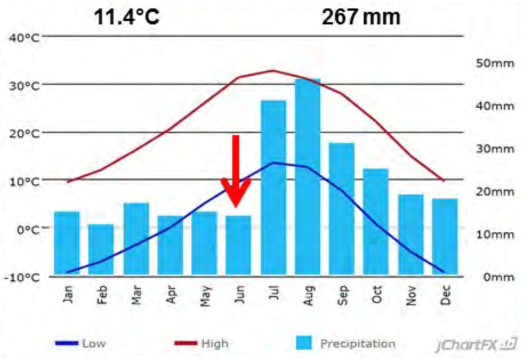
Lakeview, Oregon

- cold/dry
- thin vulnerable cover

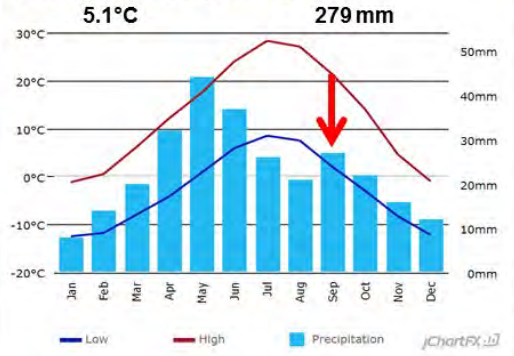
Falls City, Texas



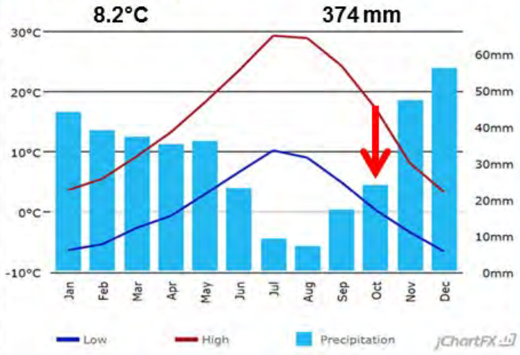
Bluewater, New Mexico

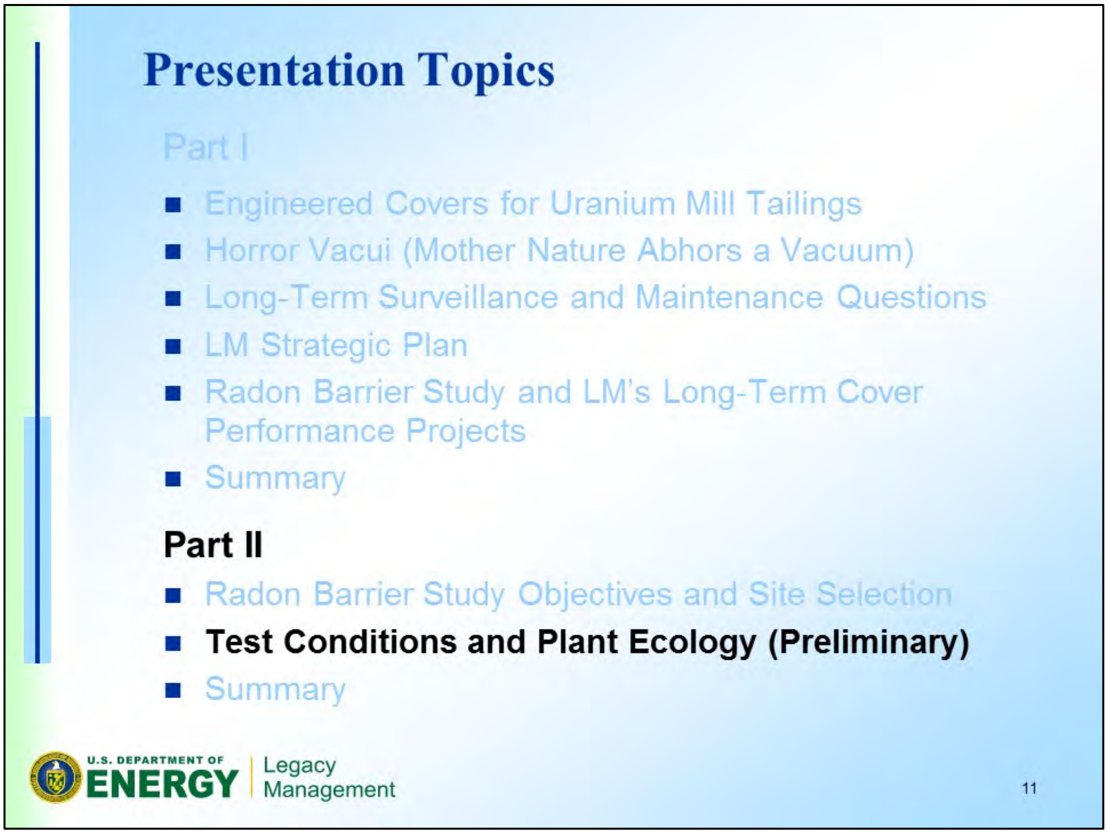


Shirley Basin, Wyoming



Lakeview, Oregon





Presentation Topics

Part I

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- Horror Vacui (Mother Nature Abhors a Vacuum)
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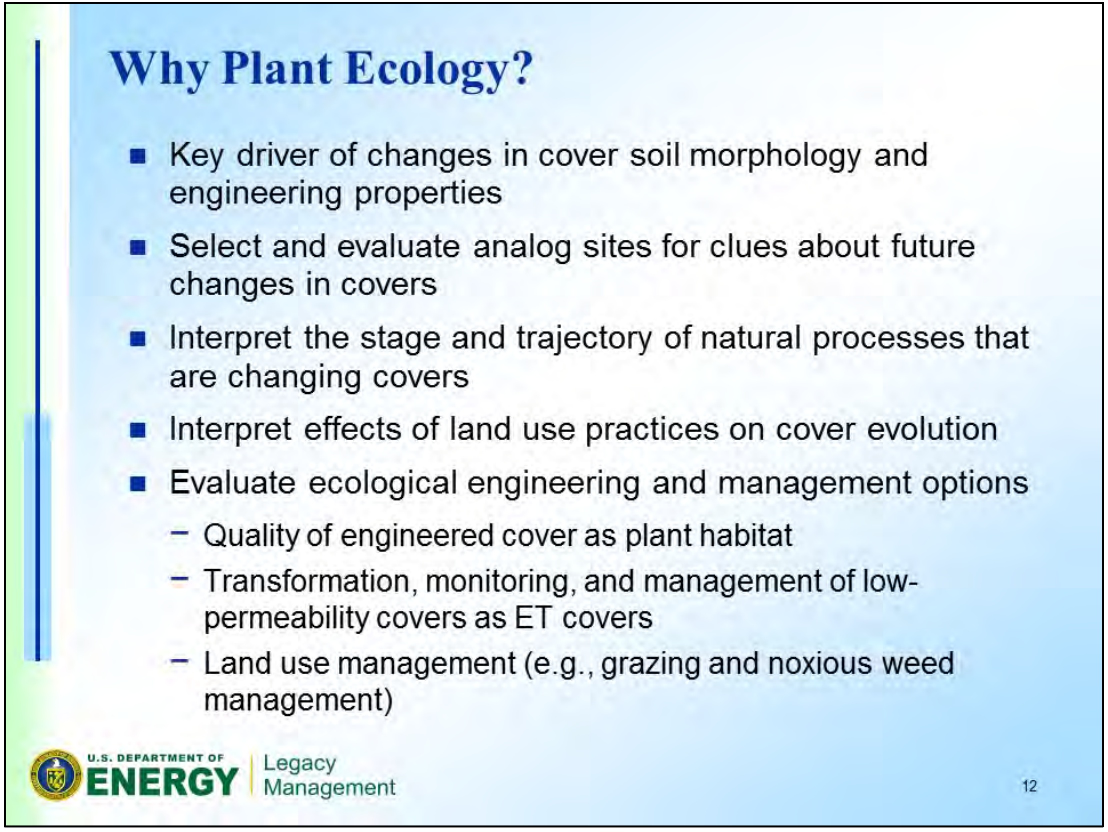
- Summary

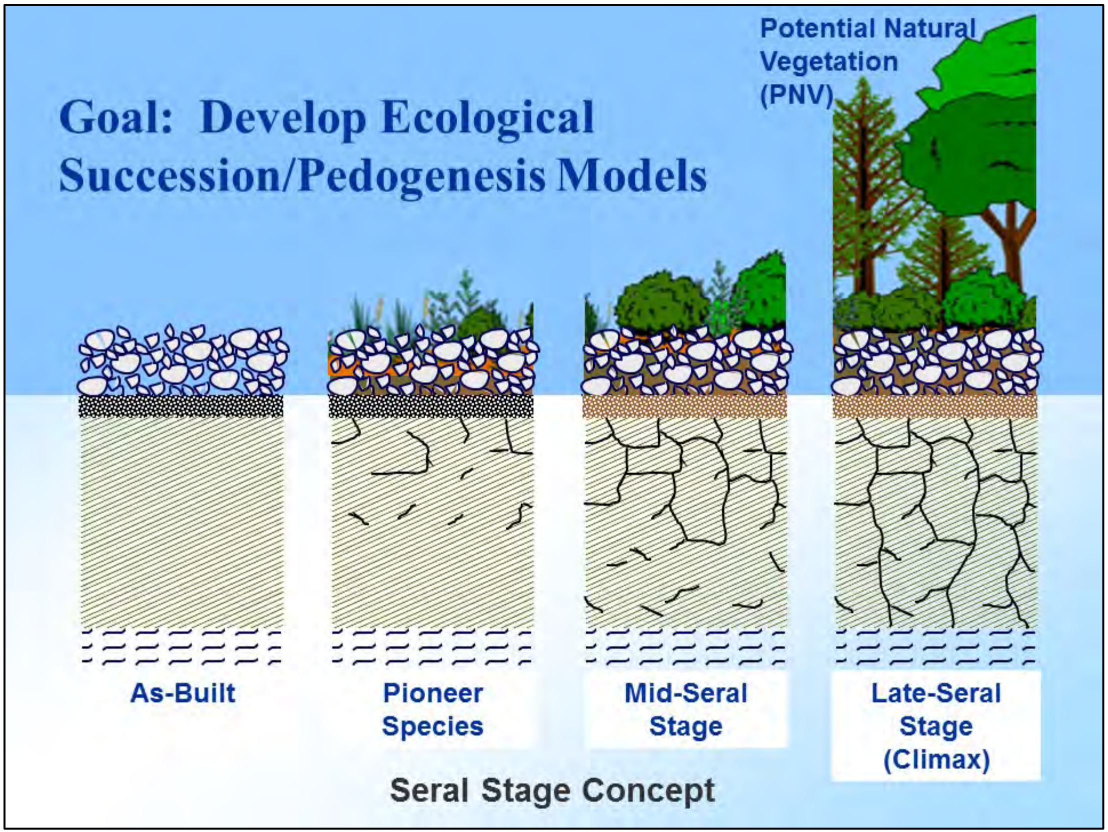
Part II

- Radon Barrier Study Objectives and Site Selection
- **Test Conditions and Plant Ecology (Preliminary)**
- Summary



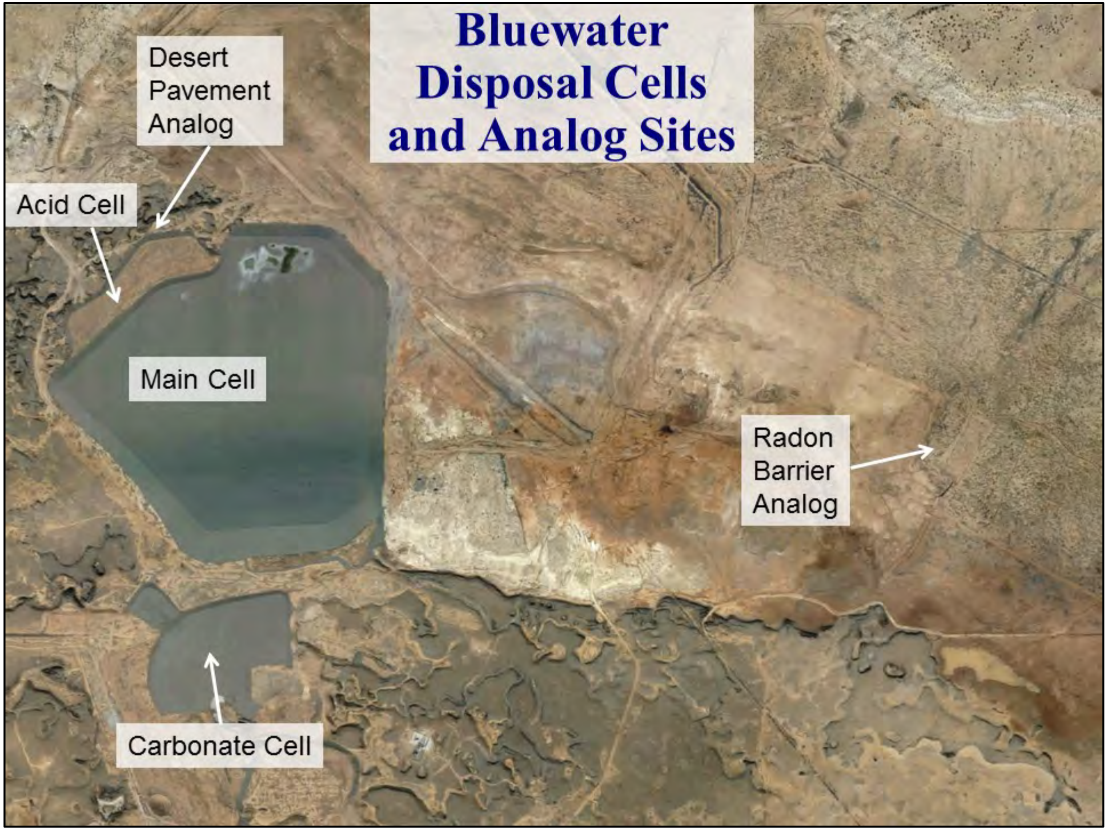
Why Plant Ecology?

- Key driver of changes in cover soil morphology and engineering properties
- Select and evaluate analog sites for clues about future changes in covers
- Interpret the stage and trajectory of natural processes that are changing covers
- Interpret effects of land use practices on cover evolution
- Evaluate ecological engineering and management options
  - Quality of engineered cover as plant habitat
  - Transformation, monitoring, and management of low-permeability covers as ET covers
  - Land use management (e.g., grazing and noxious weed management)



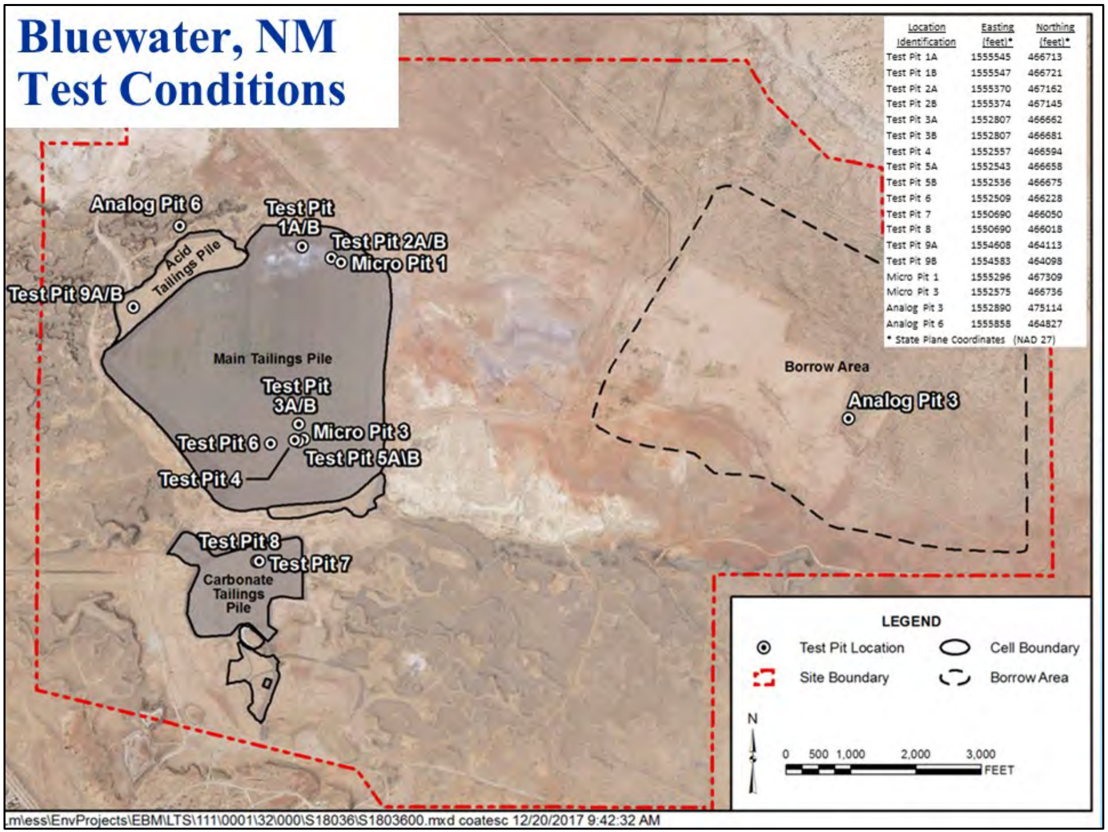
Goal: Develop Ecological Succession/Pedogenesis Models

Seral Stage Concept



Bluewater Disposal Cells and Analog Sites

Bluewater, NM
Test Conditions



Location Identification	Easting (feet)*	Northing (feet)*
Test Pit 1A	1555545	466713
Test Pit 1B	1555547	466721
Test Pit 2A	1555370	467162
Test Pit 2B	1555374	467145
Test Pit 3A	1552807	466662
Test Pit 3B	1552807	466681
Test Pit 4	1552557	466594
Test Pit 5A	1552543	466658
Test Pit 5B	1552536	466675
Test Pit 6	1552509	466228
Test Pit 7	1550690	466050
Test Pit 8	1550690	466018
Test Pit 9A	1554608	464113
Test Pit 9B	1554583	464098
Micro Pit 1	1555296	467309
Micro Pit 3	1552575	466736
Analog Pit 3	1552890	475114
Analog Pit 6	1555858	464827

* State Plane Coordinates (NAD 27)

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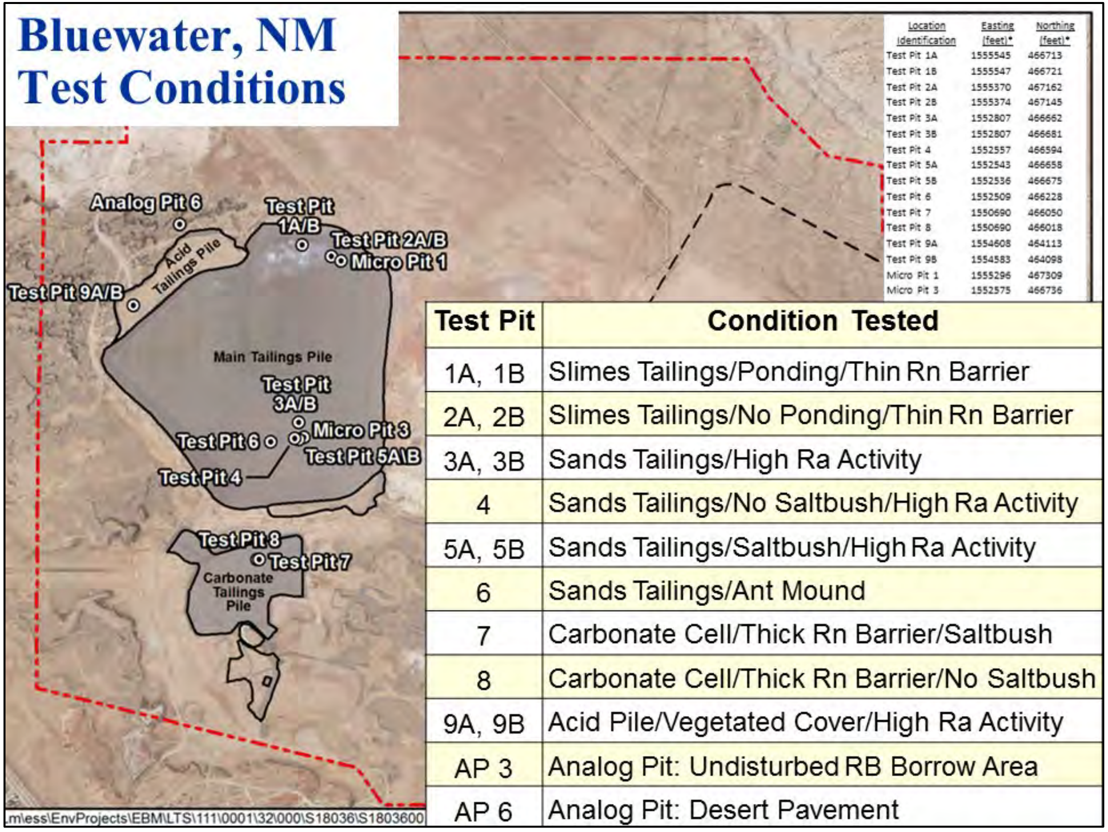
Bluewater, NM
Test Conditions



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Test Pit 9A	1554608	464113
Test Pit 9B	1554583	464098
Micro Pit 1	1555296	467309
Micro Pit 3	1552575	466736

Test Pit	Condition Tested
1A, 1B	Slimes Tailings/Ponding/Thin Rn Barrier
2A, 2B	Slimes Tailings/No Ponding/Thin Rn Barrier
3A, 3B	Sands Tailings/High Ra Activity
4	Sands Tailings/No Saltbush/High Ra Activity
5A, 5B	Sands Tailings/Saltbush/High Ra Activity
6	Sands Tailings/Ant Mound
7	Carbonate Cell/Thick Rn Barrier/Saltbush
8	Carbonate Cell/Thick Rn Barrier/No Saltbush
9A, 9B	Acid Pile/Vegetated Cover/High Ra Activity
AP 3	Analog Pit: Undisturbed RB Borrow Area
AP 6	Analog Pit: Desert Pavement

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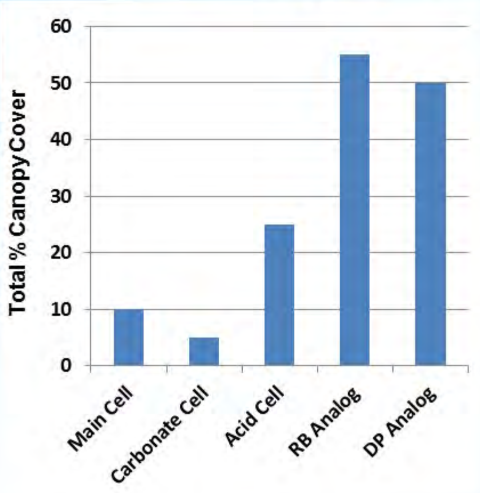
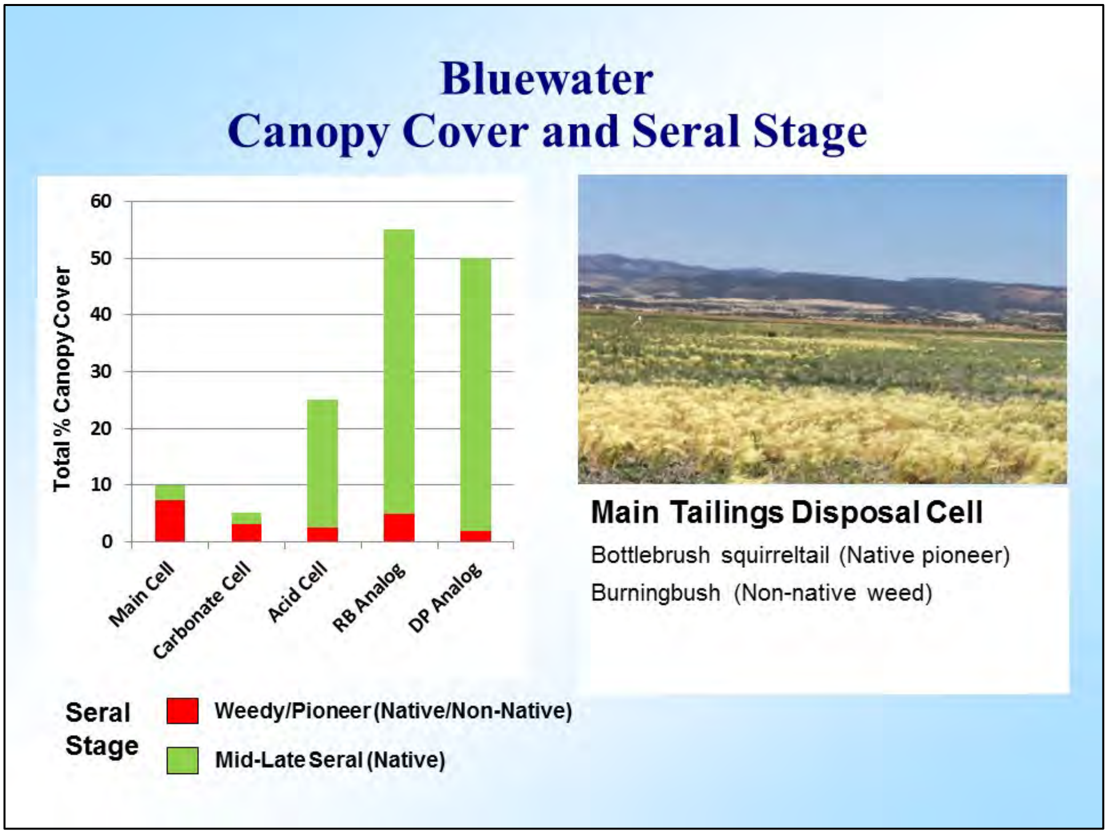
Bluewater Example

- Total of 71 plant species identified
- 21 common species

Genus species	Common Name	Growth Form	Main Tailings Cell	Carbonate Tailings Cell	Acid Tailings Cell	Radon Barrier Analog	Desert Pavement Analog
Achnatherum hymenoides	Indian ricegrass	N grass				X	
Amaranthus polygonoides	tropical amaranth	N forb				X	
Aristida purpurea	purple threeawn	N grass	X			X	
Artemisia nova	black sagebrush	N shrub				X	X
Atriplex canescens	fourwing saltbush	N shrub	X	X		X	X
Atriplex cuneata	valley saltbush	N shrub				X	
Bassia scoparia	burningbush (kochia)	I forb	X				
Bouteloua eriopoda	black grama	N grass					X
Bouteloua gracilis	blue grama	N grass			X	X	X
Elymus elymoides	bottlebrush squirreltail	N grass	X	X			
Ericameria nauseosa	rubber rabbitbrush	N shrub		X		X	
Erigeron divergens	spreading fleabane	N forb				X	
Gutierrezia sarothrae	broom snakeweed	N shrub				X	X
Heterotheca villosa	hairy false goldenaster	N forb				X	
Krascheninnikovia lanata	Winterfat	N shrub				X	X
Lactuca serriola	prickly lettuce	I forb	X				
Muhlenbergia torreyi	ring muhly	N grass				X	X
Pleuraphis jamesii	James' galleta	N grass				X	X
Salsola tragus	Russian thistle	I forb	X	X			
Sporobolus cryptandrus	sand dropseed	N grass			X	X	X
Tetradymia canescens	spineless horsebrush	N shrub					X

Bluewater
Canopy Cover and Seral Stage





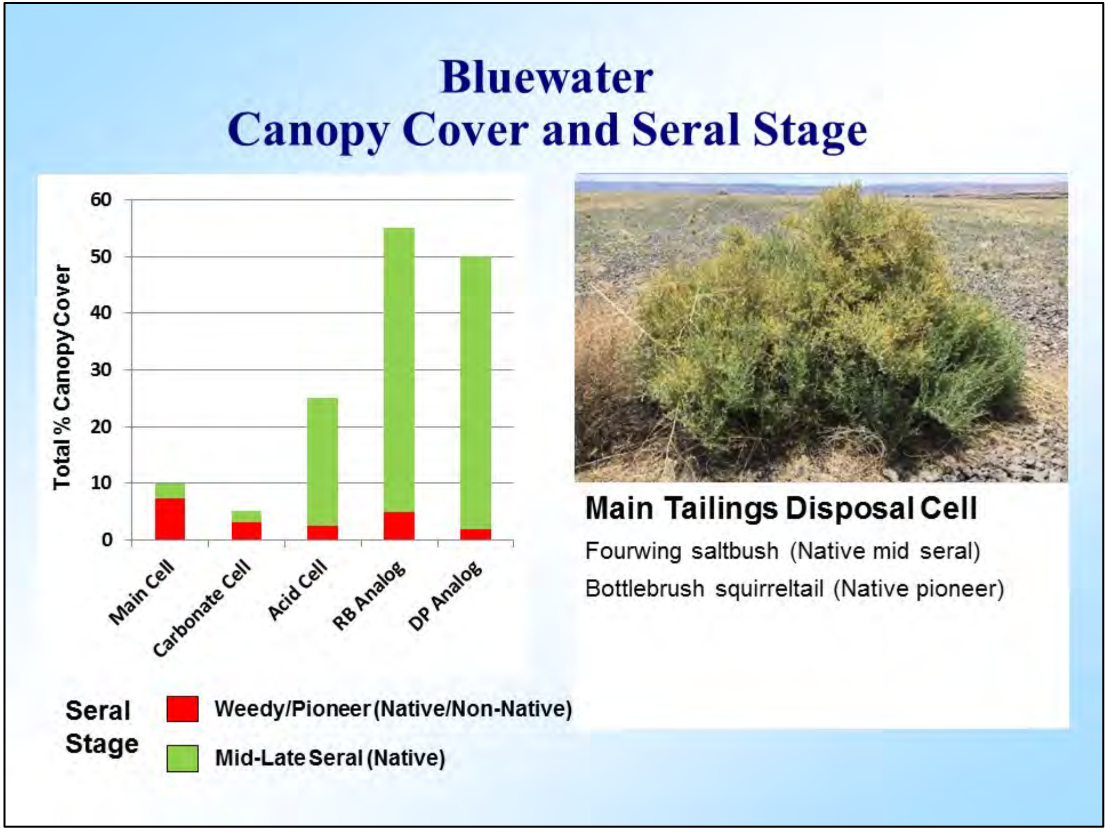
Bluewater
Canopy Cover and Seral Stage

Seral Stage
🟥 Weedy/Pioneer (Native/Non-Native)
🟩 Mid-Late Seral (Native)

Main Tailings Disposal Cell

Bottlebrush squirreltail (Native pioneer)

Burningbush (Non-native weed)



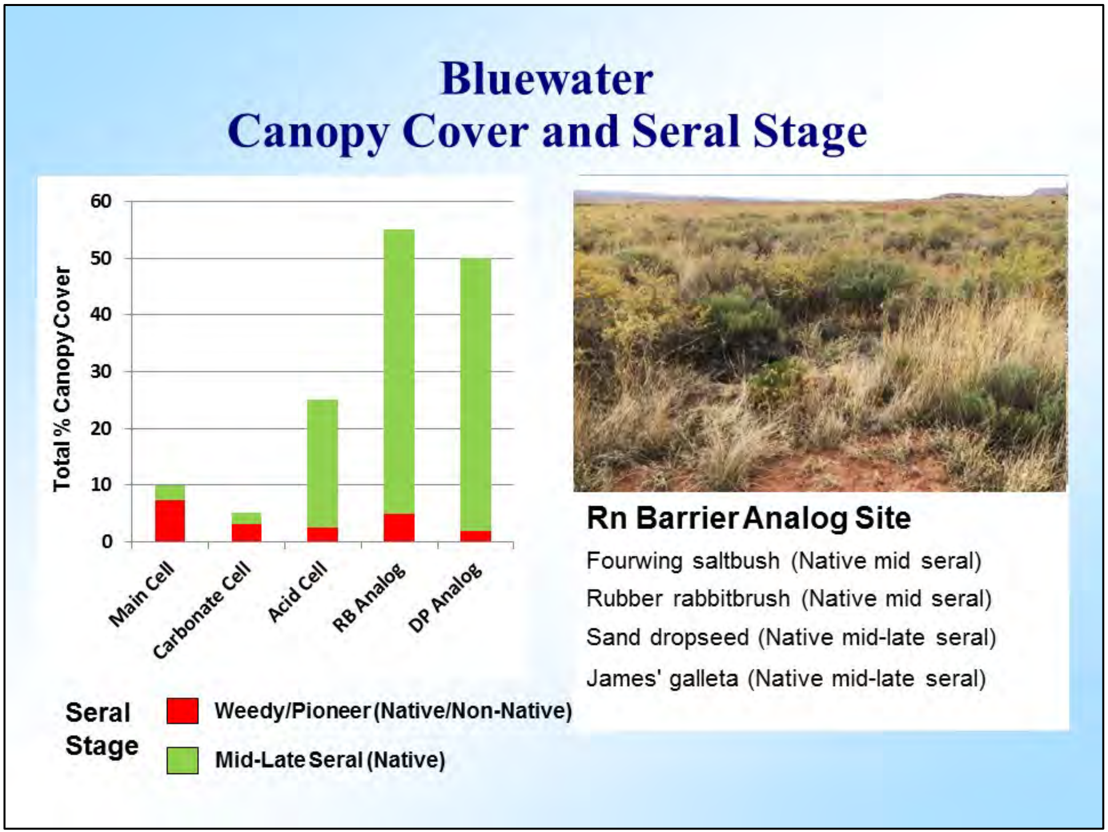
Bluewater
Canopy Cover and Seral Stage

Seral Stage
🟥 Weedy/Pioneer (Native/Non-Native)
🟩 Mid-Late Seral (Native)

Main Tailings Disposal Cell

Fourwing saltbush (Native mid seral)

Bottlebrush squirreltail (Native pioneer)



Bluewater
Canopy Cover and Seral Stage

Seral Stage

- 🟥 **Weedy/Pioneer (Native/Non-Native)**
- 🟩 **Mid-Late Seral (Native)**

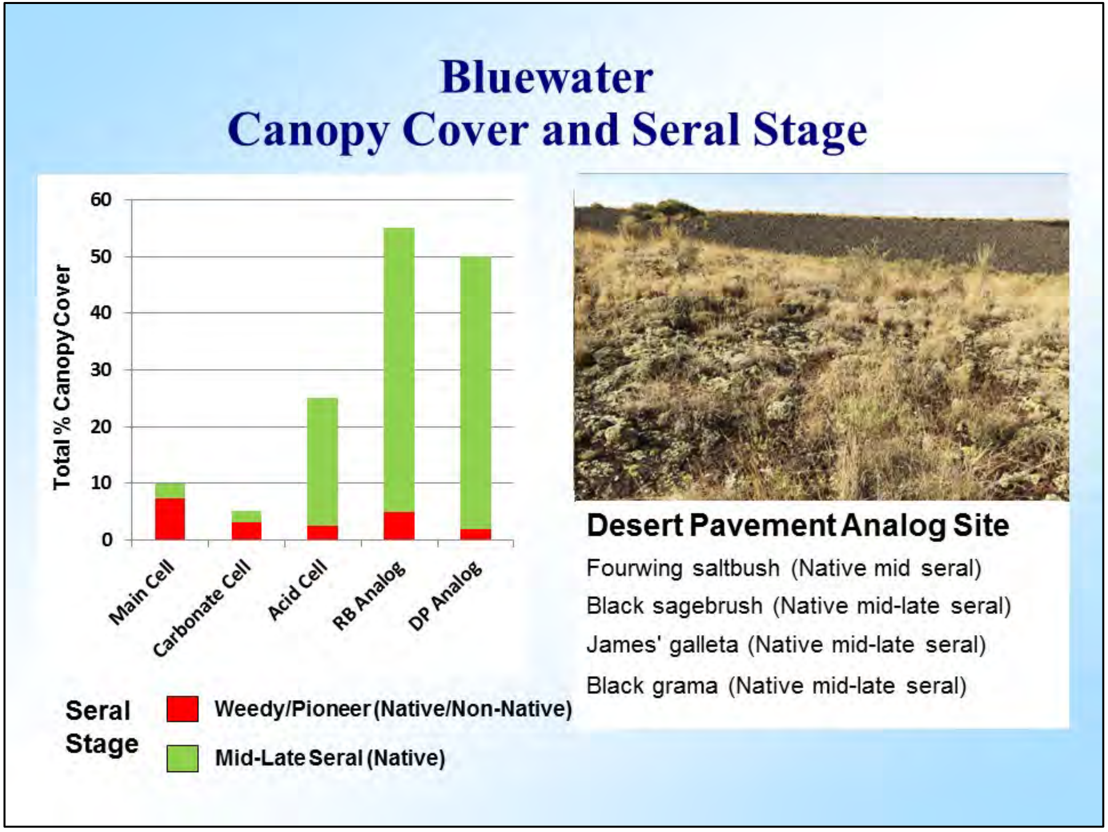
Rn Barrier Analog Site

Fourwing saltbush (Native mid seral)

Rubber rabbitbrush (Native mid seral)

Sand dropseed (Native mid-late seral)

James' galleta (Native mid-late seral)



Bluewater
Canopy Cover and Seral Stage

Seral Stage

- 🟥 **Weedy/Pioneer (Native/Non-Native)**
- 🟩 **Mid-Late Seral (Native)**

Desert Pavement Analog Site

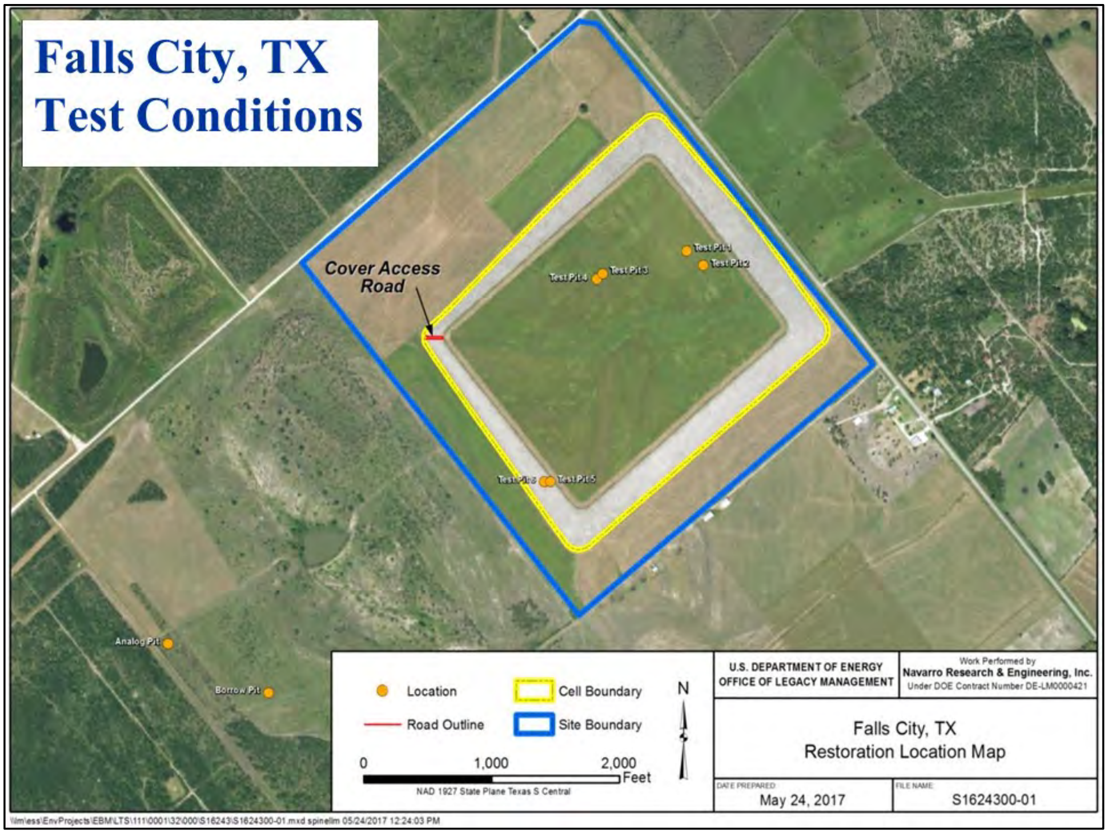
Fourwing saltbush (Native mid seral)

Black sagebrush (Native mid-late seral)

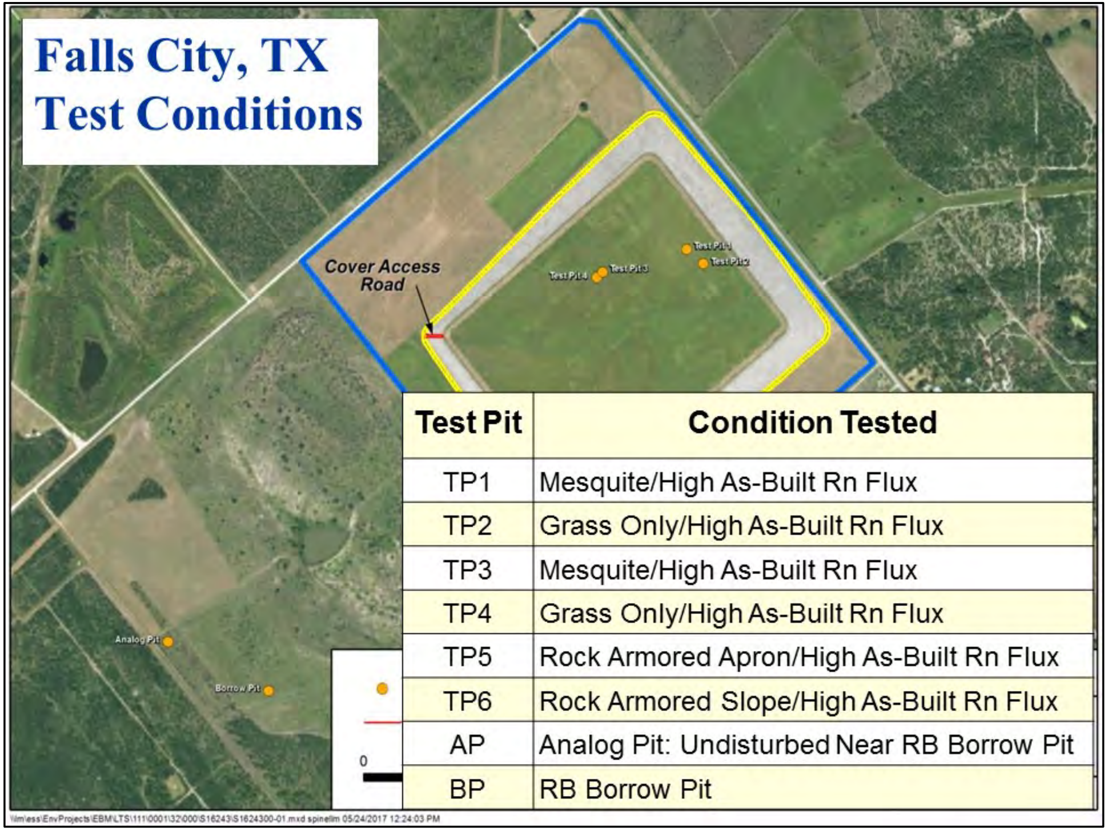
James' galleta (Native mid-late seral)

Black grama (Native mid-late seral)

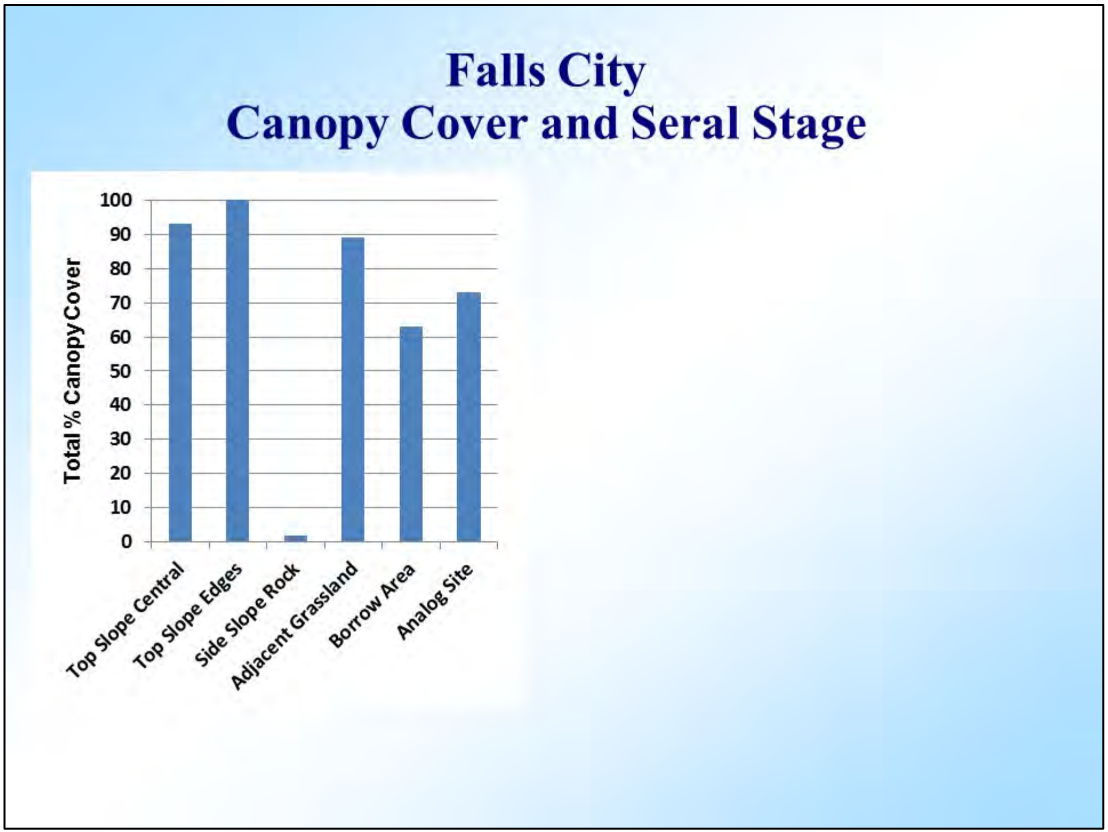
Falls City, TX
Test Conditions



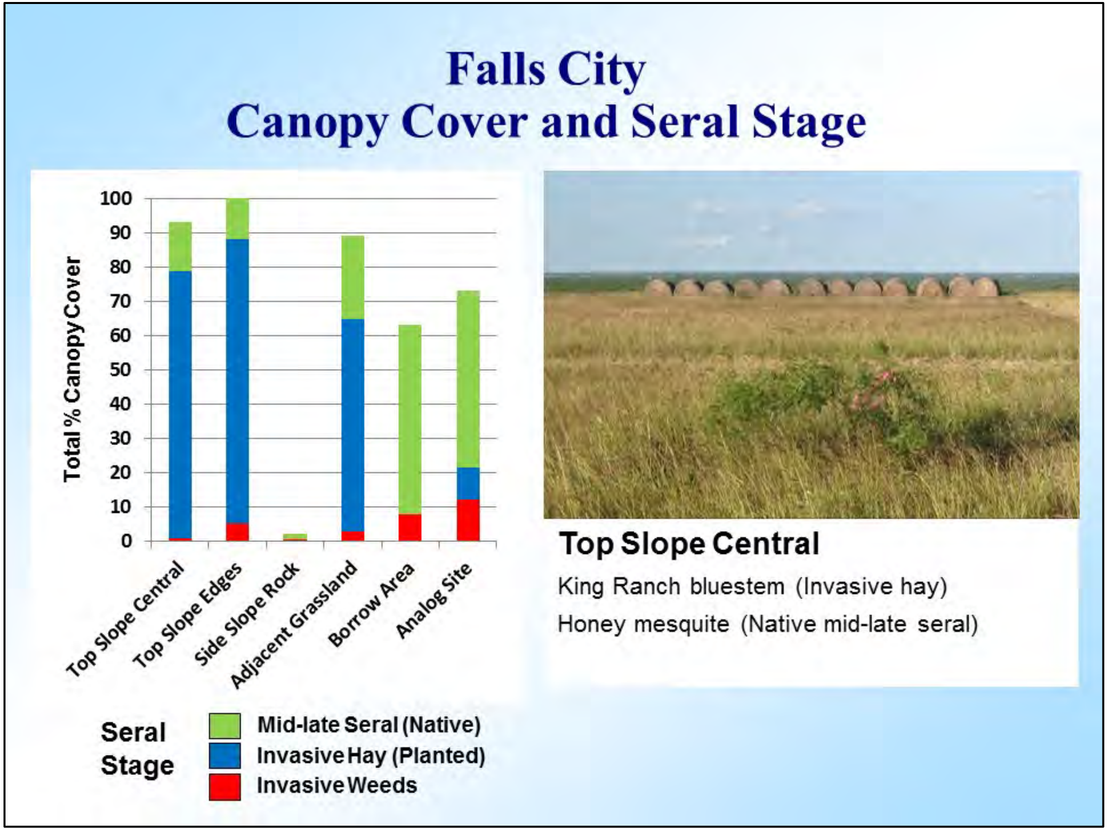
Falls City, TX
Test Conditions



Test Pit	Condition Tested
TP1	Mesquite/High As-Built Rn Flux
TP2	Grass Only/High As-Built Rn Flux
TP3	Mesquite/High As-Built Rn Flux
TP4	Grass Only/High As-Built Rn Flux
TP5	Rock Armored Apron/High As-Built Rn Flux
TP6	Rock Armored Slope/High As-Built Rn Flux
AP	Analog Pit: Undisturbed Near RB Borrow Pit
BP	RB Borrow Pit



Falls City
Canopy Cover and Seral Stage



Falls City
Canopy Cover and Seral Stage

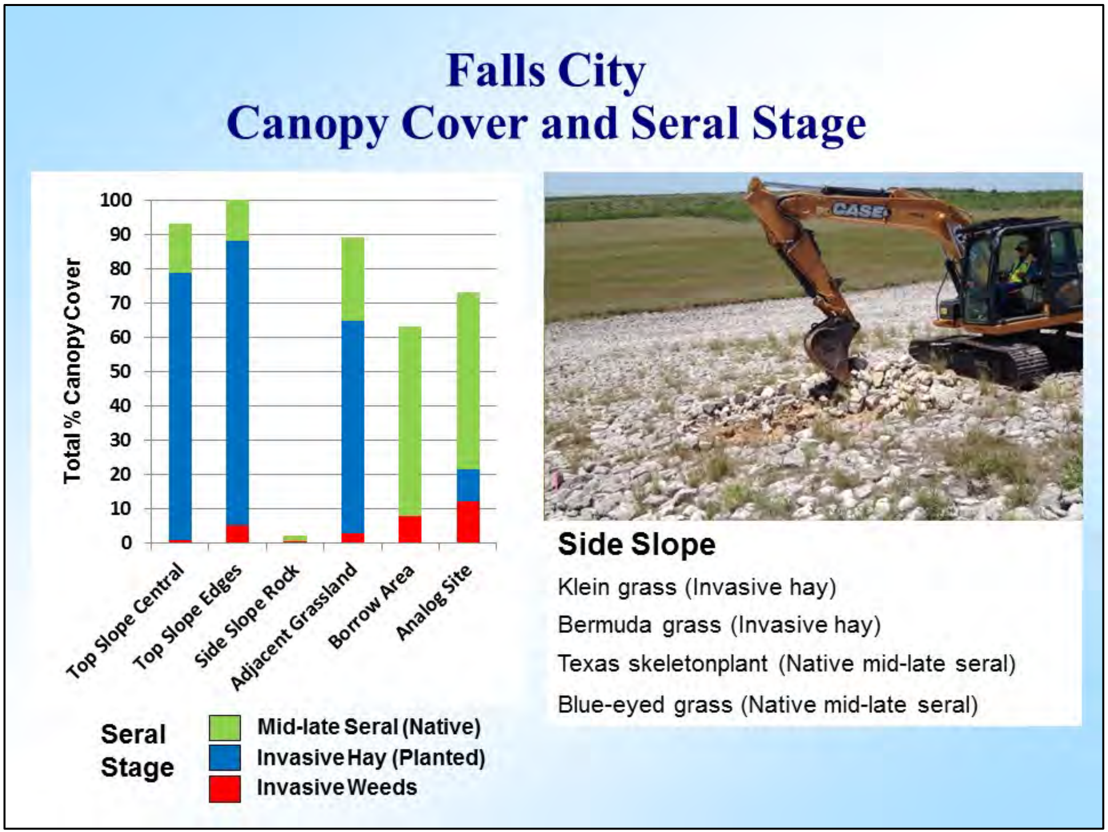
Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Invasive Hay (Planted)
- 🟥 Invasive Weeds

Top Slope Central

King Ranch bluestem (Invasive hay)

Honey mesquite (Native mid-late seral)



Falls City
Canopy Cover and Seral Stage

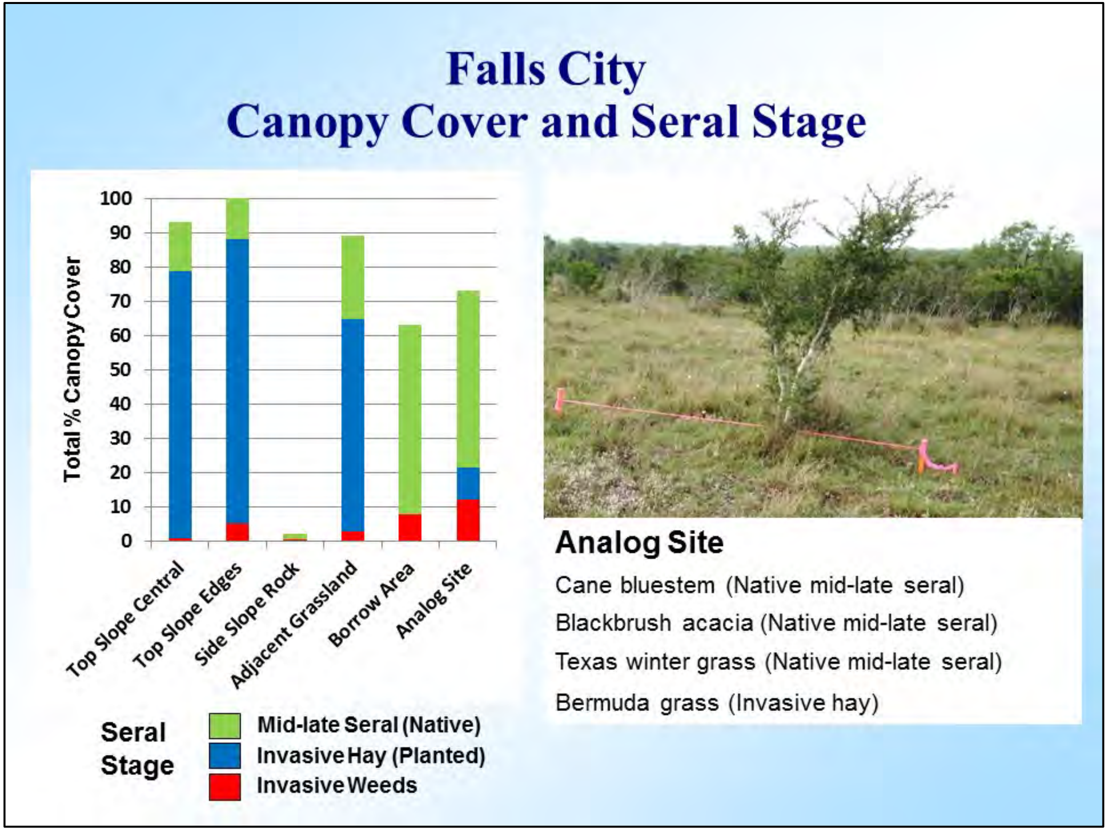
Side Slope

Klein grass (Invasive hay)

Bermuda grass (Invasive hay)

Texas skeletonplant (Native mid-late seral)

Blue-eyed grass (Native mid-late seral)



Falls City
Canopy Cover and Seral Stage

Analog Site

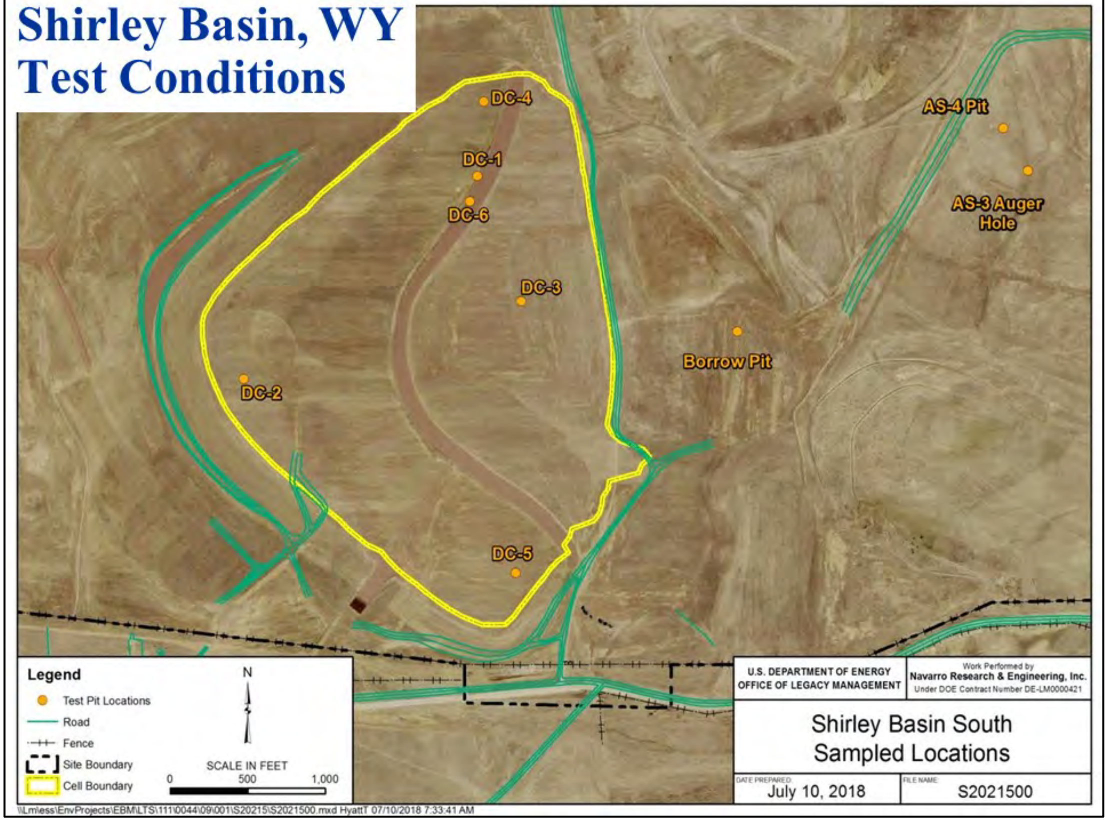
Cane bluestem (Native mid-late seral)

Blackbrush acacia (Native mid-late seral)

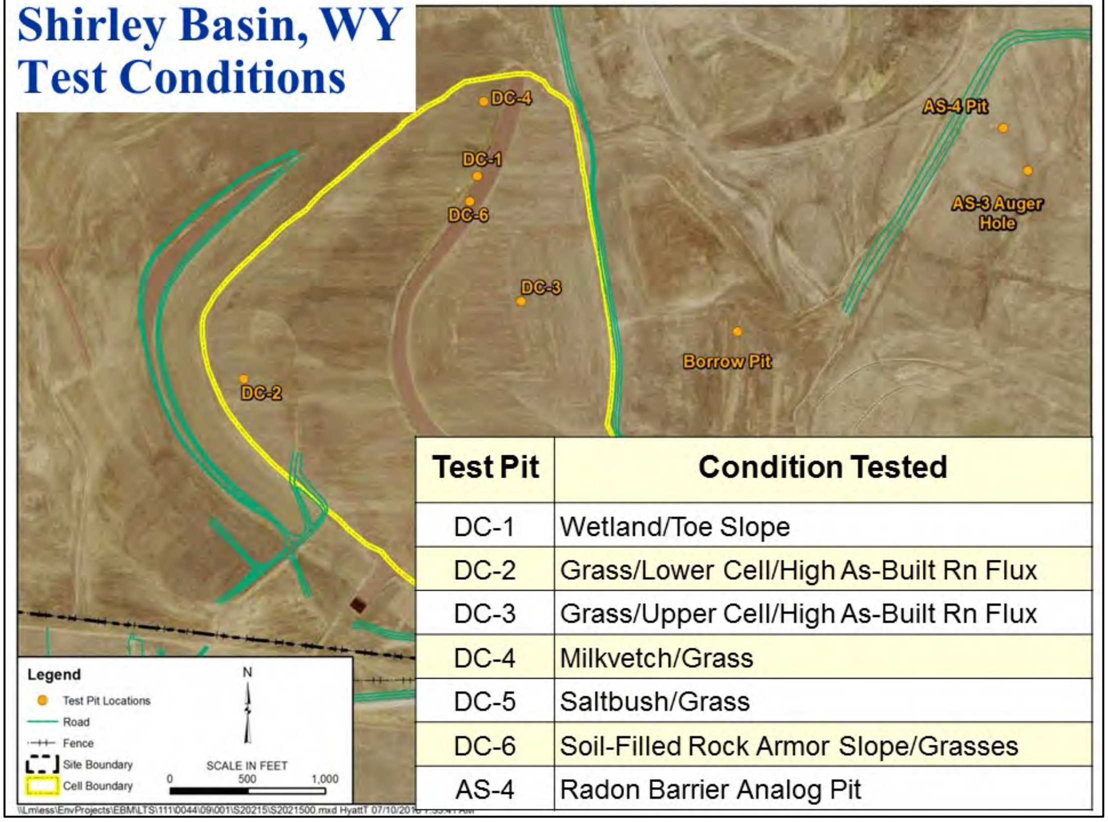
Texas winter grass (Native mid-late seral)

Bermuda grass (Invasive hay)

Shirley Basin, WY Test Conditions

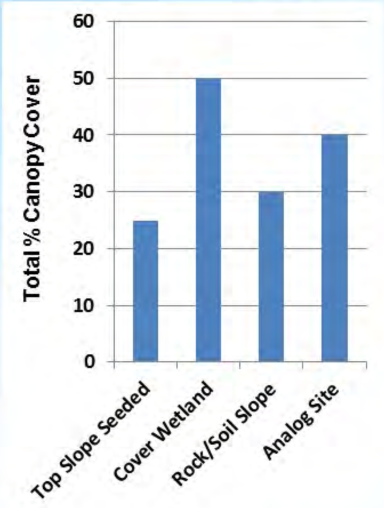


Shirley Basin, WY Test Conditions

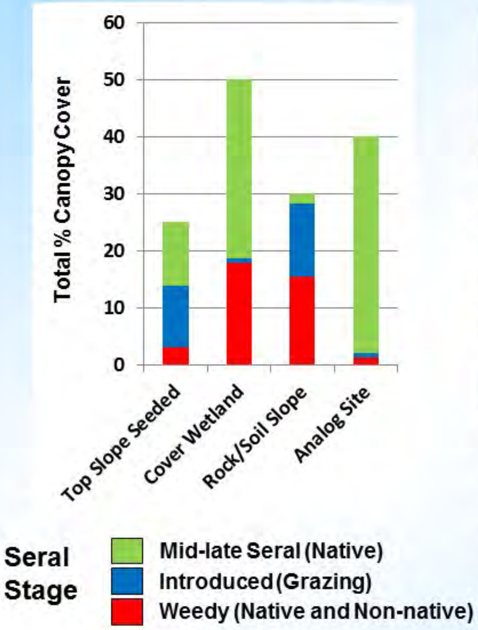


Test Pit	Condition Tested
DC-1	Wetland/Toe Slope
DC-2	Grass/Lower Cell/High As-Built Rn Flux
DC-3	Grass/Upper Cell/High As-Built Rn Flux
DC-4	Milkvetch/Grass
DC-5	Saltbush/Grass
DC-6	Soil-Filled Rock Armor Slope/Grasses
AS-4	Radon Barrier Analog Pit

Shirley Basin South
Canopy Cover and Seral Stage

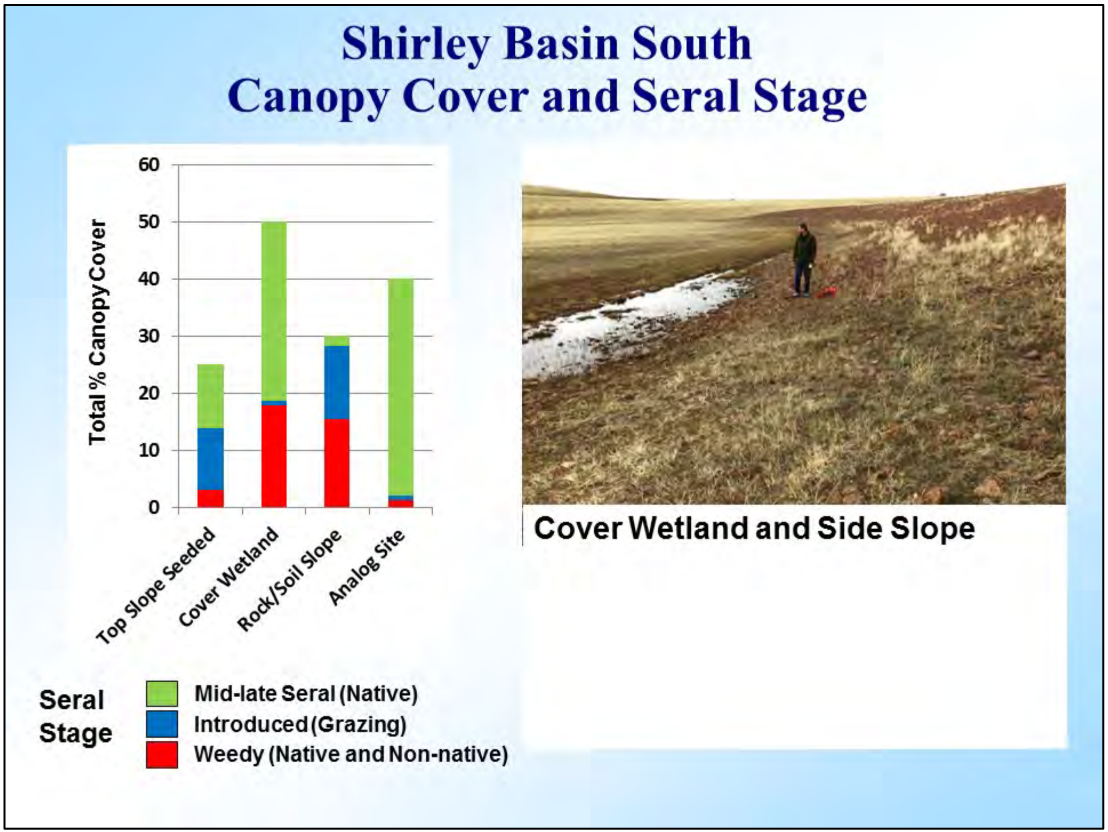


Shirley Basin South
Canopy Cover and Seral Stage



Seeded Top Slope

Crested wheatgrass (Introduced grazing)
Smooth brome (Introduced grazing)
Thickspike wheatgrass (Native mid-late seral)
Western wheatgrass (Native mid-late seral)

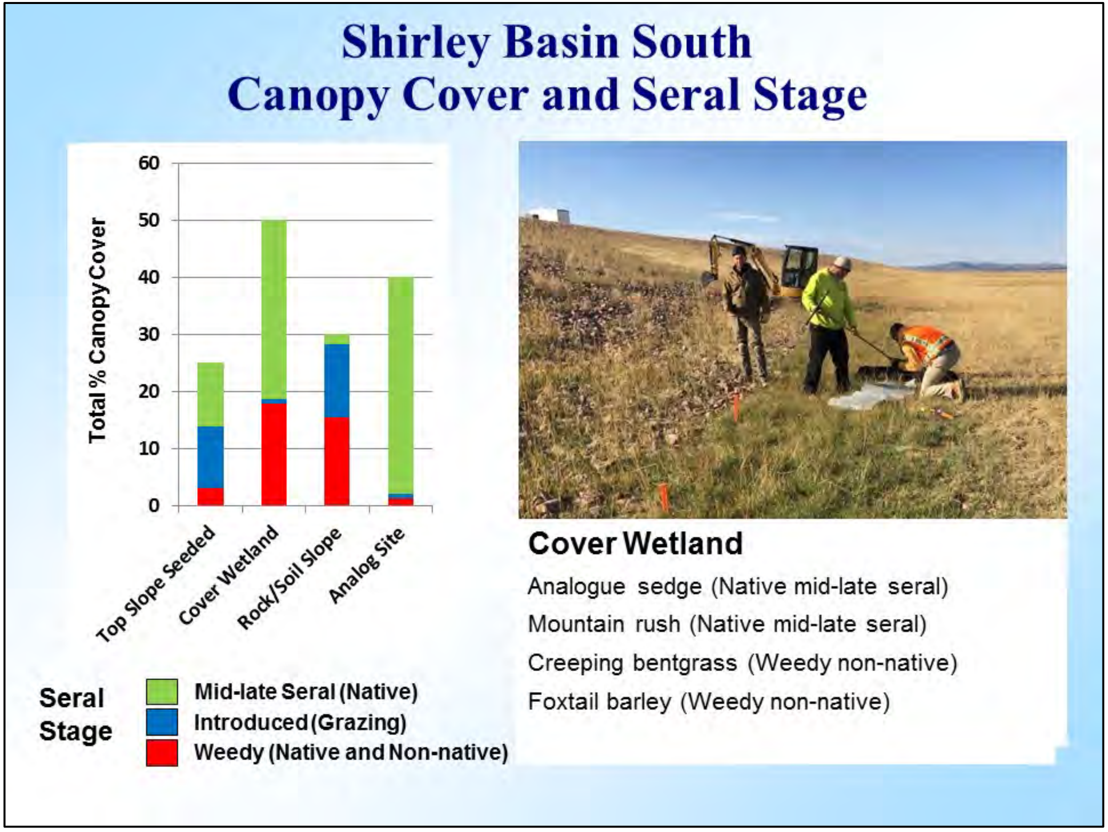


Shirley Basin South
Canopy Cover and Seral Stage

Seral Stage

🟩 Mid-late Seral (Native)
🟦 Introduced (Grazing)
🟥 Weedy (Native and Non-native)

Cover Wetland and Side Slope



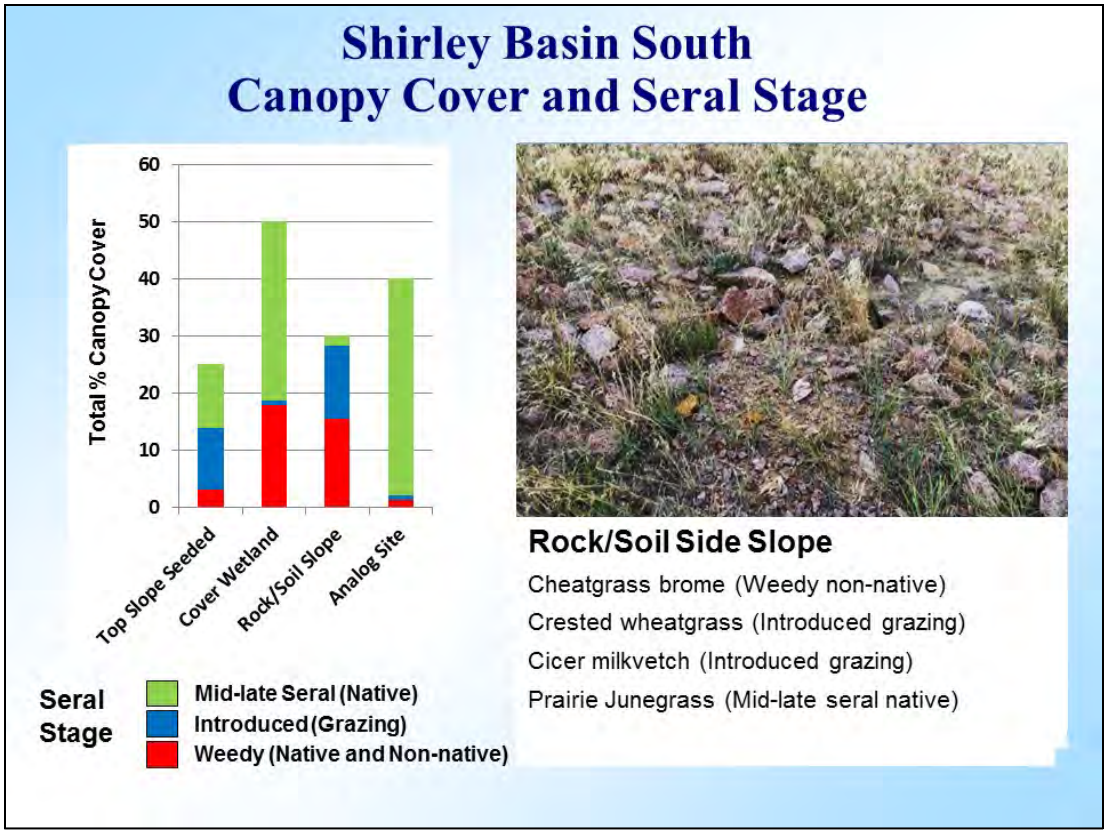
Shirley Basin South
Canopy Cover and Seral Stage

Seral Stage

🟩 Mid-late Seral (Native)
🟦 Introduced (Grazing)
🟥 Weedy (Native and Non-native)

Cover Wetland

Analogue sedge (Native mid-late seral)
Mountain rush (Native mid-late seral)
Creeping bentgrass (Weedy non-native)
Foxtail barley (Weedy non-native)



Shirley Basin South
Canopy Cover and Seral Stage

Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Introduced (Grazing)
- 🟥 Weedy (Native and Non-native)

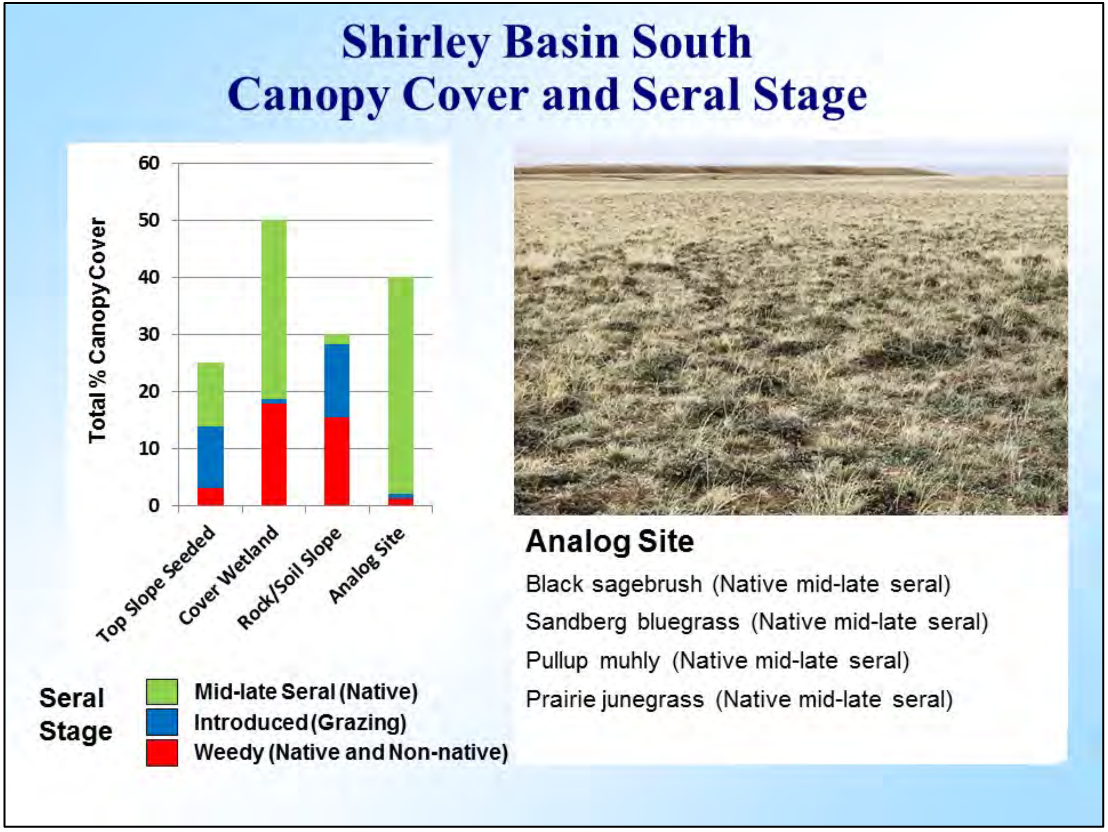
Rock/Soil Side Slope

Cheatgrass brome (Weedy non-native)

Crested wheatgrass (Introduced grazing)

Cicer milkvetch (Introduced grazing)

Prairie Junegrass (Mid-late seral native)



Shirley Basin South
Canopy Cover and Seral Stage

Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Introduced (Grazing)
- 🟥 Weedy (Native and Non-native)

Analog Site

Black sagebrush (Native mid-late seral)

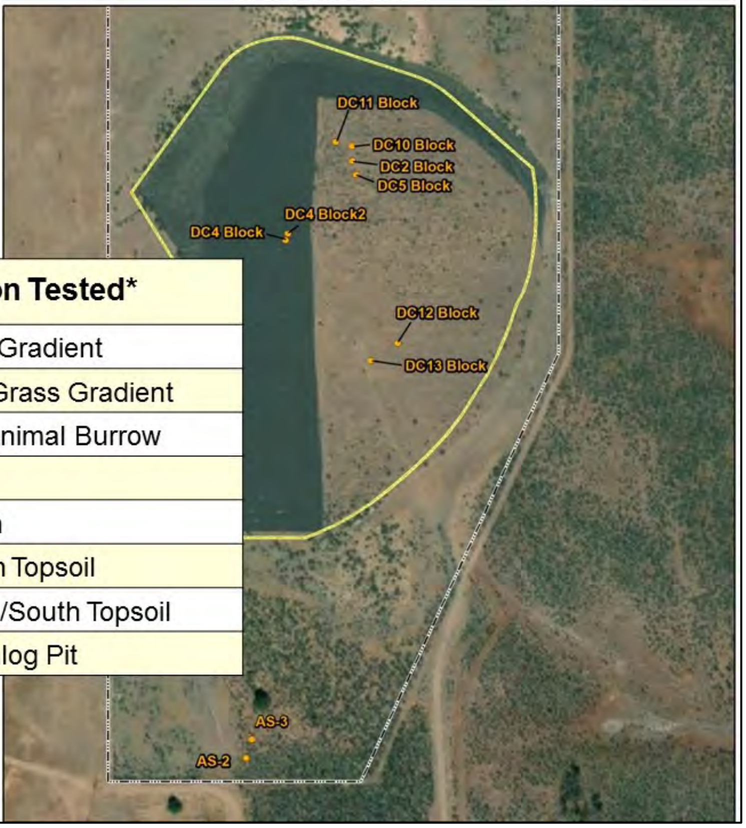
Sandberg bluegrass (Native mid-late seral)

Pullup muhly (Native mid-late seral)

Prairie junegrass (Native mid-late seral)

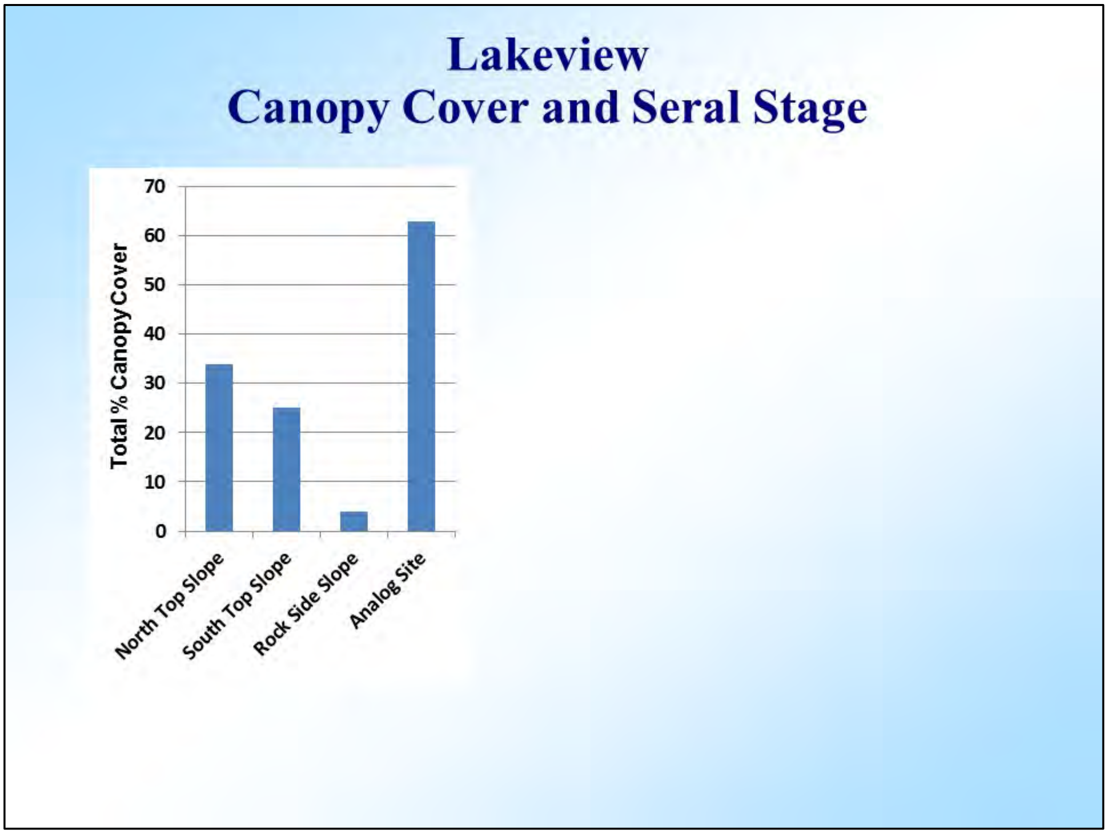
Lakeview, OR Test Conditions

Lakeview, OR Test Conditions

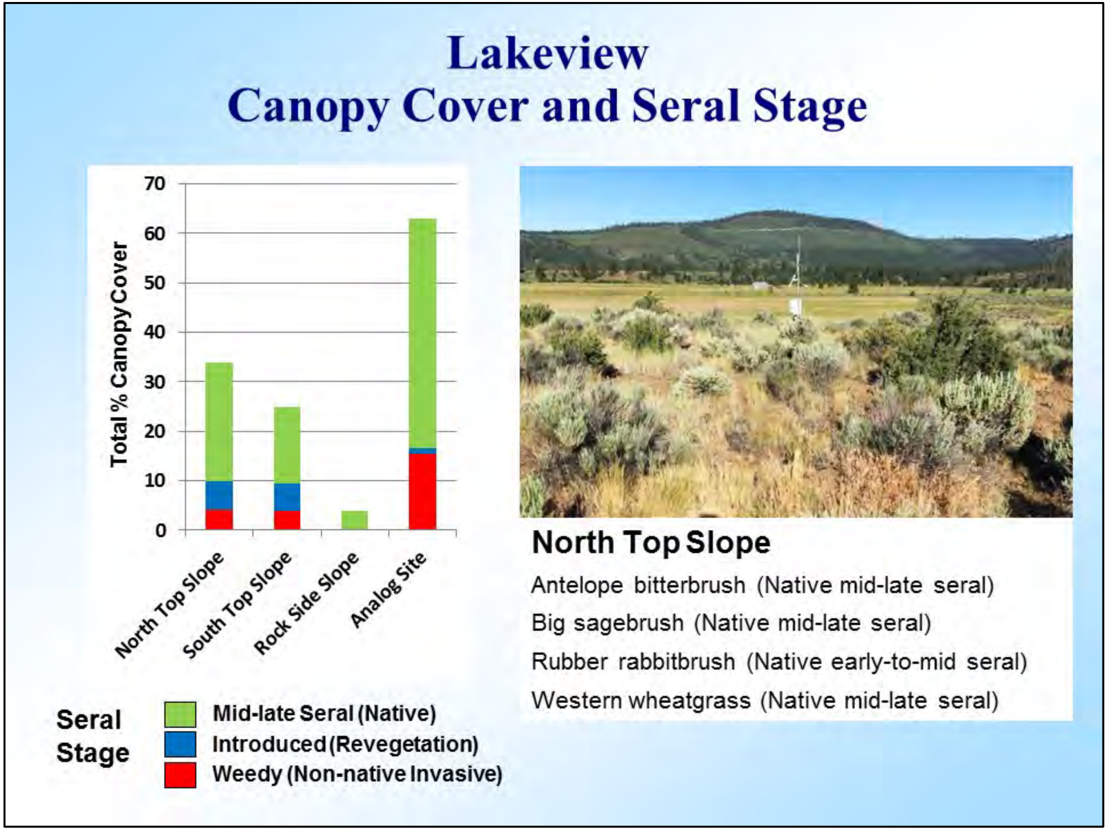


Test Pit	Condition Tested*
DC-2	Bitterbrush/Grass Gradient
DC-4	Rock Side Slope/Grass Gradient
DC-5	Rabbitbrush and Animal Burrow
DC-10	Sparse Grass
DC-11	Mature Bitterbrush
DC-12	Rabbitbrush/South Topsoil
DC-13	Sparse Vegetation/South Topsoil
AS-2	Radon Barrier Analog Pit

*No as-built radon flux data



Lakeview
Canopy Cover and Seral Stage



Lakeview
Canopy Cover and Seral Stage

Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Introduced (Revegetation)
- 🟥 Weedy (Non-native Invasive)

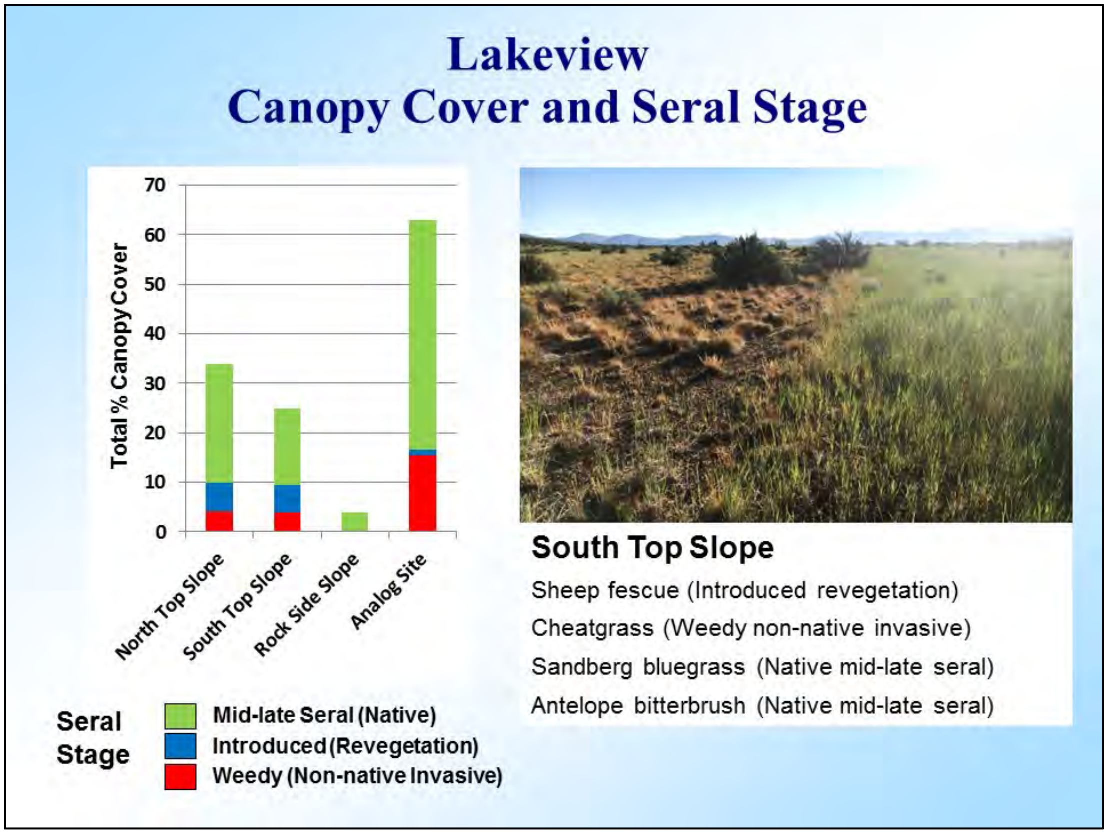
North Top Slope

Antelope bitterbrush (Native mid-late seral)

Big sagebrush (Native mid-late seral)

Rubber rabbitbrush (Native early-to-mid seral)

Western wheatgrass (Native mid-late seral)



Lakeview
Canopy Cover and Seral Stage

Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Introduced (Revegetation)
- 🟥 Weedy (Non-native Invasive)

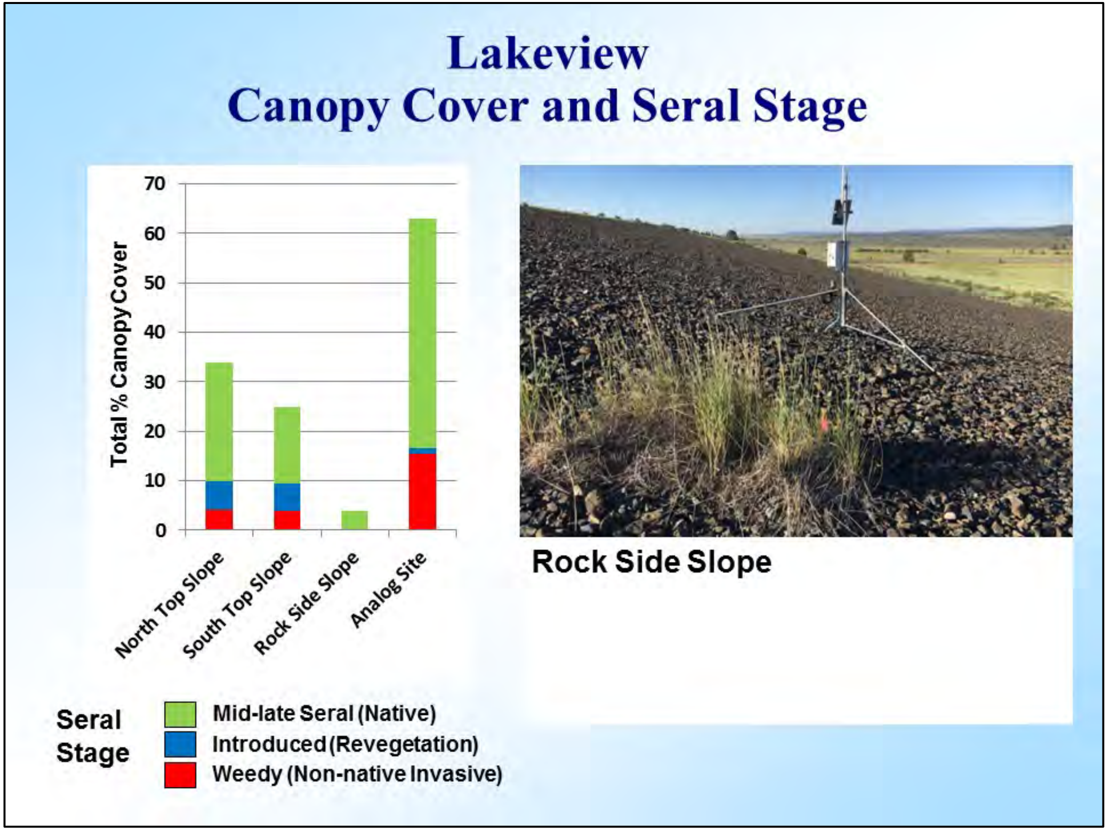
South Top Slope

Sheep fescue (Introduced revegetation)

Cheatgrass (Weedy non-native invasive)

Sandberg bluegrass (Native mid-late seral)

Antelope bitterbrush (Native mid-late seral)

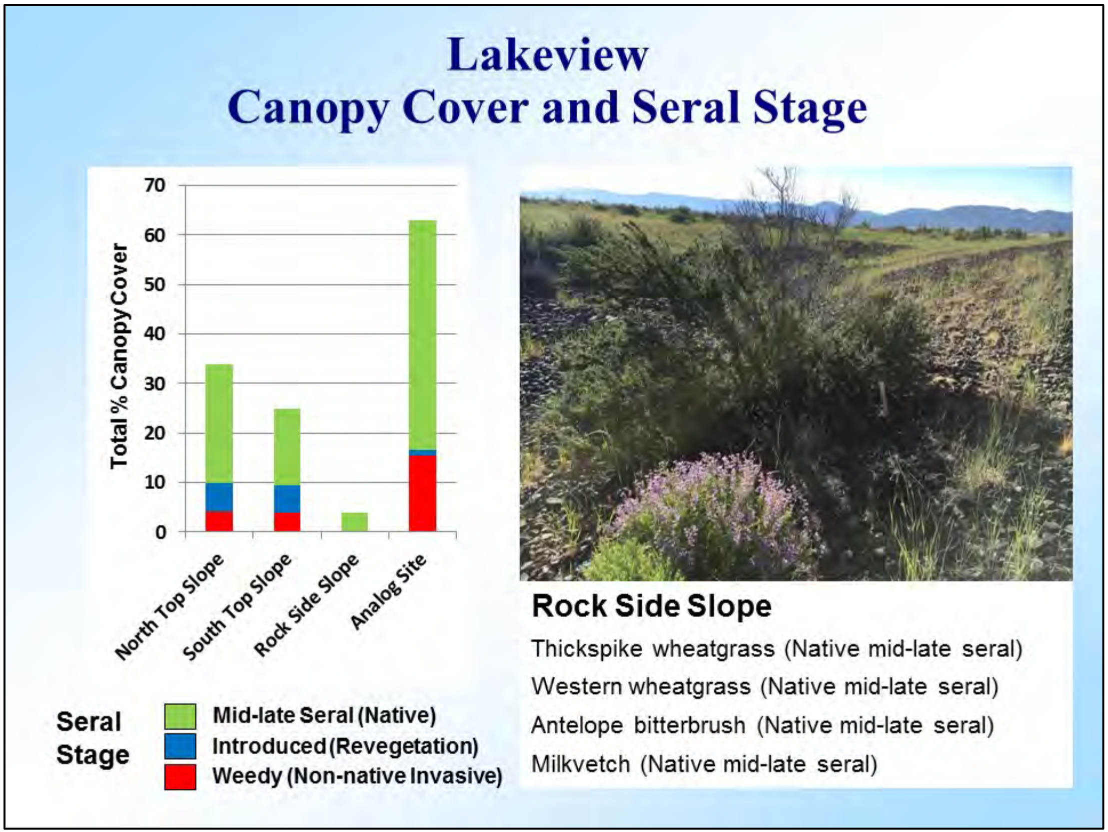


Lakeview
Canopy Cover and Seral Stage

Seral Stage

- 🟩 Mid-late Seral (Native)
- 🟦 Introduced (Revegetation)
- 🟥 Weedy (Non-native Invasive)

Rock Side Slope



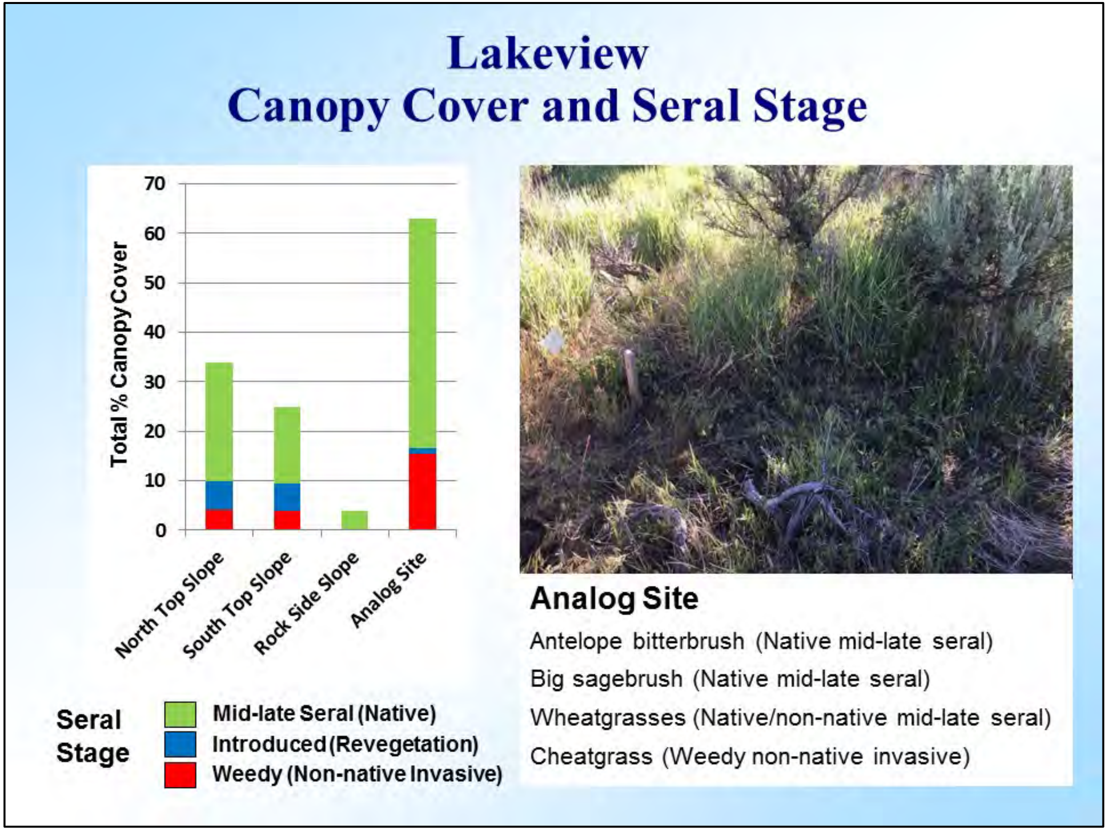
Lakeview
Canopy Cover and Seral Stage

Seral Stage

- 🟩 **Mid-late Seral (Native)**
- 🟦 **Introduced (Revegetation)**
- 🟥 **Weedy (Non-native Invasive)**

Rock Side Slope

Thickspike wheatgrass (Native mid-late seral)
Western wheatgrass (Native mid-late seral)
Antelope bitterbrush (Native mid-late seral)
Milkvetch (Native mid-late seral)



Lakeview
Canopy Cover and Seral Stage

Seral Stage

- 🟩 **Mid-late Seral (Native)**
- 🟦 **Introduced (Revegetation)**
- 🟥 **Weedy (Non-native Invasive)**

Analog Site

Antelope bitterbrush (Native mid-late seral)
Big sagebrush (Native mid-late seral)
Wheatgrasses (Native/non-native mid-late seral)
Cheatgrass (Weedy non-native invasive)

Preliminary Plant Ecology

Bluewater

- Main and Carbonate Disposal Cells (DCs): Early seral stages
- Acid DC: Revegetation successful, succession uncertain
- Radon Barrier and Desert Pavement Analog sites: Relatively undisturbed, late seral stage, good reference areas for potential natural vegetation (PNV)

Falls City

- Top slope: Managed for haying introduced invasive grasses, succession uncertain
- Analog site: Managed for grazing, poor PNV reference area

Preliminary Plant Ecology (cont.)

Shirley Basin South

- Cover terraces: Seeded with introduced and native forage grasses and forbs, grazed, succession uncertain
- Rock/soil slope: Mostly weedy species,early seral stage
- Wetland: Species indicate ephemeral saturation
- Analog site: Mid-late seral stage, moderately grazed

Lakeview

- Top slope: Mid seral stage north, south less developed
- Side slope: West side mostly bare, north side beginning to resemble top slope
- Analog site: Mid-late seral stage

All sites: Uncertainty in ecological succession projections given climate change, invasive species, and future land use

Presentation Topics

Part I

- Engineered Covers for Uranium Mill Tailings
- Horror Vacui (Mother Nature Abhors a Vacuum)
- Long-Term Surveillance and Maintenance Questions
- LM Strategic Plan
- Radon Barrier Study and LM's Long-Term Cover Performance Projects
- Summary

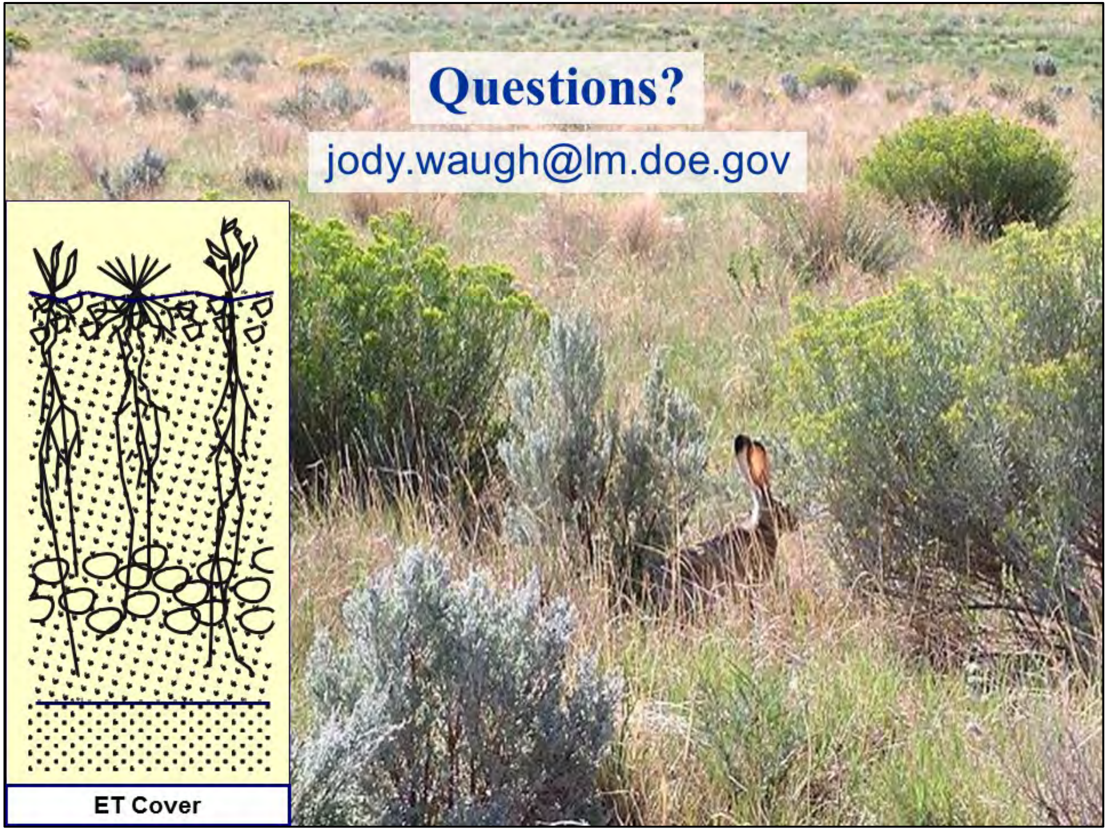
Part II

- Radon Barrier Study Objectives and Site Selection
- Test Conditions and Plant Ecology
- **Summary**

Summary

- Study sites were selected to represent the range of cover designs, climates, soils, and ecologies within the LM UMTRCA portfolio
- Selection of test conditions on covers favored high as-built radon flux, deep-rooted plants, soil-forming processes, and drier seasons (not average conditions)
- Analog sites were selected and evaluated for clues about long-term changes in cover ecology, soil morphology, and engineering properties
- Plant ecology, a driver of changes in soil morphology and engineering properties, is needed to select analog sites, interpret the stage and trajectory of succession, interpret effects of land management practices, and evaluate LTS&M options

Dinner in Floresville, Texas, April 25, 2016



Questions?

jody.waugh@lm.doe.gov

2.4.3 Question and Answer Session for: The Radon Barriers Project Objectives, Test Conditions, and Plant Ecology.

Question. Do these cover sites have permanent meteorological stations?
Reply. Yes, some do, but they have not been in place since the covers were built. Some were put in place to monitor soil moisture probes.

Question. Did the DOE/LM Monitoring Plan feed into your choice of the sites for the Radon Barriers Project?
Reply. Yes, to some degree. We considered certain LM sites that are currently monitored or that may be monitored in the future. But screening was primarily separate from LM monitoring. We looked at an NRC document that examined site parameters, especially radon flux, and used that as input [editor's note: this report is Arlt et al, 2011]. The primary input for site selection was a table of parameters that was put together by the project team. Other factors came into play such as timing for the field work relative to climate seasonality. Radon flux may be higher during dry seasons.

Question. First, are these studies trying to determine whether we need to do any active maintenance or what maintenance is needed? Second, over the longer term, how do you factor in other variables in the evolution process, such as fire and its impact on ecology and ET?
Reply. On the second part of the question; in some ecosystems fire rejuvenates vegetation by returning nutrients to the soil and increasing productivity. It may return the vegetation to an earlier successional stage. At Monticello, where we now have a late successional vegetation, the ET cover functioned well when only pioneer species were present before the late successional vegetation became established. So evapotranspiration has been adequate over the entire 18 years of plant succession. At one point sagebrush populations on the cover were reduced due to voles eating roots, but we still had a favorable water balance. Regarding the first part of the question; all of these studies, the earlier LM work and our current Radon Barriers Project, are intended to glean information about how well these covers are performing. This will tell us what we should be monitoring during inspections and what we can do to improve sustainability of the covers. All of these studies will inform future management of these sites.

Question. Do you have recommendations for sites coming into the portfolio that provide an opportunity at time equals zero? What do you recommend to integrate into annual monitoring as opposed to what was done at sites 20 or 30 years ago? What can we build on from the onset of monitoring?
Reply. DOE/LM is both a land manager as well as a remedy manager. In Texas we have a site called Ray Point which is a Title II site that will be transitioned. This could present an opportunity to do landscape management. Everything around that site is hayed. So we have an island that could be managed as habitat for pollinators. It might be an area where woody plants like honey mesquite and black acacia could be allowed to establish. We have proposed allowing these plants to establish in test plots, and then monitoring soil moisture profiles and using RAECOM to estimate radon fluxes. This monitoring data would be compared to areas on the cover where these woody plants are not allowed to grow. So this is one example of how we might manage a site differently and monitor to see if this is a favorable management strategy.

Question. We talked about moisture profiles and how ecological succession will impact soil structures and permeability or ET. There is a tradeoff when soil structure is developed with increased percolation or suitability for plants to grow, creating evapotransporative demand, but this leads to increased radon diffusion.

Reply. This study will factor into weighing the pros and cons of these natural processes acting on covers. We need to look at this site by site. For example, does the radon barrier have adequate storage to act as an ET cover? Do we continue to manage these covers as low permeability covers as they were designed, even though permeability and saturated conductivity have increased, or do we go to other management strategies? At some point we need to screen sites. For example, at sites where groundwater contamination is a problem, we may be more interested in limiting percolation. At other sites we may want to start looking at radon from a risk standpoint rather than using the 20 pCi/m2/s criterion? So there may be opportunities for monitoring on a site by site basis.

Question. What is your opinion on grazing these sites? Would it be better to let the grazed sites go to more native vegetation?
Reply. Managed grazing can increase productivity and increase ET. That can be part of a management tool kit. However, the sites currently being hayed are not necessarily managed for maximum ET. It is just a way to manage vegetation on the site. Land use and vegetation management need to be considered from the perspective of long-term cover performance.

2.5 Cover Soil Development and Changes in Engineering Properties

Presented by Craig Benson
Dean of Engineering, University of Virginia

2.5.1 Abstract

Earthen covers for waste disposal facilities often are constructed under conditions that are in disequilibrium with the surrounding environment. Atmospheric interactions with the cover that cause freeze-thaw and wet-dry cycles induce structural development in cover soils, resulting in substantial changes in the engineering properties until they reach equilibrium with the environment. Biota intrusion also induces structural development and alterations in engineering properties. Understanding these changes in the engineering properties of cover soils and their transition to an equilibrium hydrologic condition is critical to predicting the long-term efficacy of final covers to control the ingress of meteoric water and the egress of gases within the waste mass.

Identifying changes in the hydraulic properties of earthen covers, and relating these changes to the structure in the cover profile, was an objective of this study. Understanding how these changes are influenced by depth below ground surface was also an objective, particularly identifying a limiting depth (if it exists) beyond which structure does not develop and the hydraulic properties do not change. The findings from this study build on findings from the Alternative Cover Assessment Program (ACAP), in which numerous final cover test sections were constructed, monitored, and ultimately exhumed to determine whether the hydraulic properties of the cover soils (or geosynthetics) had changed. The ACAP study showed that saturated hydraulic conductivity (K_s) of the cover soils generally increased, sometimes by several orders of magnitude, and ultimately reached an equilibrium state between 1×10^{-7} and 1×10^{-5} m/s independent of the initial condition or the climatic setting. Changes in water retention characteristics, defined by the soil-water characteristic curve SWCC), were also observed. Formation of soil structure caused the porosity (i.e., saturated volumetric water content) and van Genuchten's α parameter to increase, and the n parameter to decrease. These changes in the SWCC generally correspond to a broader distribution of pore sizes, the presence of large pores from structural development, and lower water retention. The covers examined in the ACAP study were much younger and generally thinner than those used at UMTRCA sites. The ACAP study did not include measurements of gas flux.

This study evaluated covers at four disposal facilities for uranium mill tailings. The covers were located in different regions of the United States with widely varying climates: Falls City, TX; Bluewater, NM; Shirley Basin South, WY; and Lakeview, OR. The covers at these sites had been in service for 17 to 22 years at the time of this study and were constructed in response to UMTRCA. The covers employed different designs, were constructed with different materials, were located in widely varying climates, and had very different vegetative communities [editor's note: see Section 2.4, pp. 2-62 to 2-81]. Samples were collected at various depths from the cover at each site to evaluate changes in hydraulic properties. Geomorphological surveys were conducted to characterize the structure that developed in the cover profile [editor's note: see Section 2.8, pp.2-144]. Sampling and geomorphological characterization were also conducted at analog sites adjacent to each facility to understand the likely very long-term equilibrium of the cover soils. This presentation describes data from three sites (Falls City, Bluewater, and Shirley Basin South). Data from the Lakeview site were not available for dissemination at the time of the workshop.

Hydraulic properties of the cover soils at depths shallower than 1.5 meters below ground surface generally were consistent with ranges of hydraulic properties recommended in NUREG/CR-7028. At deeper depths, the changes in hydraulic properties were more modest. At the analog sites, hydraulic properties of the soils were comparable to the upper bounds reported in NUREG/CR-7028, regardless of depth, suggesting that the depth dependence observed in the covers represented an intermediate condition rather than a long-term condition and that the upper limits in NUREG/CR-7028 were representative of the long-term equilibrium state.

The Shirley Basin South site was an exception. At this site, the hydraulic properties remained virtually unchanged at all but the shallowest depths. The cover soils were very hard and had very little structure associated with pedogenesis, except near the surface. The cover at Shirley Basin South was constructed with natural montmorillonite-rich clays (bentonites) that resist structural change, at least in the near-term (17-year) service life of the cover at the Shirley Basin South site at the time of this study.

2.5.2 Presentation

Cover Soil Development and Changes in Engineering Properties

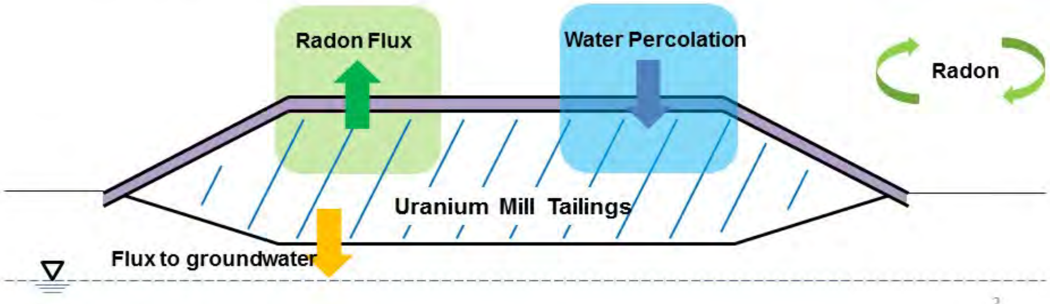
Craig H. Benson, PhD, PE, NAE
University of Virginia/CRESP
chbenson@virginia.edu

25 July 2018

Uranium Mill Tailings Radiation Control Act (UMTRCA 1978)

- UMTRCA requirements include:
  - Limit radon flux to atmosphere
  - Limit water percolation into waste
  - Limit groundwater contamination

> 1000 yr



Typical Disposal Site

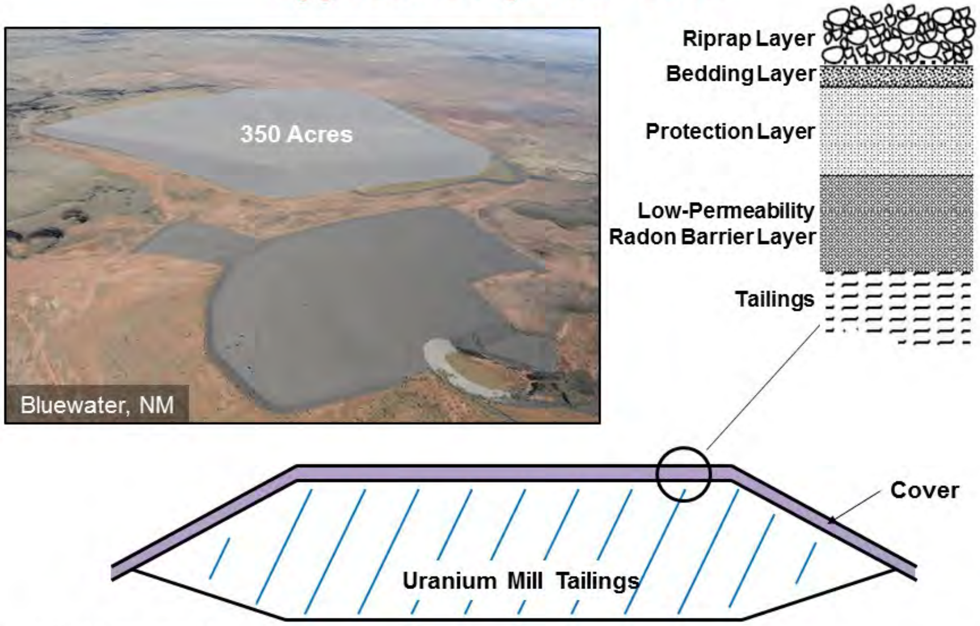
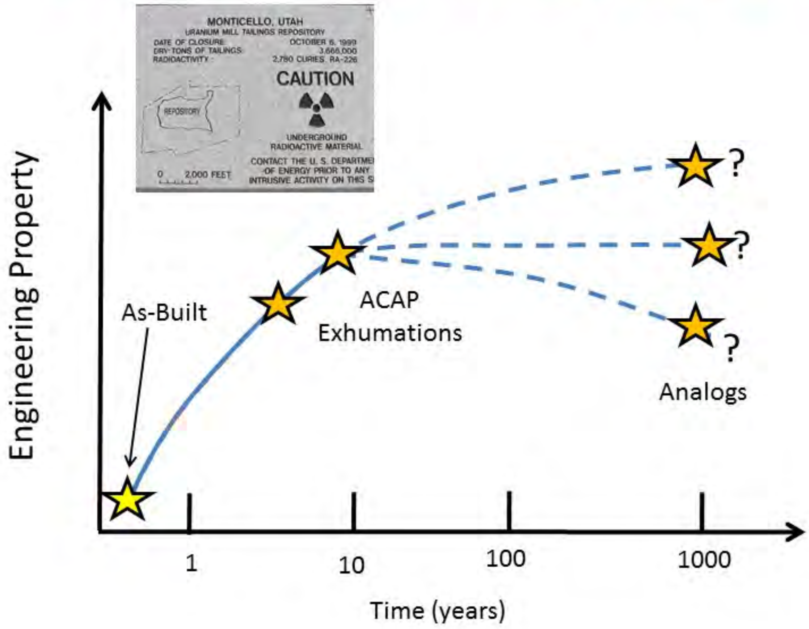


Photo: The Center for Land Use Interpretation

Challenges – Predicting the Future



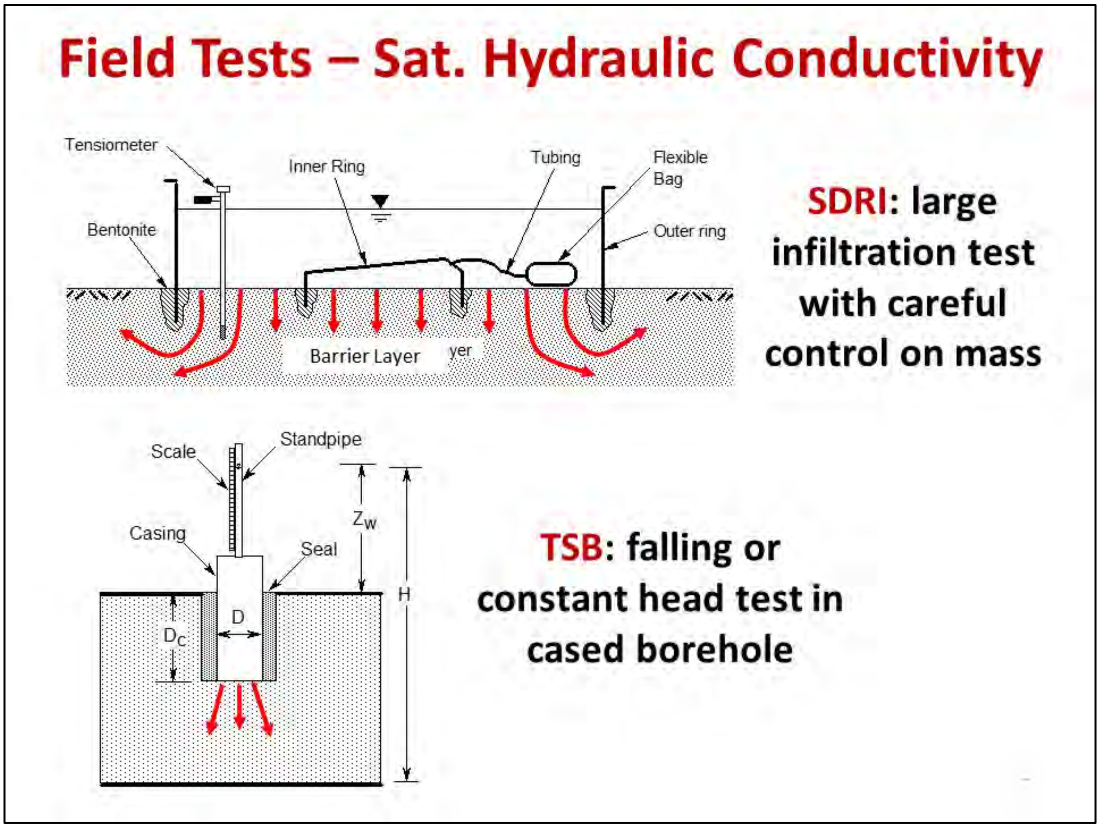
MONTICELLO, UTAH
URANIUM MILL TAILINGS REPOSITORY
DATE OF CLOSURE: OCTOBER 6, 1999
DRY-TONS OF TAILINGS: 3,666,000
RADIOACTIVITY: 2,780 CURIES, RA-226
CAUTION
UNDERGROUND
RADIOACTIVE MATERIAL
CONTACT THE U. S. DEPARTME
OF ENERGY PRIOR TO ANY
INTRUSIVE ACTIVITY ON THIS S

ACAP Exhumation Study

- **Elements**
  - Field testing of hydraulic properties of cover materials
  - Collect large-scale undisturbed samples for lab analysis
  - Collect geosynthetic materials (geomembranes, geocomposite drainage materials, GCLs) for lab analysis
  - Geomorphological surveys
- **Objectives**
  - Identify changes in engineering properties
  - Relate changes in properties to structural development
  - Recommend monitoring strategies to detect changes in performance

Barrier System Elements

- Earthen components
  - Store-and-release layers: saturated and unsaturated hydraulic properties
  - Hydraulic barrier layers (clays and geosynthetic clay liners, GCLs): saturated hydraulic conductivity
- Geosynthetic components
  - Geocomposite drainage layers: transmissivity, permittivity
  - Geomembranes: integrity
  - Geosynthetic clay liners: sat. hydraulic conductivity



Field Tests – Sat. Hydraulic Conductivity

SDRI: large infiltration test with careful control on mass

TSB: falling or constant head test in cased borehole

SDRI Being Installed – Iowa Site

SDRI Being Operated – Iowa Site

TSB Being Installed and Operated – Utah Site

Collecting Block Sample

Laboratory Testing – Saturated and Unsaturated Hydraulic Properties

- Collect large-scale (400 mm diameter) undisturbed samples from field for characterizing hydraulic properties.
- Saturated hydraulic conductivity (K_s) measured at different scales.
- Soil water characteristic curve (SWCC) measured at different scales (water content vs. water potential).

Preparing Blocks for Hydraulic Properties Tests

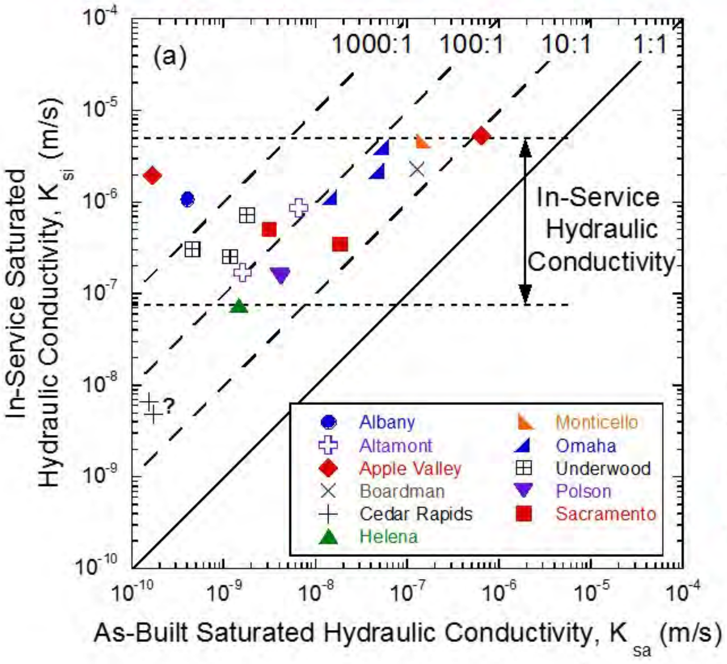
Block sample

Trimming roughly to take ring-off

Placing the block sample

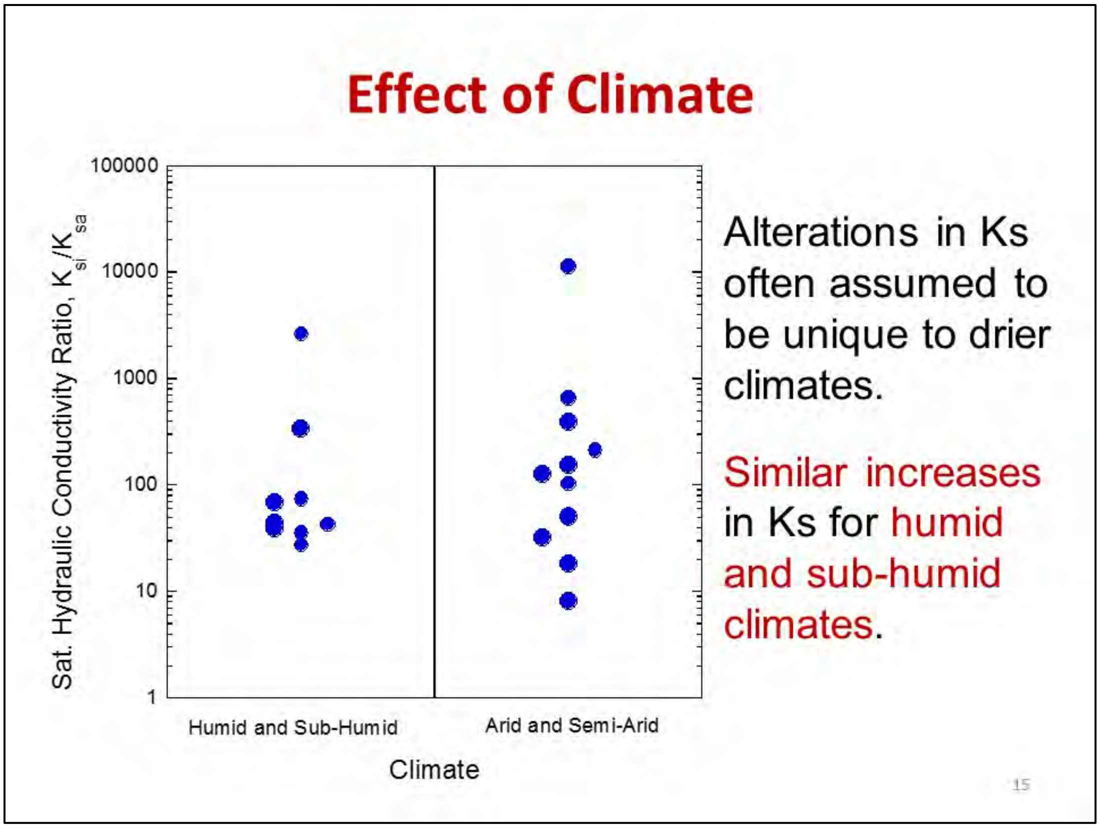
Trimming to the pedestal size

Changes in Sat. Hydraulic Conductivity



If *no* change, data would scatter around 1:1 line

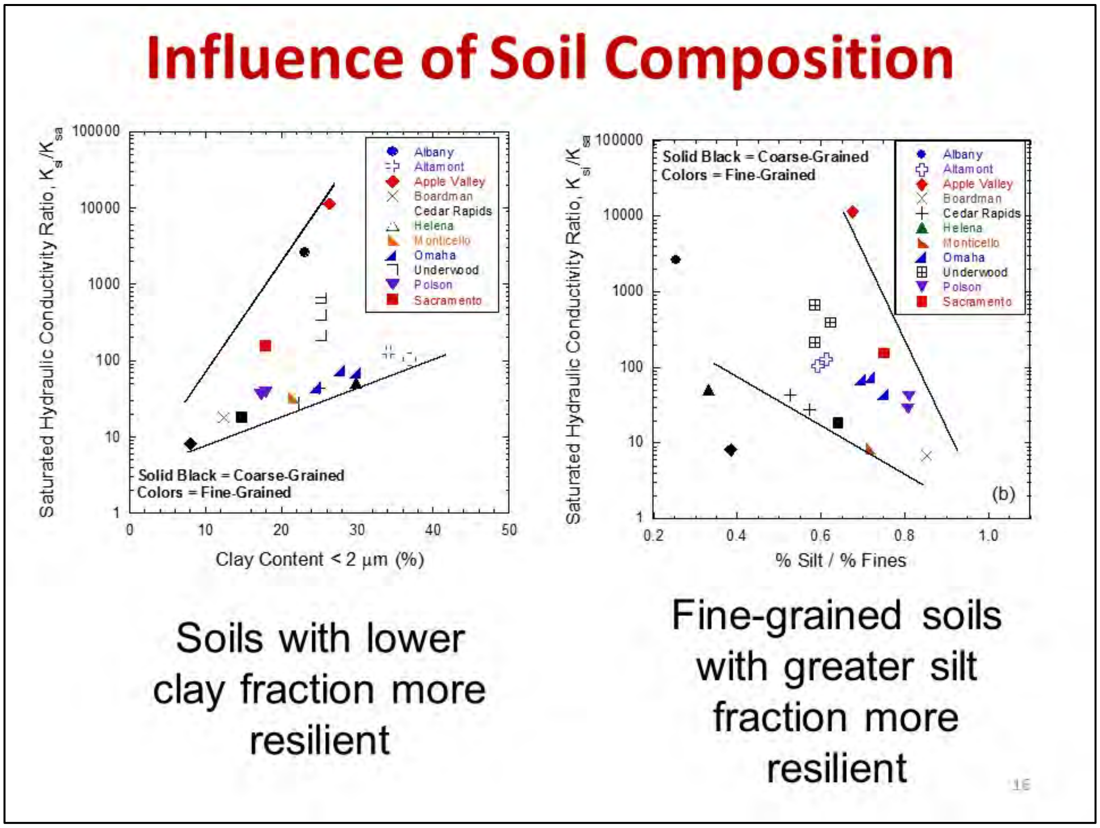
Data coalesce into band with K_s = 10^{-7} - 10^{-5} cm/s independent of initial K_s



Effect of Climate

Alterations in Ks often assumed to be unique to drier climates.

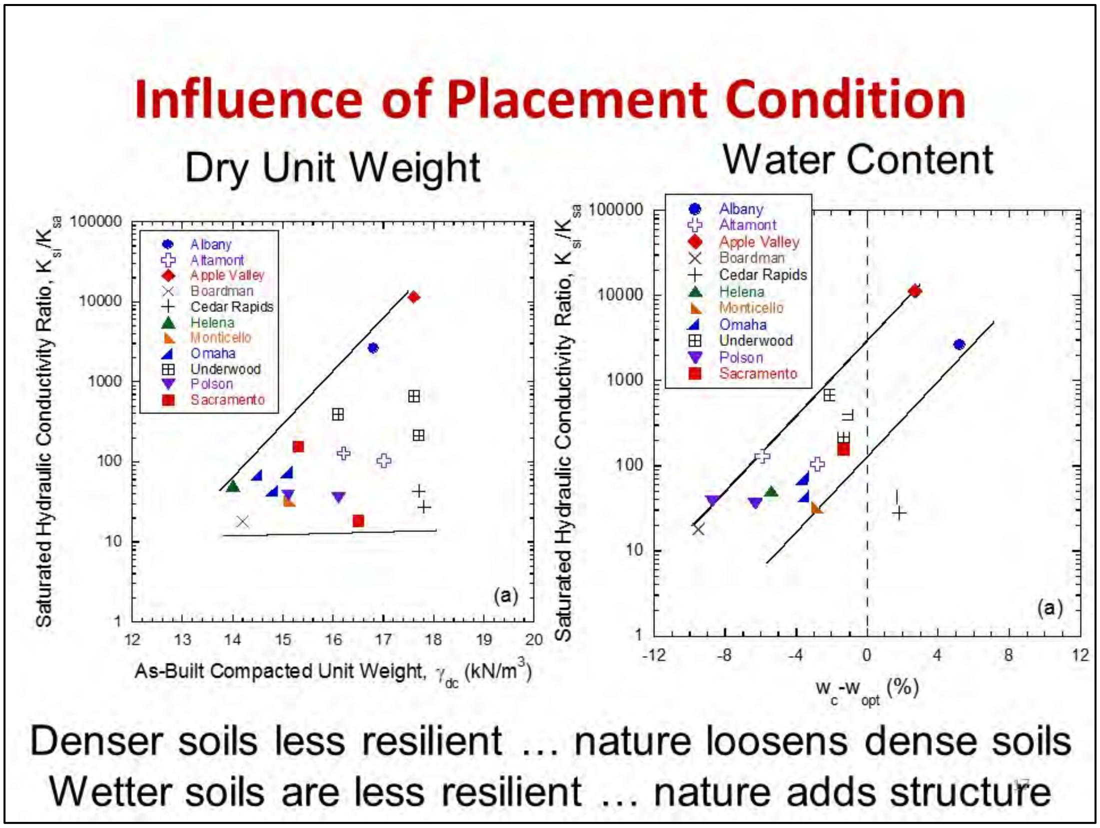
Similar increases in Ks for humid and sub-humid climates.



Influence of Soil Composition

Soils with lower clay fraction more resilient

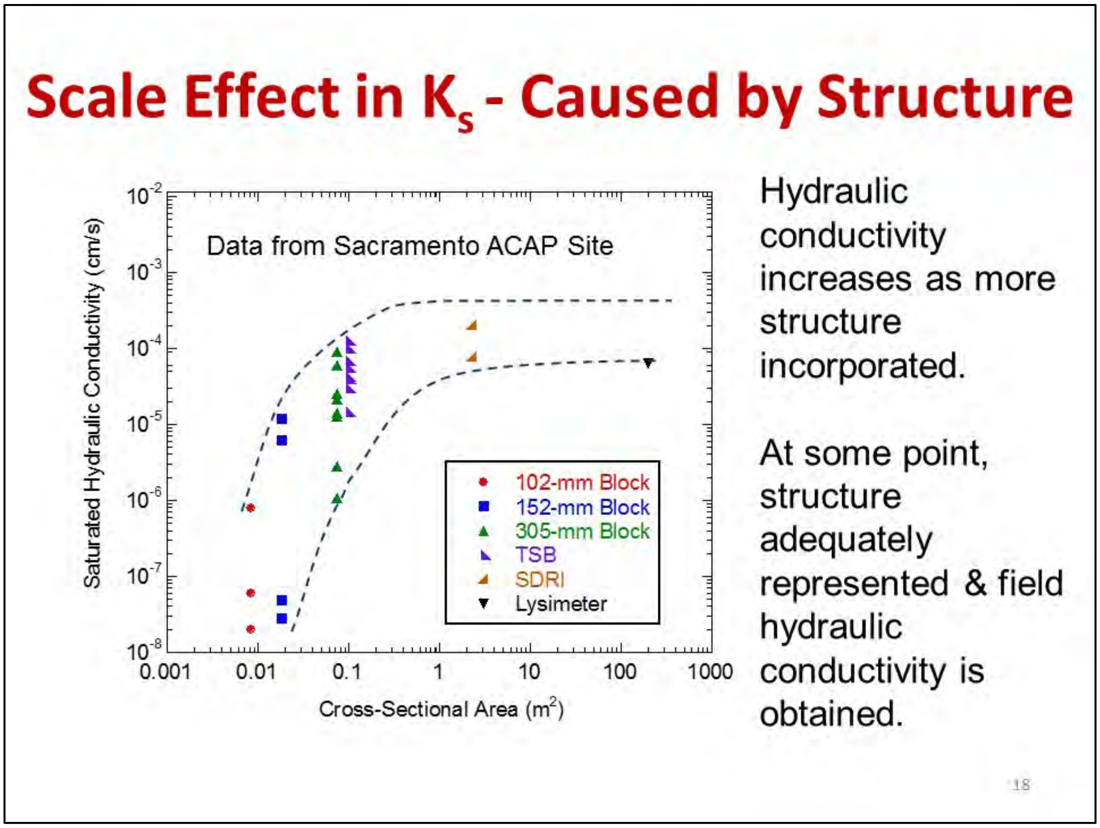
Fine-grained soils with greater silt fraction more resilient



Influence of Placement Condition

Denser soils less resilient … nature loosens dense soils

Wetter soils are less resilient … nature adds structure

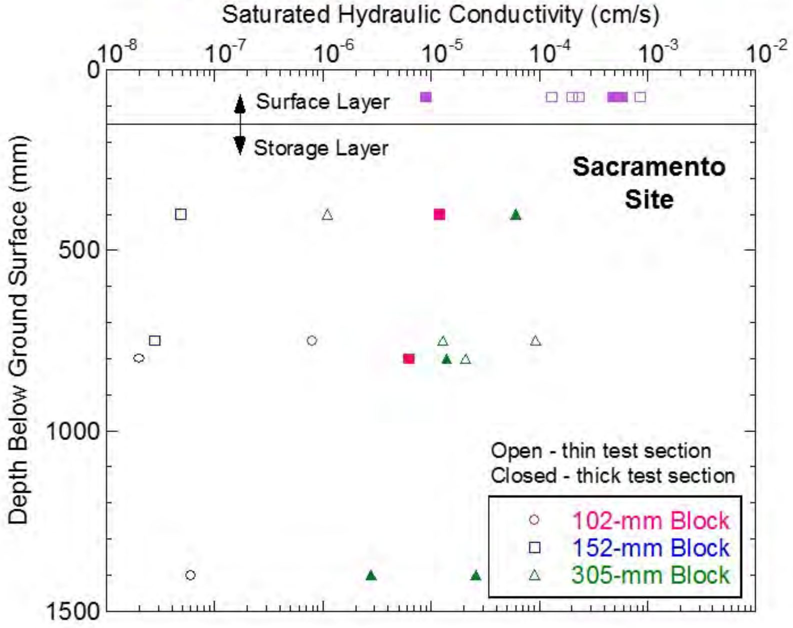


Scale Effect in K_s - Caused by Structure

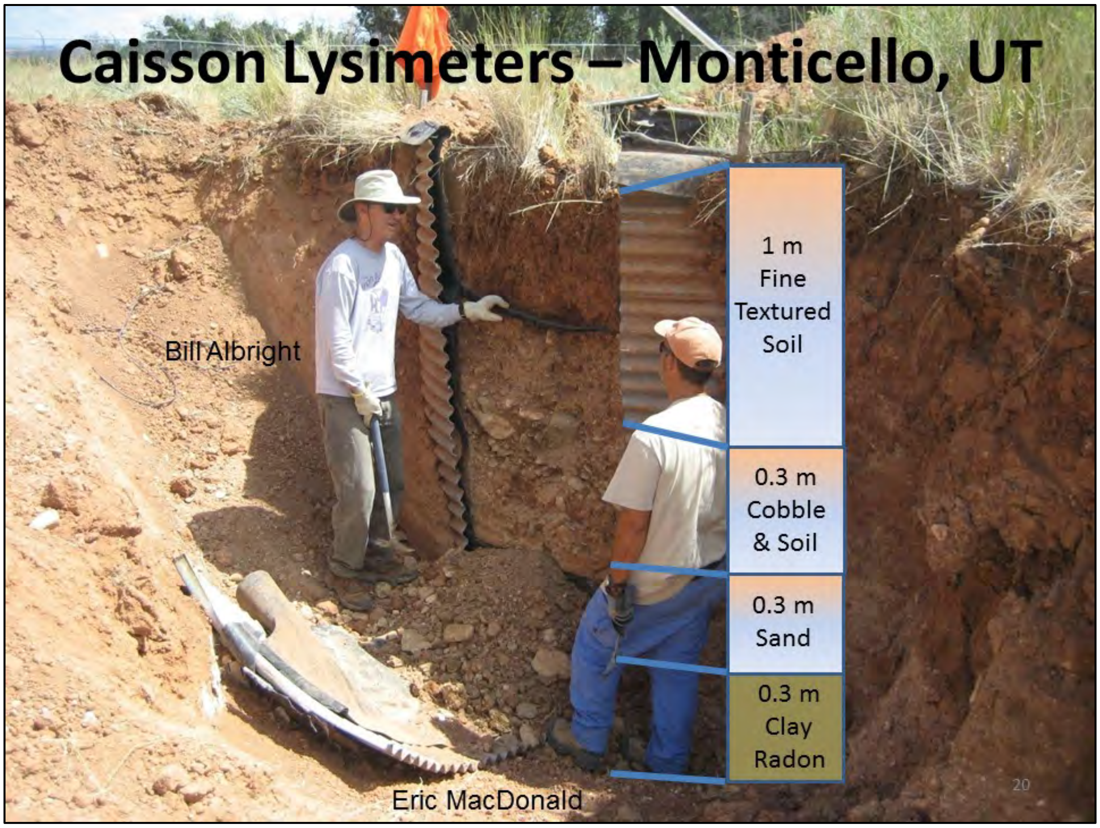
Hydraulic conductivity increases as more structure incorporated.

At some point, structure adequately represented & field hydraulic conductivity is obtained.

Effect of Depth and Scale on Saturated Hydraulic Conductivity



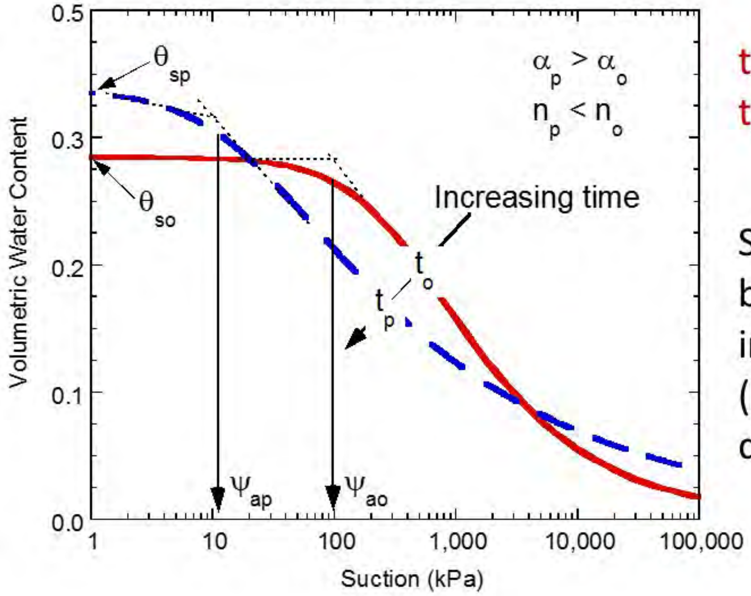
Caisson Lysimeters – Monticello, UT



Radon Barrier – Monticello, UT

Roots seek out water in wet fine-grained soils, e.g., clay radon barriers, even at 1.6-1.9 m depth

Soil-Water Characteristic Curves (SWCC)

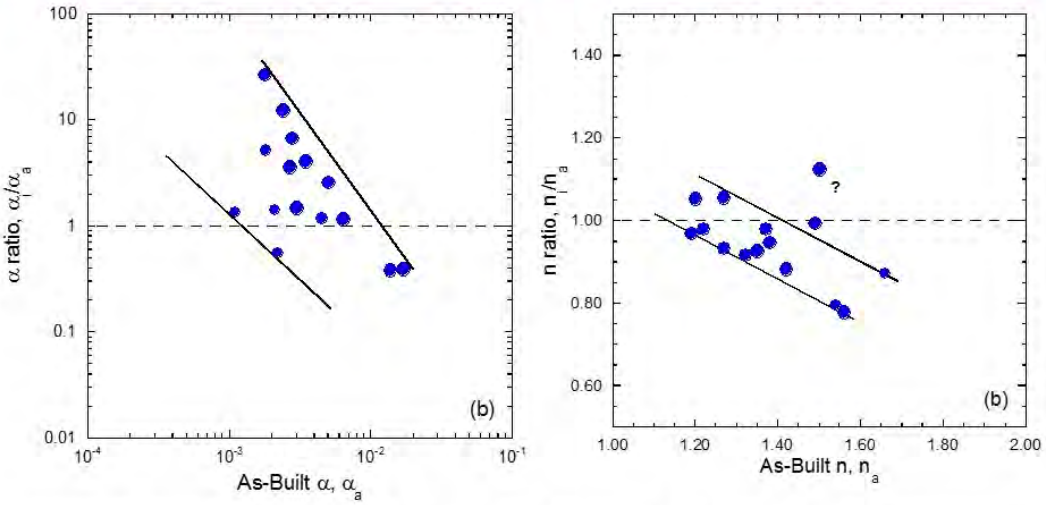


t_o: initial condition

t_p: after pedogenesis

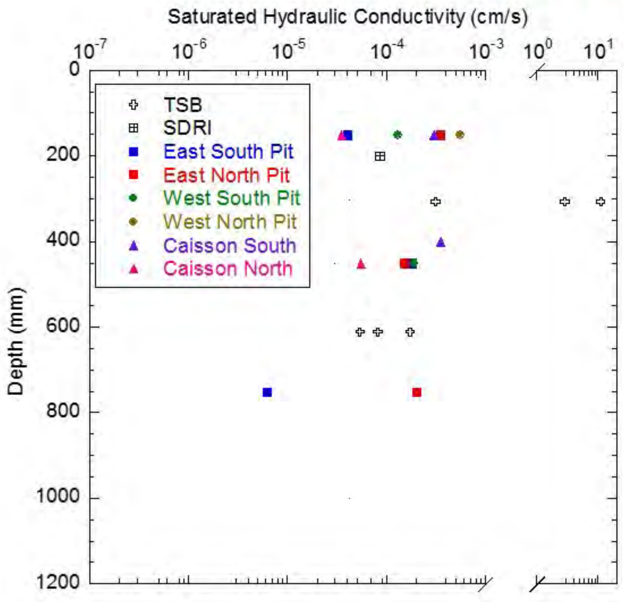
Structure formed by pedogenesis increases θ_s and α (lower ψ_a); decreases n.

Changes to the SWCC Due to Structure



Formation of larger pores in soil structure results in lower air entry pressure (higher α) and broader pore size distribution (lower n) … net result is lower water retention. Looser soils (higher initial a and lower initial n) resilient.

Effect of Depth on Sat. Hydraulic Conductivity - Monticello

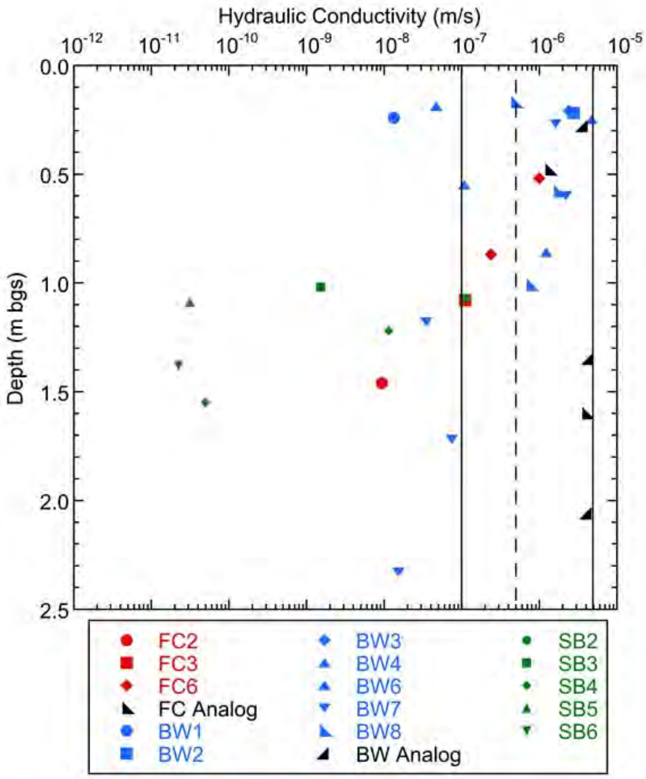


Little to no depth dependence.

Similar hydraulic conductivities with all large scale methods.

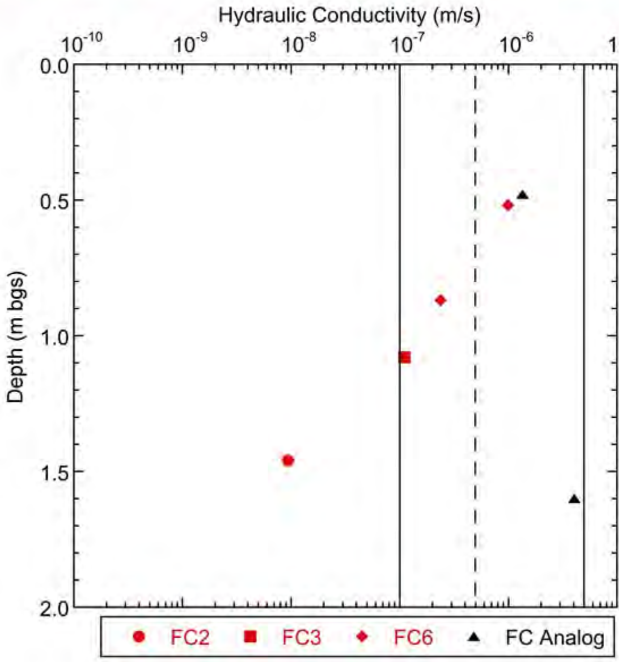
No discernable effect of location.

Some very high hydraulic conductivities near surface with BH tests.

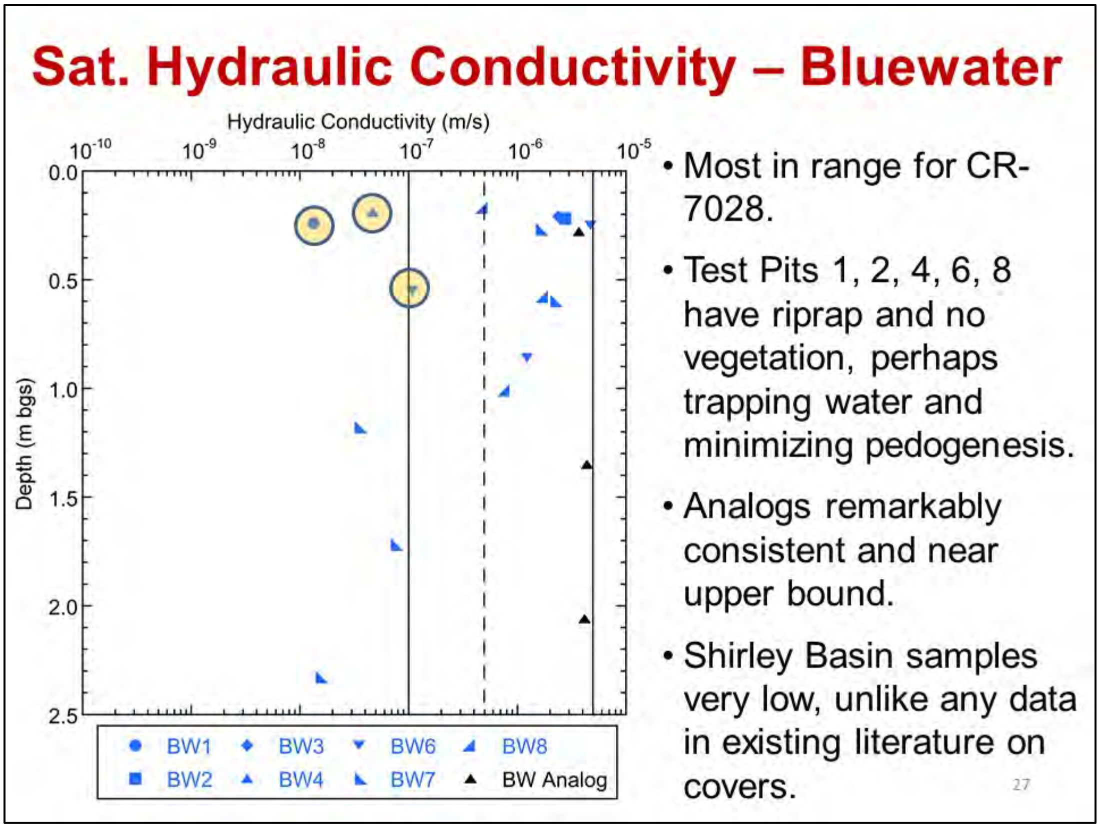


- Substantial portion of data consistent with bounds and recommendations in NUREG CR-7028
- Analogs at high end of CR-7028 bounds.
- Analogs remarkably consistent.
- Shirley Basin samples very low, unlike any data in existing literature on covers.

Sat. Hydraulic Conductivity – Falls City

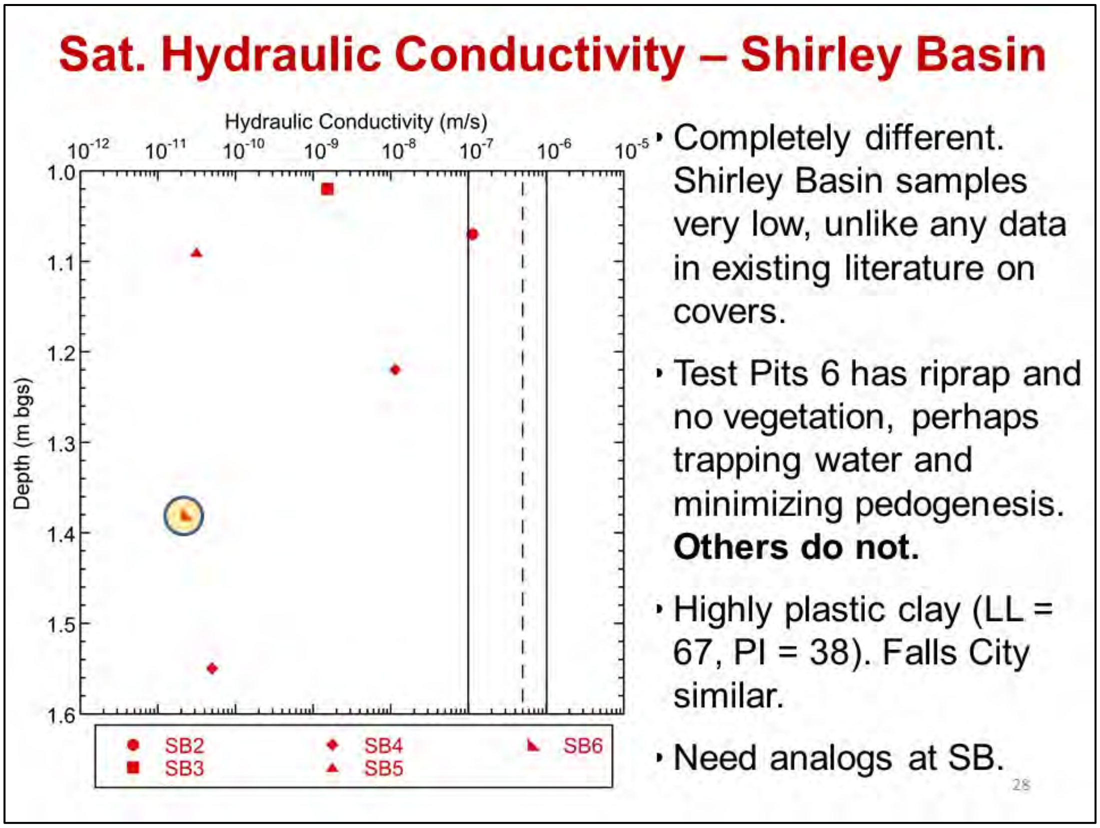


- All but one sample (FC2) in range from CR-7028.
- FC2 is in area **without** riprap and has vegetation. Exposed to natural pedogenesis.



Sat. Hydraulic Conductivity – Bluewater

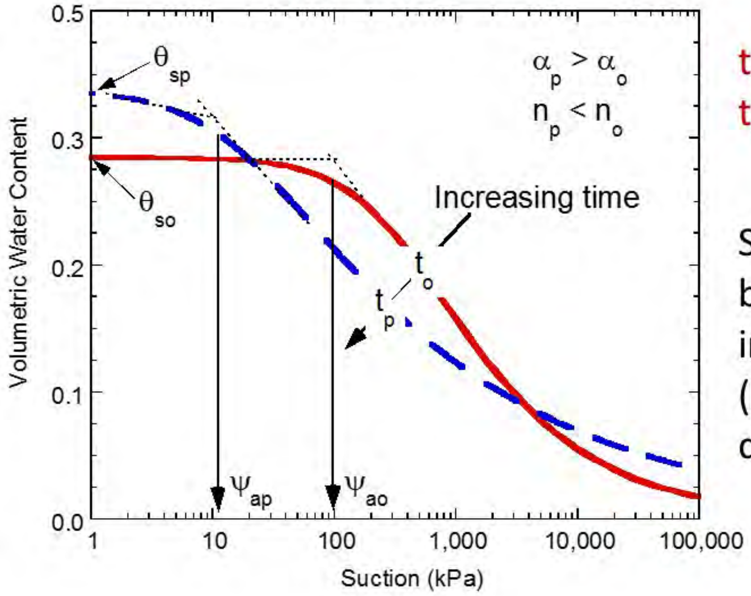
- Most in range for CR-7028.
- Test Pits 1, 2, 4, 6, 8 have riprap and no vegetation, perhaps trapping water and minimizing pedogenesis.
- Analogs remarkably consistent and near upper bound.
- Shirley Basin samples very low, unlike any data in existing literature on covers.



Sat. Hydraulic Conductivity – Shirley Basin

- Completely different. Shirley Basin samples very low, unlike any data in existing literature on covers.
- Test Pits 6 has riprap and no vegetation, perhaps trapping water and minimizing pedogenesis. **Others do not.**
- Highly plastic clay (LL = 67, PI = 38). Falls City similar.
- Need analogs at SB.

Soil-Water Characteristic Curves (SWCC)

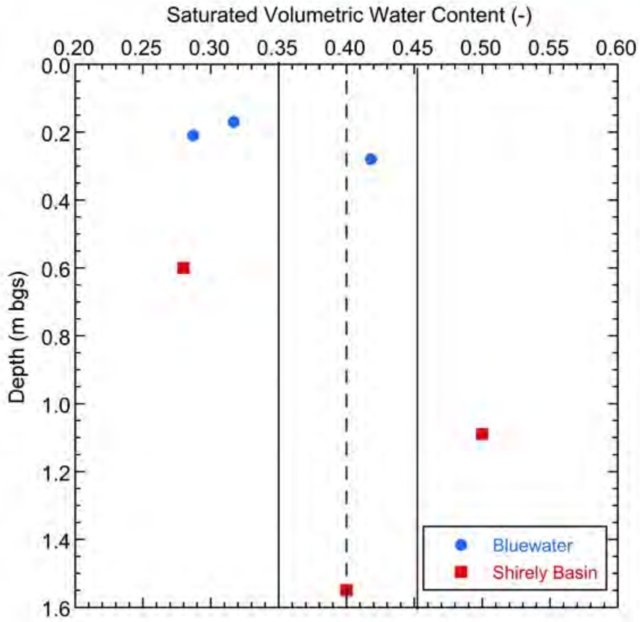


t_o: initial condition

t_p: after pedogenesis

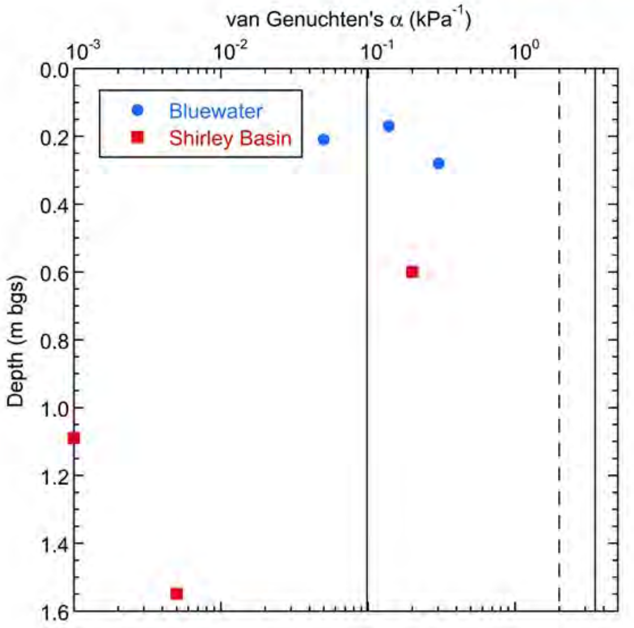
Structure formed by pedogenesis increases θ_s and α (lower ψ_a); decreases n.

SWCC Properties - θ_s



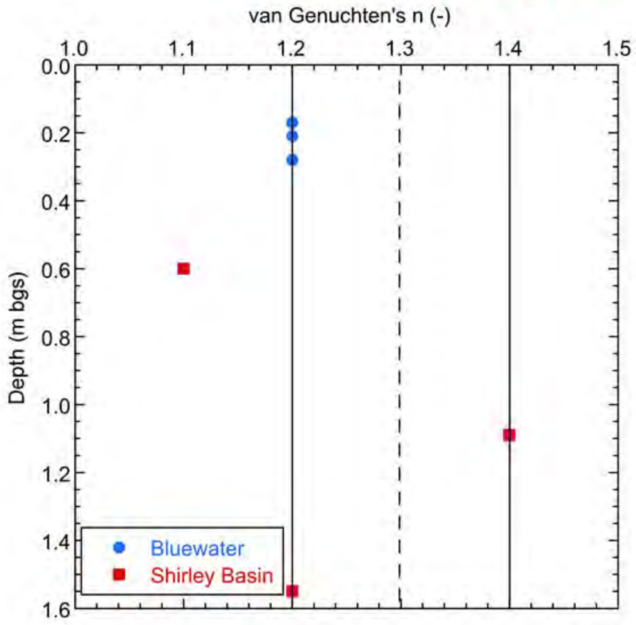
- Comparable to bounds in NUREG CR-7028.
- Depth dependence?
- Sparse data set

SWCC Properties - α



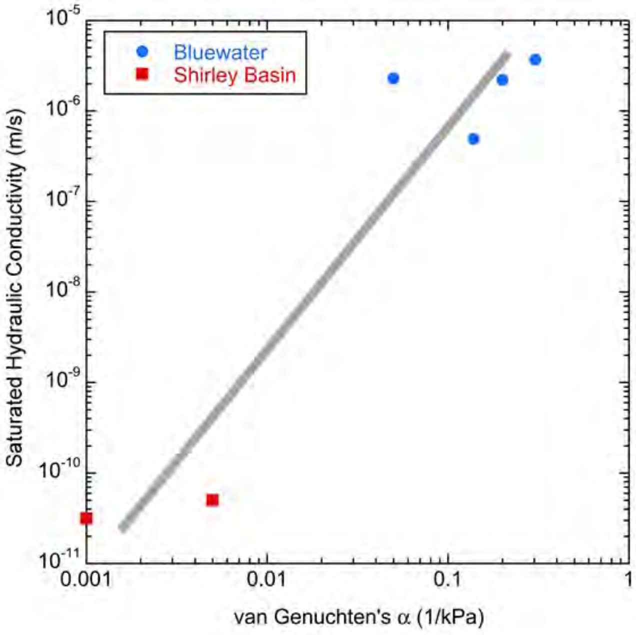
- Near lower bound in NUREG CR-7028 near surface.
- Much lower at depth for Shirley Basin, consistent with very low saturated hydraulic conductivity.

SWCC Properties - n



- Comparable to bounds in NUREG CR-7028.
- No depth dependence.

K_s – α Relationship



- Consistent with theory and correlation in Benson and Gurdal (2013).
- Sparse.

Lessons Learned

- Nature alters engineered condition in short period: dense soils become looser and unstructured soils gain structure.
- Hydraulic properties of engineered fine-textured soils become similar over time, regardless of initial condition or climate. Use these longer term properties for design and modeling.
- Recognize that soil properties will change and construct covers to mimic the longer term condition.
- Chose soils with lower clay content if possible to ensure greater resiliency.

2.5.3 Question and Answer Session for: Cover Soil Development and Changes in Engineering Properties.

Question. The barrier material at Shirley Basin South is a montmorillonitic clay. All your past data have shown that this type of material has high swelling capacity and can shrink a lot; what is so special about this material that gives it the very low saturated conductivities that you measured?
Reply. This kind of cuts across the grain; a plastic clay that is less permeable should shrink the most. This material is very plastic. When we have looked at bentonitic clays in earlier studies, they were in thin layers, such as in geosynthetic liners that had relatively low stresses. This is a deep system. It has a lot of ion exchange capacity. I'd be interested to see from Morgan Williams's work if this clay is sodic, and I suspect that it is highly sodic (that is, has a lot of sodium in it). There may be no mechanism in the field to exchange ions that would change its structure.

Question. These clays are potentially more vulnerable if there is a change in a characteristic such as pH that could change the clay's double layer.
Reply. Bentonites are very sensitive to chemistry, which controls the swelling and water that binds to the clay. The question is whether there is a mechanism for that chemical change to occur in that environment. If so, you need to account for that. The analog sites suggest, from what we are seeing, and we will learn more, that this sodic bentonite is persistent. There really is no ion exchange mechanism to drive the process where the addition of calcium or magnesium would alter the clay structure and reduce its swelling capacity. We see this with sodium bentonite geosynthetic clay liner layers when they are put into an environment with calcium or magnesium present, which, within a few years, replace the sodium and completely alter its properties. There does not seem to be a mechanism here for that to happen.

Question. You could have a riprap layer that could be a source of calcium.
Reply. Yes, if you have a surface protection barrier that is a source of calcium or magnesium that is eluted over millennia and infiltrates down in a salt front, that could change properties over time.

Question. How about aeolian dust?
Reply. That might also have the same effect.

Question. We might need to think about this a bit. At Shirley Basin South, there were actually gypsum spears distributed throughout the clay. Gypsum is calcium sulfate. There must be a lot of calcium and sulfate present to allow gypsum to precipitate or even to preserve these crystals. Maybe that is what leads to the properties of the system; it is already calcic.
Question. Another observation is that the pH was in the 3–4 range.
Reply. Yes, for spears to grow, you have essentially saturated chemical conditions.

Question. As we look at these sites, are we getting properties that resemble the natural original conditions?
Reply. That is what our analog sites are meant to tell us. The properties of the analog sites are meant to represent those natural conditions that are nearby and in the same material. They suggest that our engineering properties are trending toward those natural conditions. In retrospect, when we did our earlier studies, it would have been great to have done analog studies at every site to gather that type of information on the long-term end state. We are approaching that in our data.

Question. These cases have no synthetic layers, but how would a synthetic layer above a radon barrier change pedogenesis and the time frame?
Reply. That is an important question. These are earthen systems. At Monticello, there is a geomembrane above the radon barrier. It was not put in for radon control, but that membrane has resulted in important controls on water movement up and down and on water pressure in the radon barrier. If a plant come in and puts roots down, it begins to pull water. That changes pore water pressure, which creates stress, which in turn creates cracks.

Question. Are seams in geomembranes welded?
Reply. Yes, they are welded. There are two techniques: extrusion welding or fusion welding. One is like metal welding using a heat gun and a rod; you are adding material. The other uses clamps to press the two pieces together and applies heat and pressure. The former case provides a thicker bond and longer antioxidant depletion times. It is harder to tell with the fusion weld how good the seal is.

Question. Can you compare methods to measure hydraulic conductivity when they built these covers versus the methods used today? I am curious whether there may be a bias between the methods.
Reply. All ACAP data that I showed earlier are about 10 years old and used essentially the same method used today. A group of us developed these methods over a 30-year period. We have not looked at hydrologic data from the early sites. When they built the Title I sites, they did not measure hydrologic properties of the radon barrier because the early UMTRCA criteria were concerned only with radon. Only later did hydraulic conductivity come as a criterion. Even if measurements had been made back then, those measurements would have been pretty lousy. Back in the 1980s and late 1970s, our measurement techniques were not very good. So we have not been able to do an as-built versus recent hydraulic conductivity comparison. We have compared as-built versus recent radon fluxes. Our more recent studies with lysimeters at Cheney, Monticello, and the ACAP sites all use state-of-the-art methods.

Question. What do you recommend for measurements after these covers are built?
Reply. We collect data during construction to demonstrate that what we have built is what was designed. Therefore, hydraulic properties are generally the primary ones. For radon barriers, you would measure radon fluxes and get moisture saturation profiles. The testing methods are really important. Many methods are used for construction quality control, but generally the samples are from small, thin, tubes that really don't mean very much. You need larger samples for cover systems.

Question. You said you need 300–400-millimeter-diameter samples for hydraulic conductivity because of scale issues. Doesn't that depend on the features and processes of the system? If you have a sample with a gopher hole or a tap root that will make a difference, so wouldn't you need to look at correlation length of the system? Maybe 300 to 400 millimeters is a good rule of thumb, but it can be more complicated.
Reply. Yes, vastly more complicated. The size recommendation is very empirical. We measured properties at different sample sizes, made a graph of property versus size, and looked for changes. It is very much an engineering approach. It's a rule of thumb. In essence, we need to capture the network of pores that control flow in the field. Until the sample is big enough to get that representative network of pores, you will underestimate saturated hydraulic conductivity and bias unsaturated flow as well. A sample of 300 millimeters is pretty good; it works most of the time. [Editor's note: see slide 18 in Section 2.5.2, page 2-96.]

Question. But for construction, smaller samples can be just fine. The samples are small, but they can be representative.
Reply. That can be right; it depends. If you write good specifications for liners that are compacted and you have taken all structure out, then measurements of hydraulic conductivity and density can be fine. Partly what is shaping my thinking on this is that if we are going to build to represent the long-term conditions, we will not be compacting to a high density. Then we will need larger samples.

Question. For construction quality control, small samples can be fine, but, yes, if you excavate like you have in this project, for longer term properties then you probably need larger samples.
Reply. Certainly, for longer term properties, you need larger samples.
Comment. Something that we have observed, and Morgan Williams will talk about this later for Falls City, is that structure is sometime retained from the original borrow site material. So when the cover is being built and compaction criteria are met, it is still possible for the material to retain structure so that there is macropore flow to begin with. Then you need larger samples to capture that.
Reply. We see that in covers where original structure is present. For liners, we put a lot of energy into clod destruction and chopping everything up so that we remove all of that structure. However, that is not the case in these historic covers especially. They were being built fast.

Question. You have given us information on how systems change with time. I am more interested in performance. How do you see dynamics change from the top down? Do you see wetting fronts going further into the protective layer or is there a dampening effect?
Reply. Your question is how does percolation effect performance? Is moisture getting into the waste? Is it increasing or decreasing in response to cover evolution? It depends on the system. In systems we installed in the west, evolution of the barrier often does not have that significant an effect on percolation. Even though there is higher saturated conductivity, we can still store a lot of water. We are managing smaller amounts of water, and we are managing most of it in the top of the cover. So there is not that much percolation. That is not universal. For example, a cover in California has a protective clay barrier with 1 meter of course textured alluvium over it. When we excavated it 6 years after construction, there were lots of cracks, and it was very permeable. We got a lot of water through that cover over time, and that was in the Sonoran Desert with 100 mm of rain per year. In the east, where there is a lot of water to manage, as structure develops you will have a lot more percolation. In the southeast, we measured percolation from 20 mm per year early on to 200 millimeters per year several years later. That is in an earthen system. It will become congruent with recharge of the natural system. If the natural recharge is 200, 300, or 400 mm per year, that is where the cover system is going. Geosynthetics change that. That is why we use a lot of geomembranes for water management in the east.
Discussion. Ecology has something to do with it. At Apple Valley, we didn’t establish the anticipated vegetation and got annual grasses. They finesse water uptake and put a lot of energy into seed production. So understanding what is growing and the seasonal extraction of water is important.
Reply. It is coupling hydrology and ecology. At that site, there was a mat of roots right on top of the clay barrier. That is where the water was. The roots accumulated there, pulled the water out, and burrowed into the clay. The ecological system is very opportunistic. Coupling the ecology and the hydrology and understanding how they evolve are important.

Question. You had a dramatic-looking slide of a radon barrier that was cracked and had roots in it. Was that Monticello? I thought Monticello had a geomembrane on it.

Reply. The Monticello disposal facility has a geomembrane on top of the radon barrier. But Jody Waugh had the foresight to conduct a series of caisson experiments there, probably 10 years prior to construction of the Monticello facility. They were small, 300-millimeter-diameter caissons at first and then they were 10-foot diameter caissons. This image came from the 10-foot caisson that Jody Waugh constructed [editor's note: see Section 2-5, pp. 2-97 to 2-98]. It has the same profile but no geomembrane. The geomembrane was added to the design later because it was a Superfund site and the geomembrane was needed to meet some ARARs.

Question. Any idea what the hydraulic conductivity is of the material in that slide?
Reply. It was about $1x10^{-4}$ cm/s under stress. Actually, I measured that one and can give you the exact numbers.
Comment. On that caisson, vegetation was adequate. There was very little percolation in the lysimeters even though structure had developed, leading to greater hydraulic conductivity. The native sagebrush vegetation kept it pretty dry. Monticello has about 4 mm per year of percolation over 18 years. Monticello is toward the wetter end of the range where an ET cover will work. It is in the southwest but at high elevation, has a short growing season, and gets snow. There is a shorter window of water extraction for the plants growing there, but it still works.
Reply. If anyone is going to the DOE/LM Long-Term Stewardship Conference at Grand Junction, Craig Benson will be giving a talk on the hydrology of the three sites we have on the Colorado Plateau. There is a tour of the Cheney site too.

2.6 Field Evaluation of Radon Fluxes from Radon Barriers at In-Service Uranium Mill Tailings Disposal Facilities

Presented by Craig Benson
Dean of Engineering, University of Virginia

2.6.1 Abstract

Field studies of in-service final covers for waste containment have shown that structure develops rapidly in earthen cover soils in response to wet-dry cycles, freeze-thaw cycles, and biota intrusion. This structure includes well-connected larger pores, altering the hydraulic properties of the soils. The saturated hydraulic conductivity generally increases (sometimes by several orders of magnitude), and water retention diminishes. These same pores can be pathways for radon migration, especially as the water saturation diminishes. However, until now, no comparable field studies have been conducted to evaluate whether these alterations have resulted in an increase in radon flux.

This study measured radon fluxes at four disposal facilities for uranium mill tailings in different regions of the United States with widely varying climates: Falls City, TX; Bluewater, NM; Shirley Basin South, WY; and Lakeview, OR. These sites have been closed for approximately two decades before this study and were constructed in response to UMTRCA. The covers employed different designs, were constructed with different materials, were located in widely varying climates, and had very different vegetative communities [editor's note: see Section 2.4, p. 2-62]. Samples were collected from the cover at each site to evaluate changes in hydraulic properties of the cover soils [editor's note: see Section 2.5, p. 2-86]. Geomorphological surveys were conducted to characterize the structure that developed in the cover profile [editor's note: see Section 2.8, p. 2-144]. This presentation describes data from three sites (Falls City, Bluewater, and Shirley Basin South). Data from the Lakeview site were not available for dissemination at the time of this workshop.

At each site, test pits were exhumed in the cover profile down to the top of the radon barrier, and to the surface of the underlying tailings in some cases. Radon fluxes were measured on the surface of the radon barrier and, when possible, directly on the surface of the tailings. Flux chambers of different sizes were used to assess the importance of scale on radon flux: large (2.32 square meters (m^2)), medium (0.59 m^2), small (0.071 m^2), and extra small (area = 0.018 m^2). Radon concentration was measured with electronic radon detectors (RAD7 alpha trackers) and activated carbon canisters. Tests were conducted at various locations on each cover corresponding to conditions that can lead to different soil structure and water saturation. Profiles of gravimetric water content and dry unit weight were measured in each test pit, and water saturation profiles were computed from the data. In some locations, measurements were conducted in paired test pits, one with a surface feature such as a large deep-rooted plant and the other a nearby control.

All sites met the regulatory limit for average radon flux of 0.74 becquerel per meter square per second (Bq/m^2-s) (20 pCi/m^2-s), although some flux measurements at the Bluewater and Falls City sites exceeded this regulatory limit. Radon concentrations measured using activated carbon samplers in the flux chambers were 60 percent of the concentrations measured using the RAD7, on average, and radon fluxes computed with the activated carbon data were 9 percent of those computed with the RAD7 data, on average. Size of the flux chamber had no systematic effect on radon flux, indicating that decades of pedogenesis had not created a pore network causing scale-dependent radon flux.

Falls City, TX. The Falls City site has a grass-covered top deck and rock-covered slopes. Mesquite bushes are scattered across the top deck. The rock-covered areas retained more moisture in the radon barrier (likely because of a capillary break effect) and had lower radon fluxes than areas in the vegetated top deck. Fluxes measured in an area of the top deck where a mesquite bush had rooted into the cover were substantially higher than those from the control pit. The average flux measured during this study (2016) was comparable to the average as-built flux (1994). However, the fluxes measured in this study varied over a greater range compared to the as-built condition, and fluxes measured at several locations in this study were larger than the highest flux measured in the as-built condition.

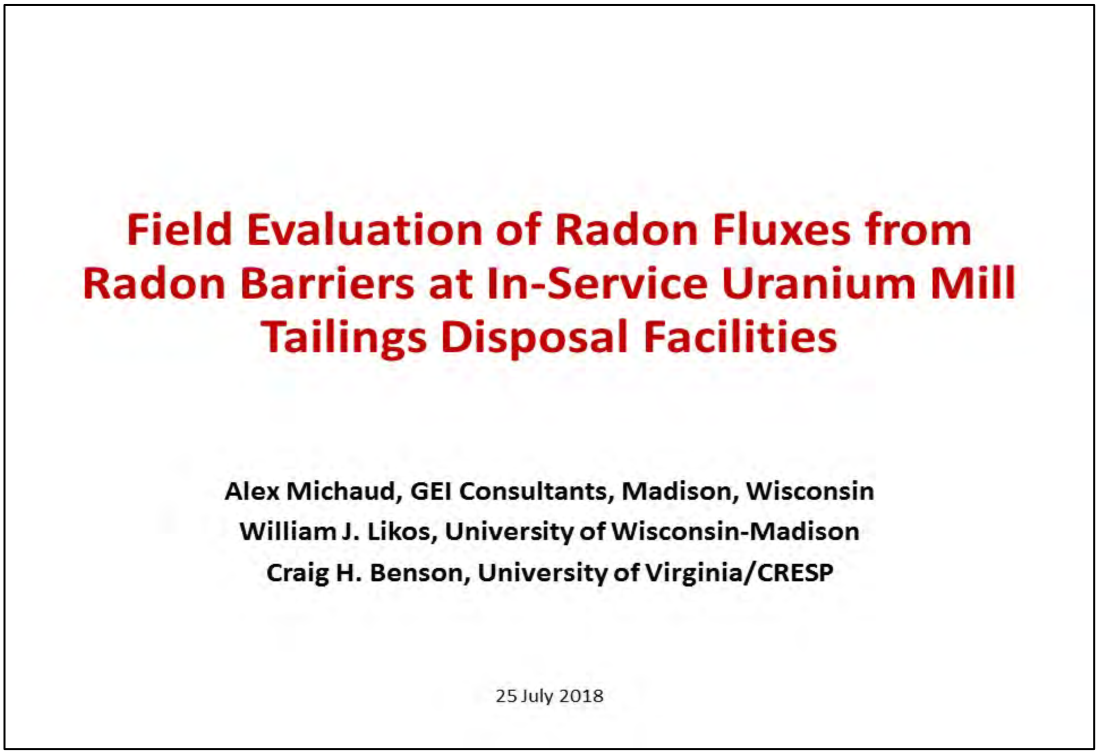
Bluewater, NM. The Bluewater site is rock covered over the entirety and is comprised of several different disposal units. The average flux in each of the disposal units at the Bluewater site evaluated in this study (2016) was below the regulatory limit. However, the average flux measured in this study was nearly 10 times higher than the average as-built flux (1995). Settlement in one area of the cover at the Bluewater site results in seasonal ponding, yielding higher water contents, higher water saturation, and lower fluxes. The highest radon fluxes at the Bluewater site, two of which were above the 0.74 Bq/m^2-s regulatory limit, were measured directly on an area where deep-rooted saltbush had established. The geometric mean of fluxes from this pit below the saltbush were about an order of magnitude greater than the average flux measured in a control pit. Fluxes were also high in an area directly below a large ant mound.

Shirley Basin South, WY. The Shirley Basin South site is vegetated with local species. The soil cover at this site is constructed with a highly plastic clay rich in montmorillonite (bentonite) that retained moisture and was extremely dense and hard. Fluxes on the surface of the radon barrier in this study (2017) were very low, even though the fluxes from the tailings were much higher in some cases than fluxes from the tailings at other sites. None of the fluxes were close to the regulatory limit, and the average flux measured in this study was similar to the average as-built flux (2000).

Summary. The average radon flux at each site remained below the 0.74 Bq/m^2-s regulatory limit after approximately two decades of service and pedogenic development in the cover profile. However, the range of radon fluxes is larger than in the as-built condition, suggesting that structural development has resulted in some areas where the flux is higher than in the as-built condition. Average fluxes were comparable to the average as-built flux at two of the sites (Falls City and Shirley Basin South), whereas the average flux at one site (Bluewater) was about an order of magnitude higher than the as-built flux. Radon fluxes were larger in areas where surface features were present that exacerbate structural development (large ant mounds, large deep-rooted woody vegetation) and reduce the water saturation of the radon barrier.

[Editor's note: The questions and answers for this presentation are combined with those for the next presentation presenting diffusion coefficients determined from the radon fluxes.]

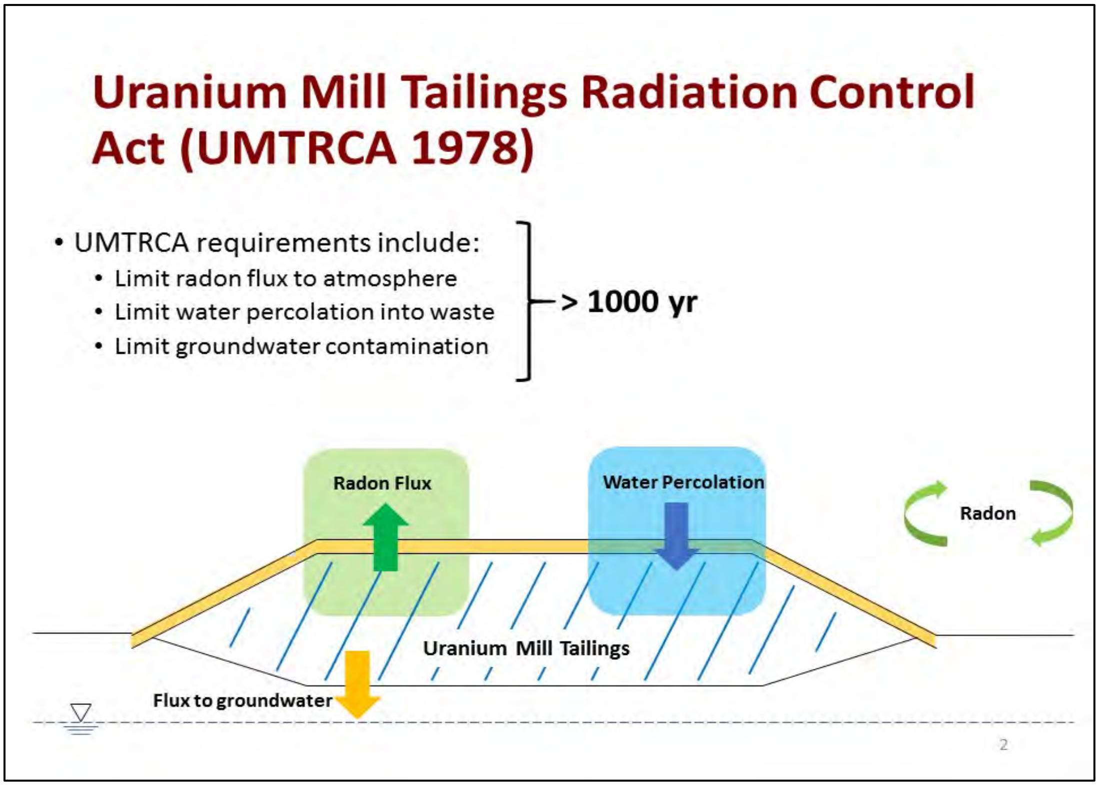
2.6.2 Presentation



Field Evaluation of Radon Fluxes from Radon Barriers at In-Service Uranium Mill Tailings Disposal Facilities

Alex Michaud, GEI Consultants, Madison, Wisconsin
William J. Likos, University of Wisconsin-Madison
Craig H. Benson, University of Virginia/CRESP

25 July 2018



Uranium Mill Tailings Radiation Control Act (UMTRCA 1978)

- UMTRCA requirements include:
  - Limit radon flux to atmosphere
  - Limit water percolation into waste
  - Limit groundwater contamination

> 1000 yr

Uranium Decay Chain

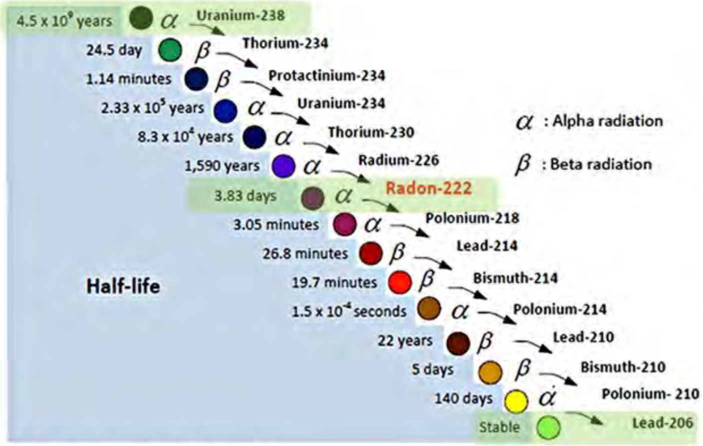
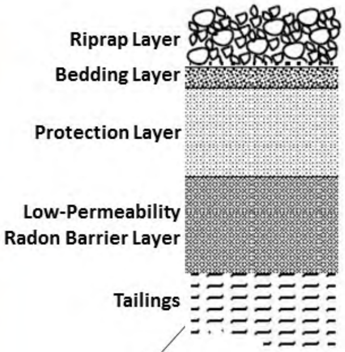


Figure: earthscience.stackexchange.com

- Uranium half-life: 4.5 billion years.
- Slow and steady decay.
- Radon half-life: 3.8 days.
- Eventually becomes stable Pb-206.

Typical Disposal Site



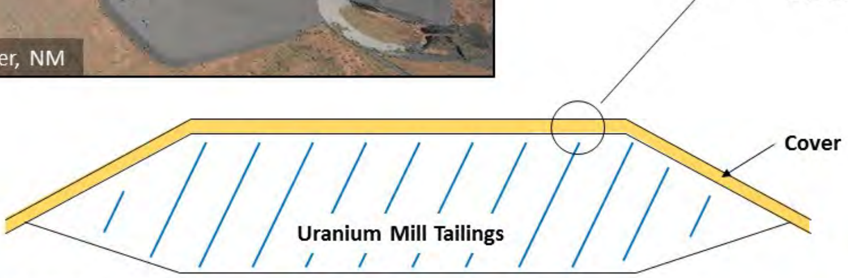
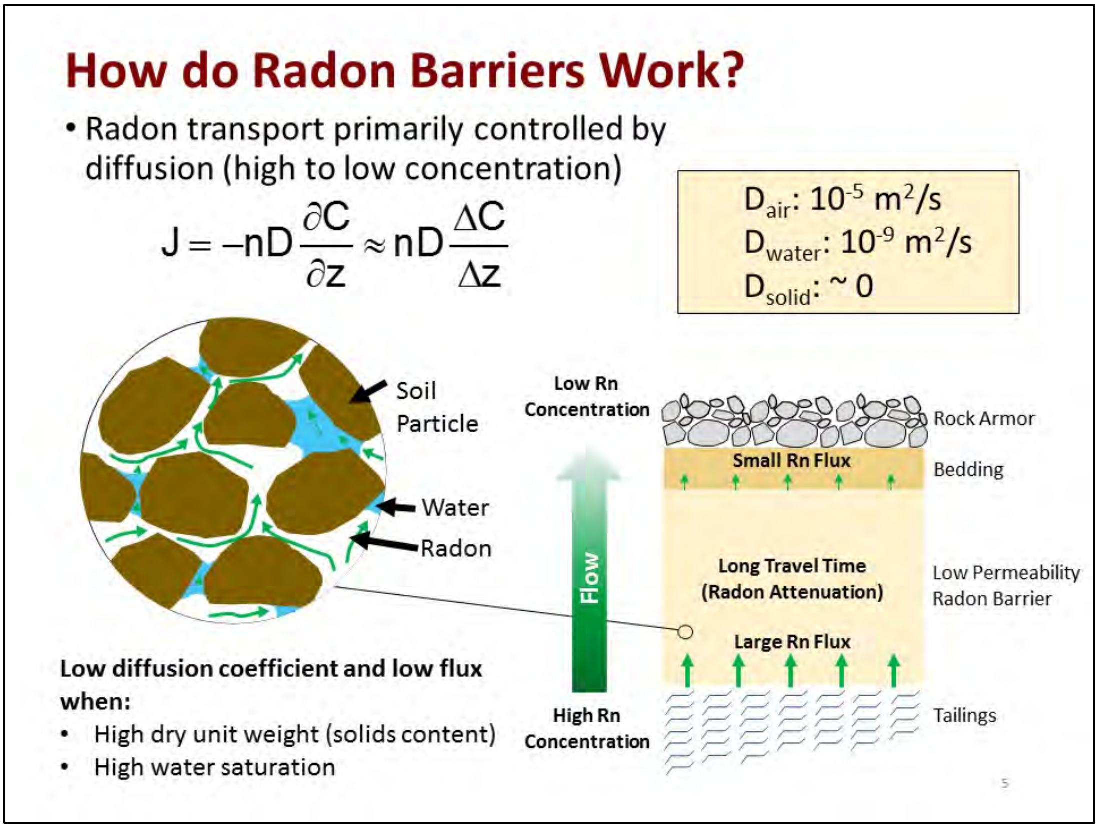


Photo: The Center for Land Use Interpretation



How do Radon Barriers Work?

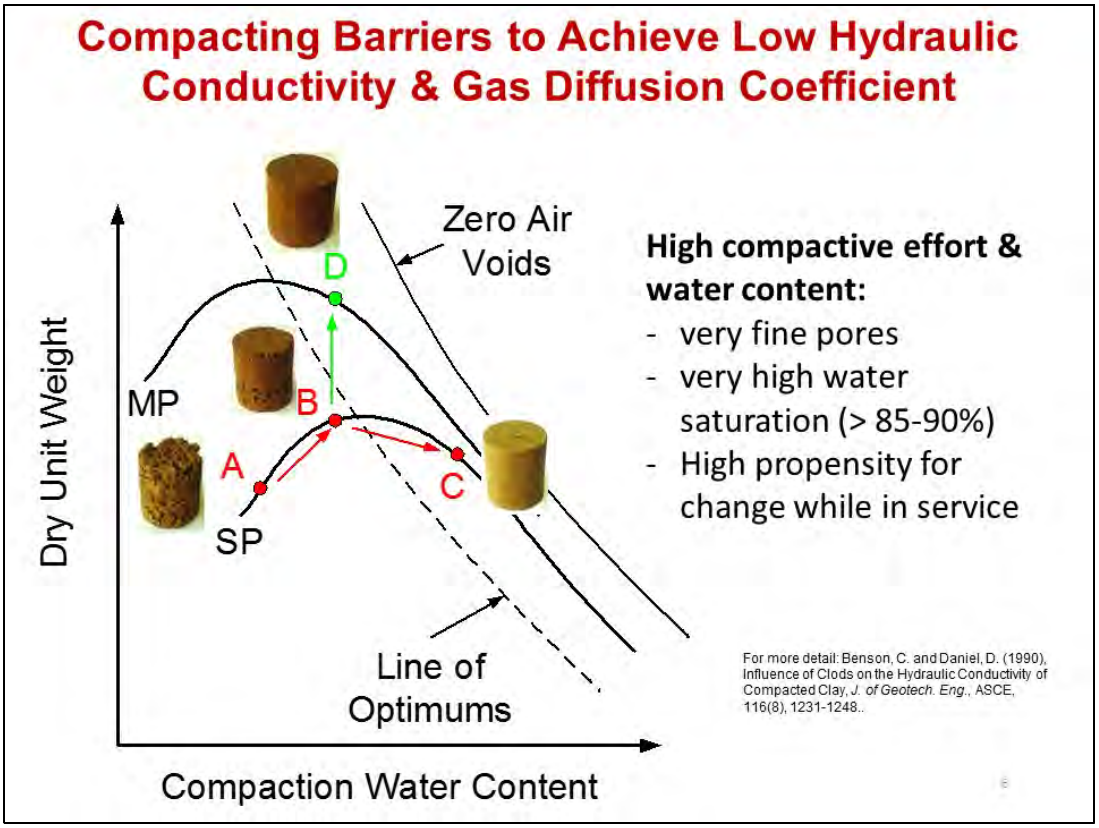
- Radon transport primarily controlled by diffusion (high to low concentration)

$$J = -nD\frac{\partial C}{\partial z} \approx nD\frac{\Delta C}{\Delta z}$$

D_{air}: 10^{-5} m^2/s
D_{water}: 10^{-9} m^2/s
D_{solid}: ~ 0

Low diffusion coefficient and low flux when:

- High dry unit weight (solids content)
- High water saturation

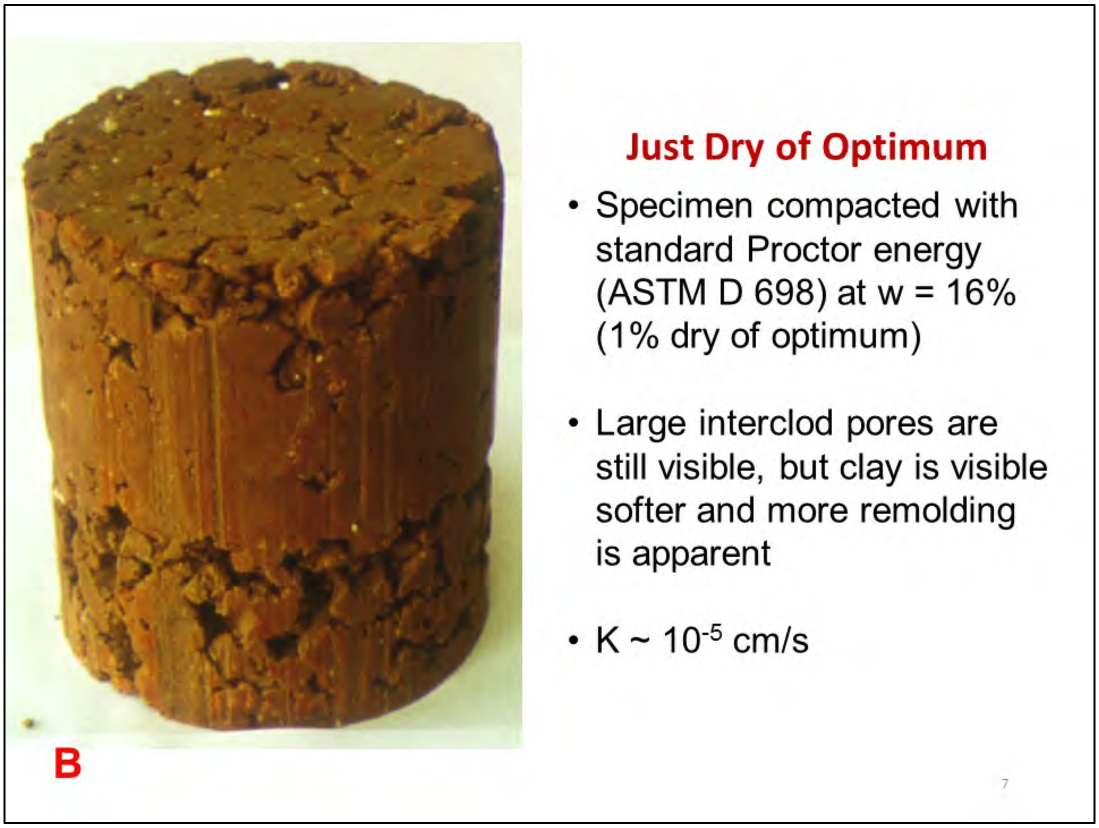


Compacting Barriers to Achieve Low Hydraulic Conductivity & Gas Diffusion Coefficient

High compactive effort & water content:

- very fine pores
- very high water saturation (> 85-90%)
- High propensity for change while in service

For more detail: Benson, C. and Daniel, D. (1990), Influence of Clods on the Hydraulic Conductivity of Compacted Clay, *J. of Geotech. Eng.*, ASCE, 116(8), 1231-1248..



Just Dry of Optimum

- Specimen compacted with standard Proctor energy (ASTM D 698) at w = 16% (1% dry of optimum)
- Large interclod pores are still visible, but clay is visible softer and more remolding is apparent
- K ~ 10^{-5} cm/s

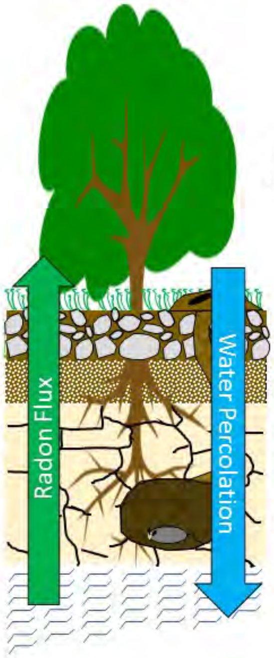
B

Wet of Optimum

- Specimen compacted with standard Proctor energy (ASTM D 698) at w = 20% (3% wet of optimum)
- Only micro-scale pores exist. Clods fully remolded and interclod voids are eliminated.
- K ~ 10^{-9} cm/s

C

How will these barriers change over centuries?



Vegetative Succession

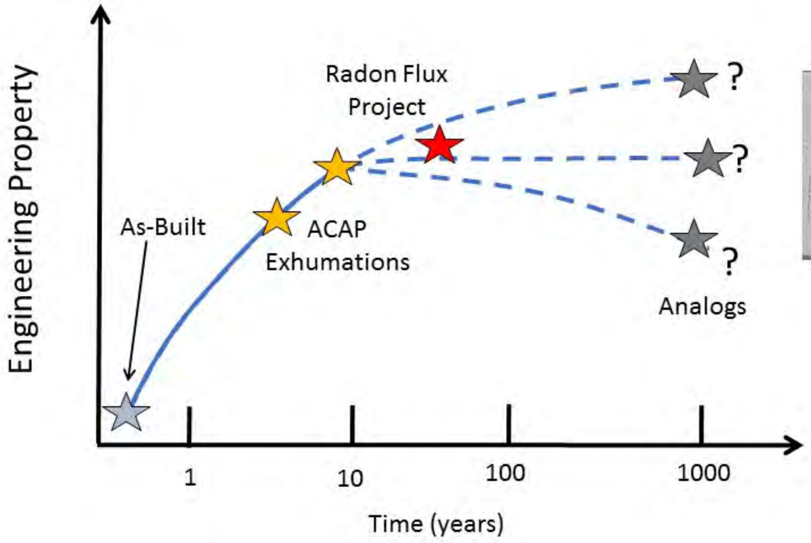
Dust Deposition

Soil Formation (desiccation cracking, freeze-thaw)

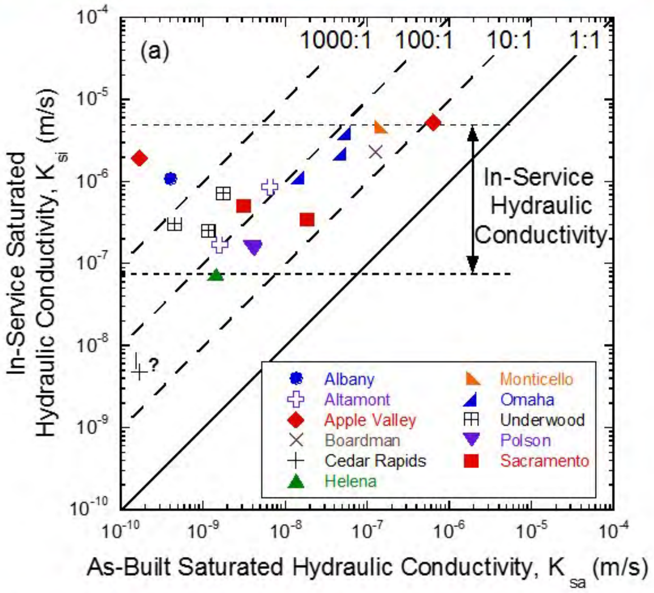
Bio-turbation

- Does pedogenesis soil cause changes in radon diffusion coefficient and flux?
- Does pedogenesis cause changes in hydraulic properties and percolation?
- Can we design barriers that are resilient in a natural system?

Challenges – Predicting the Future



Pedogenesis in Barrier Layers



Similar Impact on Radon Diffusion?

Field Study Locations

Contrasting Climates for Field Sites


Falls City, TX

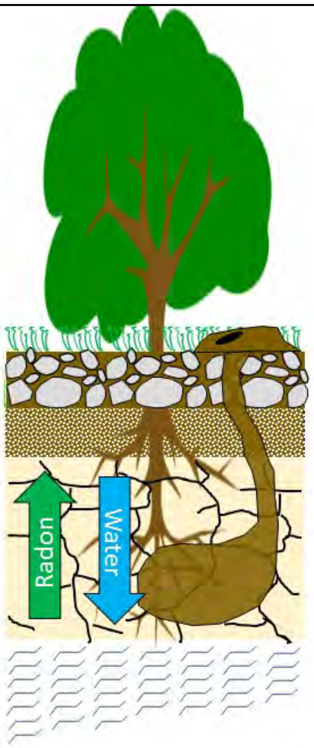

Bluewater, NM


Shirley Basin South, WY


Lakeview, OR

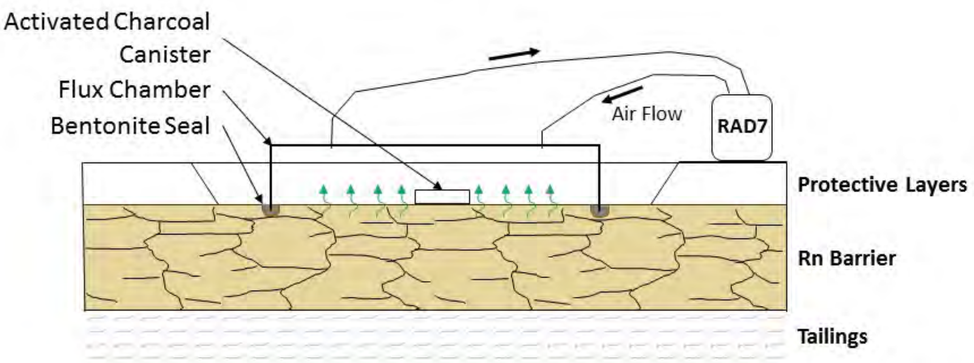
Goals of Fieldwork

- Rn flux measurements at multiple surface features & control locations.
- Block samples:
  - Water content profiles
  - Hydraulic properties
  - Physical properties
- Observe changes in cover soil profiles since construction.
- Observe and sample from local analogs (long-term condition).



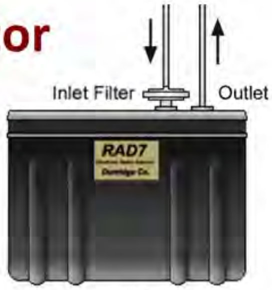
Measuring Radon Flux - Surface

1. Expose Radon Barrier
2. Install & Seal Flux Chamber
3. Measure Radon Buildup

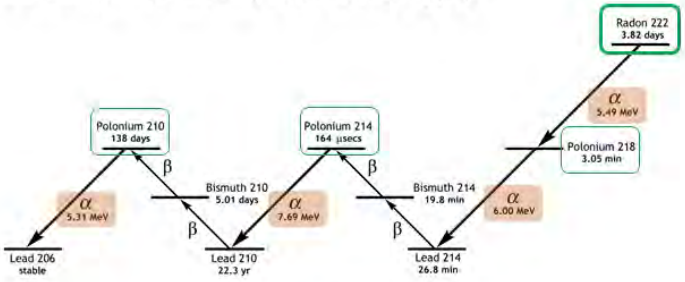


RAD7 Continuous Radon Monitor

- Alpha detector
- Measures energy emitted from alpha decay of Radon (and other, short-lived progeny)
- Converts to Rn concentration @ specified time interval (0.25 hour typ.)



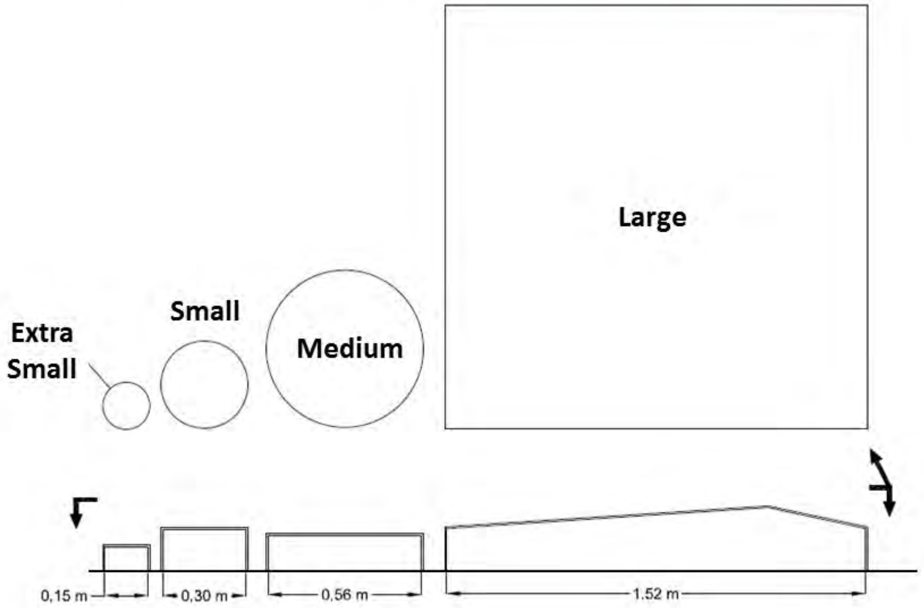
DURRIDGE RAD7
Radon Monitor



Radon decay chain

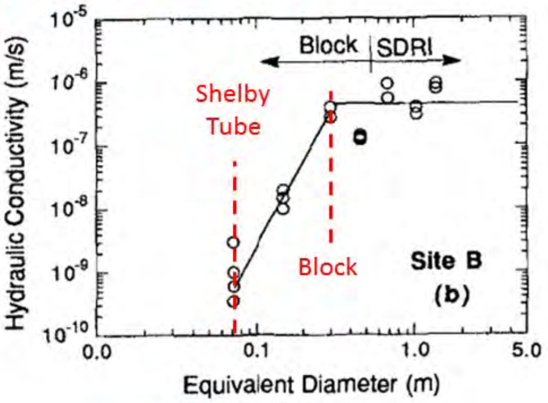
Figure: Durridge Company

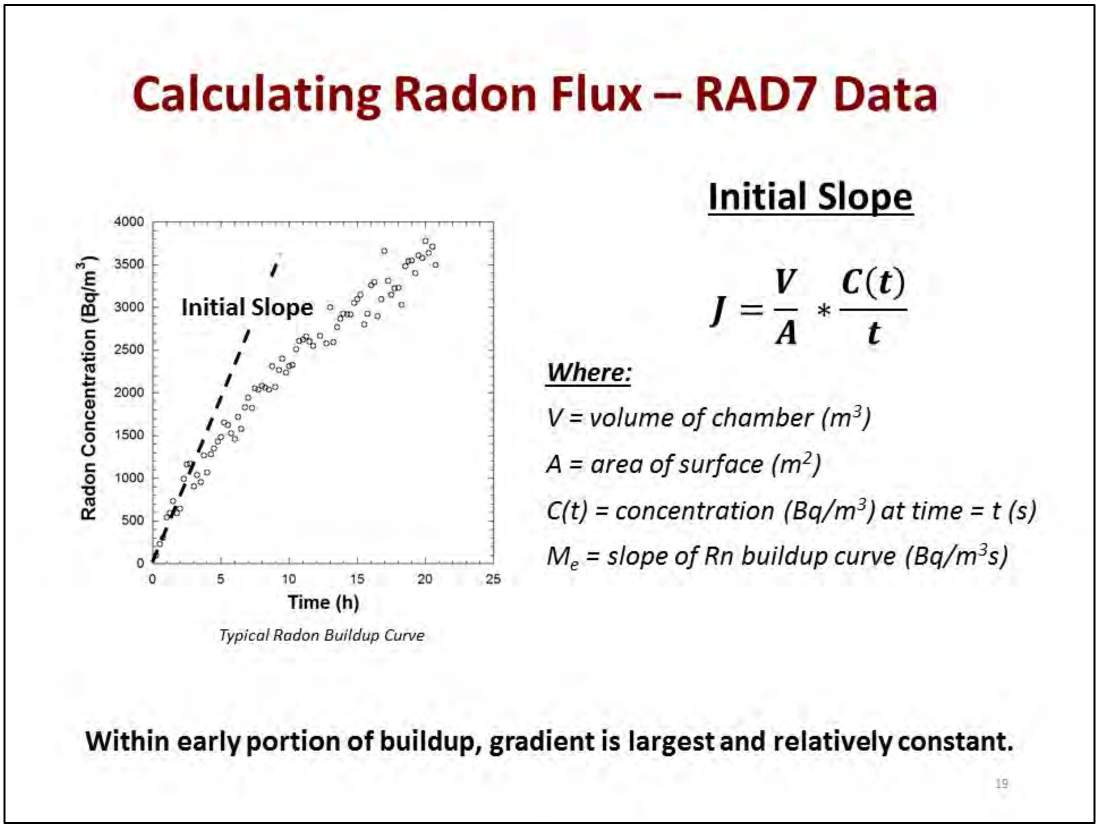
Flux Chamber: Small to Large



Evaluating Scale Effects

- Hydraulic conductivity is scale dependent.
- If large open pores, Rn diffusion should also be scale dependent





Calculating Radon Flux – RAD7 Data

Initial Slope

$$J = \frac{V}{A} * \frac{C(t)}{t}$$

Typical Radon Buildup Curve

Where:

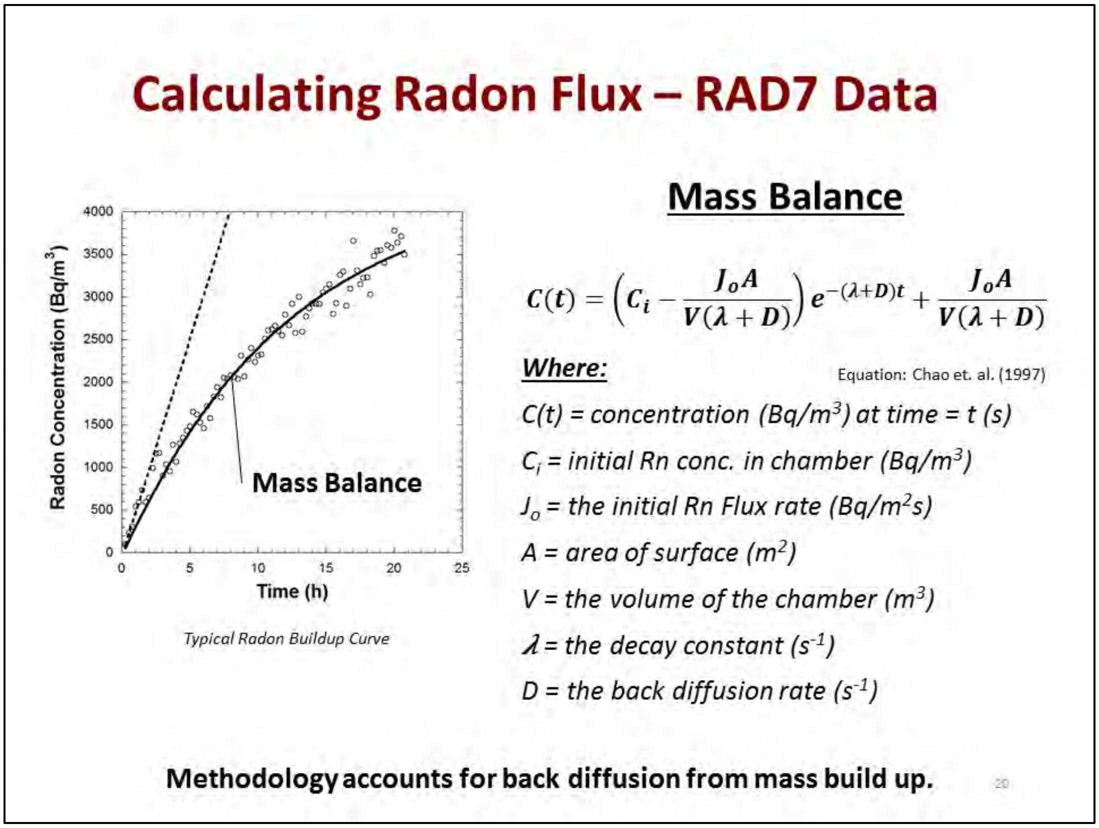
V = volume of chamber (m^3)

A = area of surface (m^2)

C(t) = concentration (Bq/m^3) at time = t (s)

M_e = slope of Rn buildup curve (Bq/m^3s)

Within early portion of buildup, gradient is largest and relatively constant.



Calculating Radon Flux – RAD7 Data

Mass Balance

$$C(t) = \left(C_i - \frac{J_o A}{V(\lambda + D)}\right) e^{-(\lambda + D)t} + \frac{J_o A}{V(\lambda + D)}$$

Typical Radon Buildup Curve

Where: Equation: Chao et. al. (1997)

C(t) = concentration (Bq/m^3) at time = t (s)

C_i = initial Rn conc. in chamber (Bq/m^3)

J_o = the initial Rn Flux rate (Bq/m^2s)

A = area of surface (m^2)

V = the volume of the chamber (m^3)

λ = the decay constant (s^{-1})

D = the back diffusion rate (s^{-1})

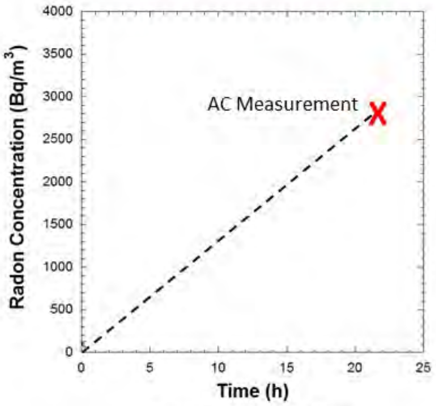
Methodology accounts for back diffusion from mass build up.

Activated Carbon/Charcoal (AC)

- Canisters contain granular AC that adsorbs Rn.
- Canisters analyzed by lab; single concentration reported.

AC Canisters: The Radon Testing Corporation of America

Calculating Radon Flux – AC Data



Typical Radon Buildup Curve

AC Point

$$J = \frac{V}{A} * \frac{C(t)}{t}$$

Where:

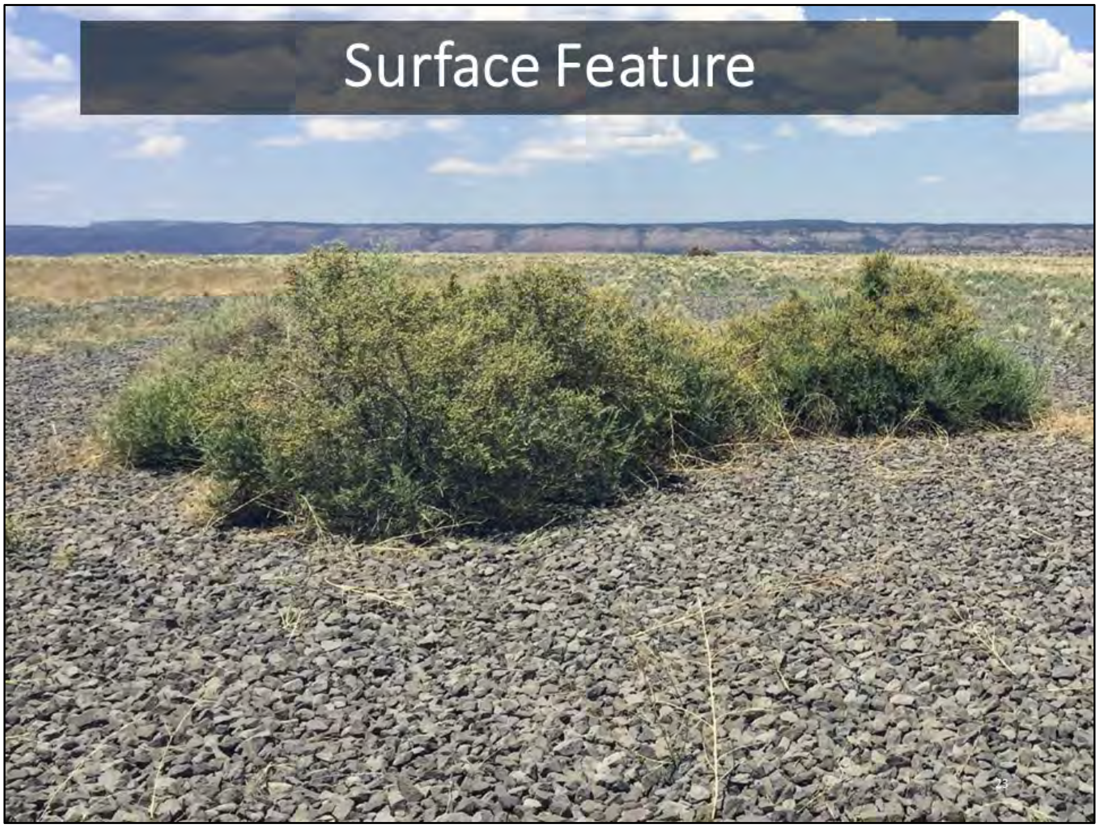
V = volume of chamber (m^3)

A = area of surface (m^2)

$C(t)$ = concentration (Bq/m^3) at time = t (s)

M_e = slope of Rn buildup curve (Bq/m^3s)

This is an adaptation of traditional AC methods, which we believe may be an inexpensive alternative (however it may over-simplify Rn buildup).

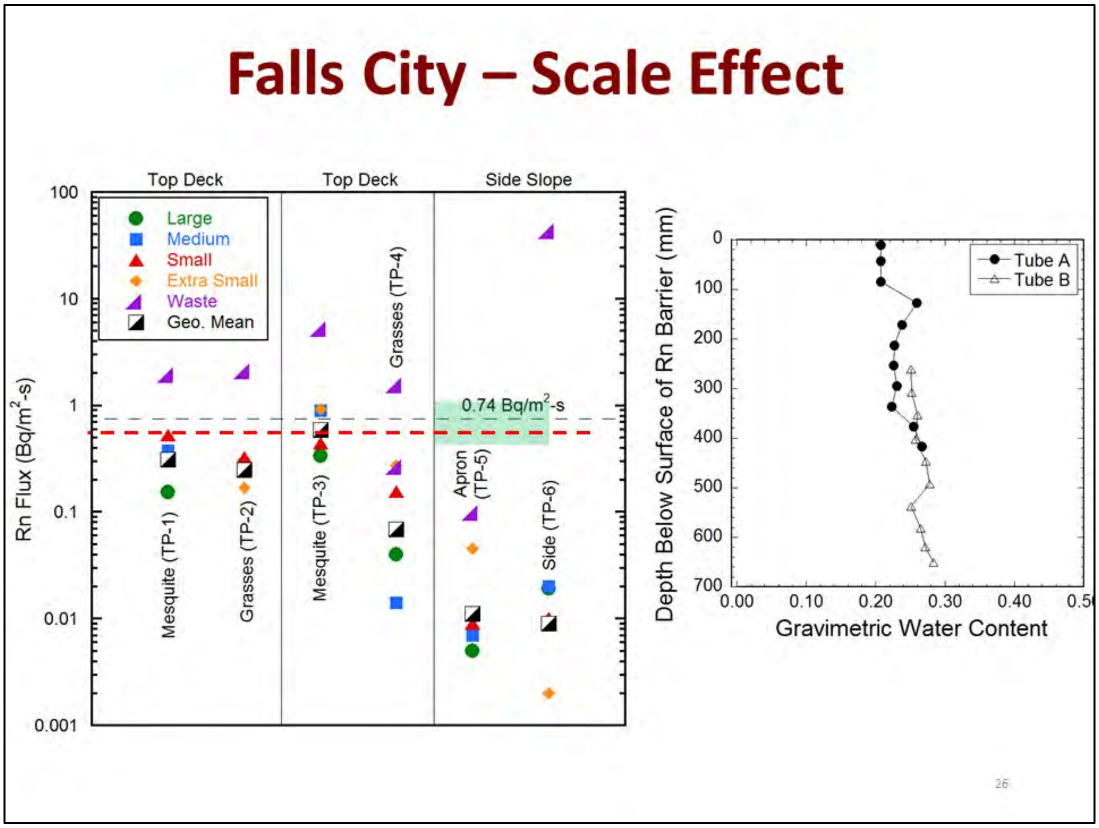


Surface Feature

Exposure of Radon Barrier

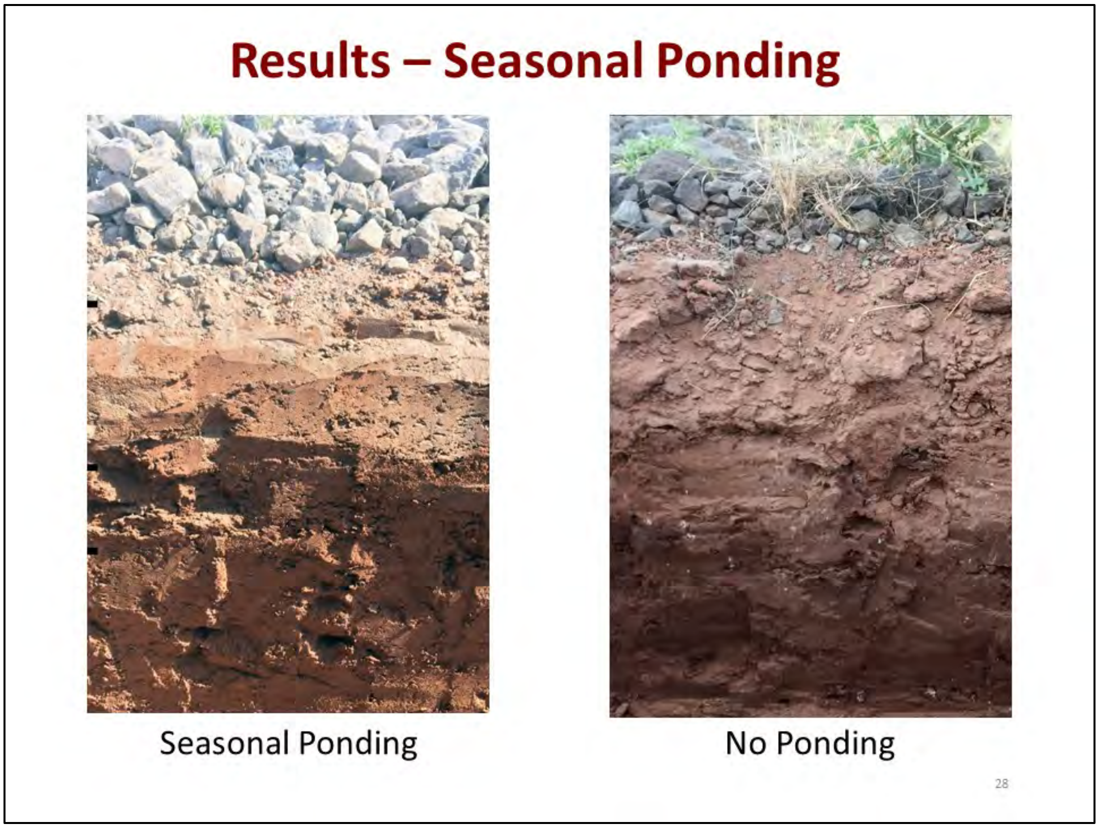
Installation of Flux Chambers

Test Duration: 5 – 20 hours



Falls City – Scale Effect

Results – Seasonal Ponding

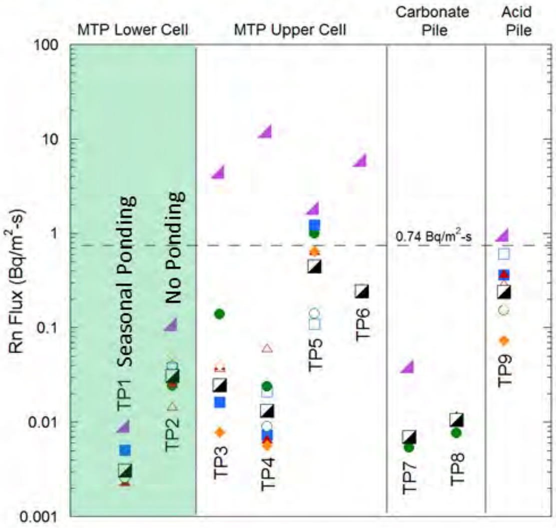


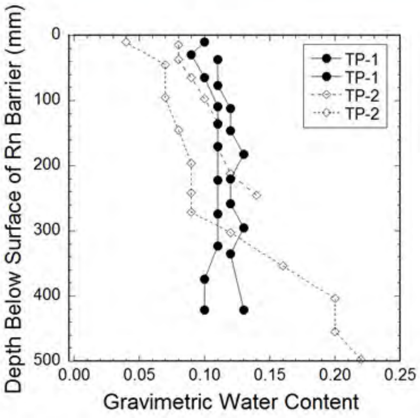
Results – Seasonal Ponding

Seasonal Ponding

No Ponding

Impact of Water Saturation from Seasonal Ponding



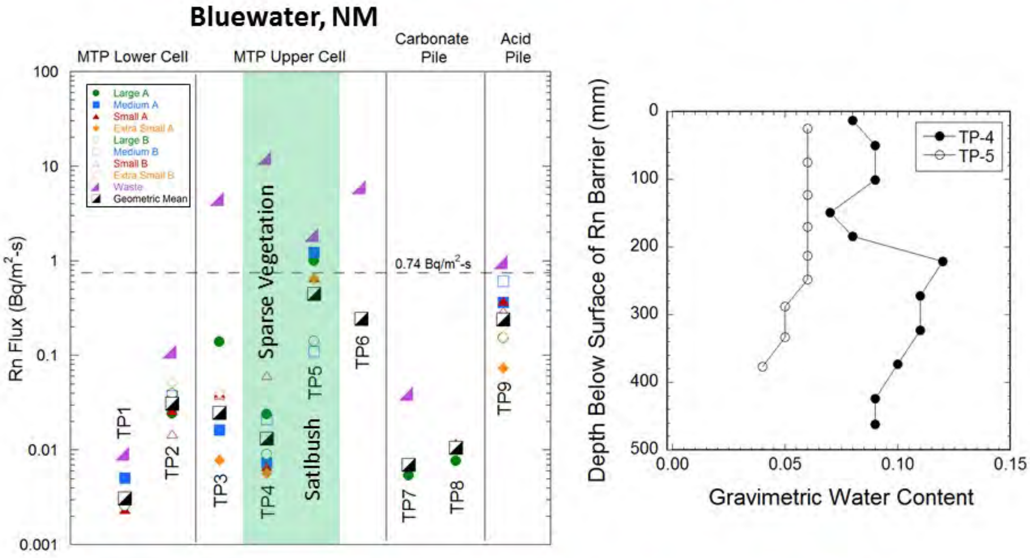


Higher water saturation – lower Rn flux

Nearly all fluxes below regulatory limit

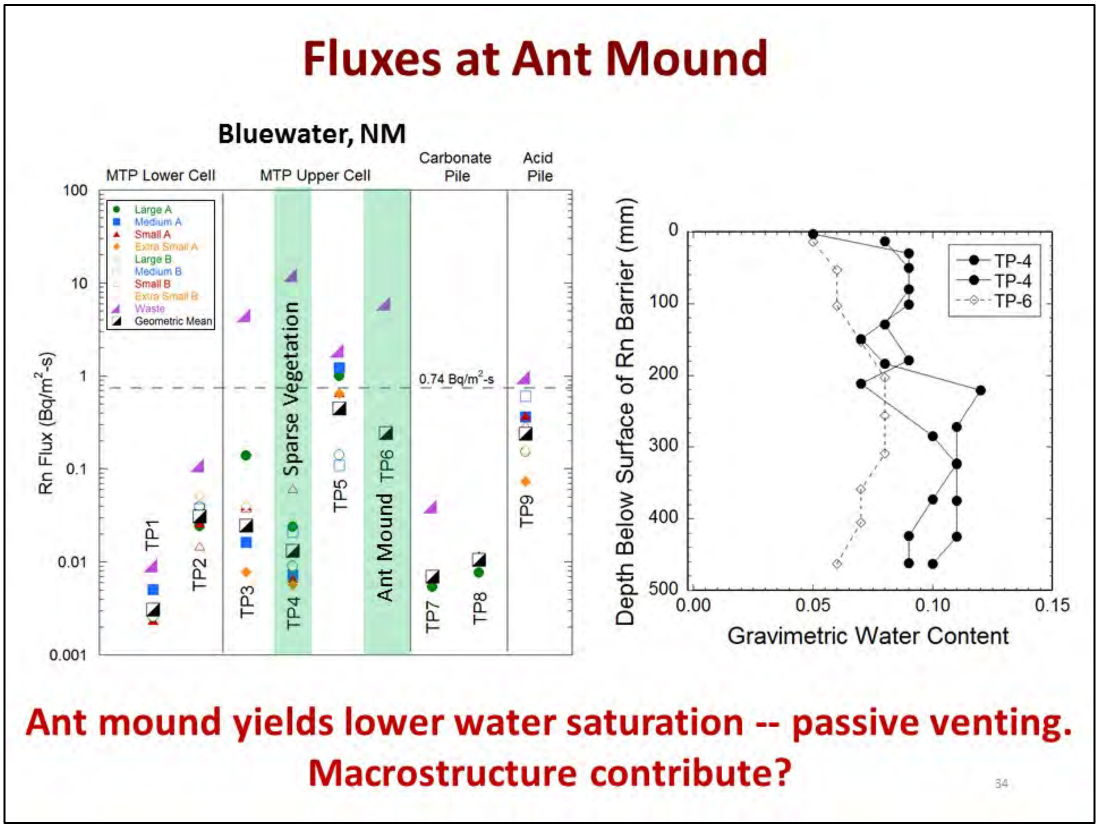
Results – Deep Rooting Vegetation

Results – Deep Rooting Vegetation



Higher water saturation – lower Rn flux
Macrostructure contribute?

Ant Mound at Bluewater, NM

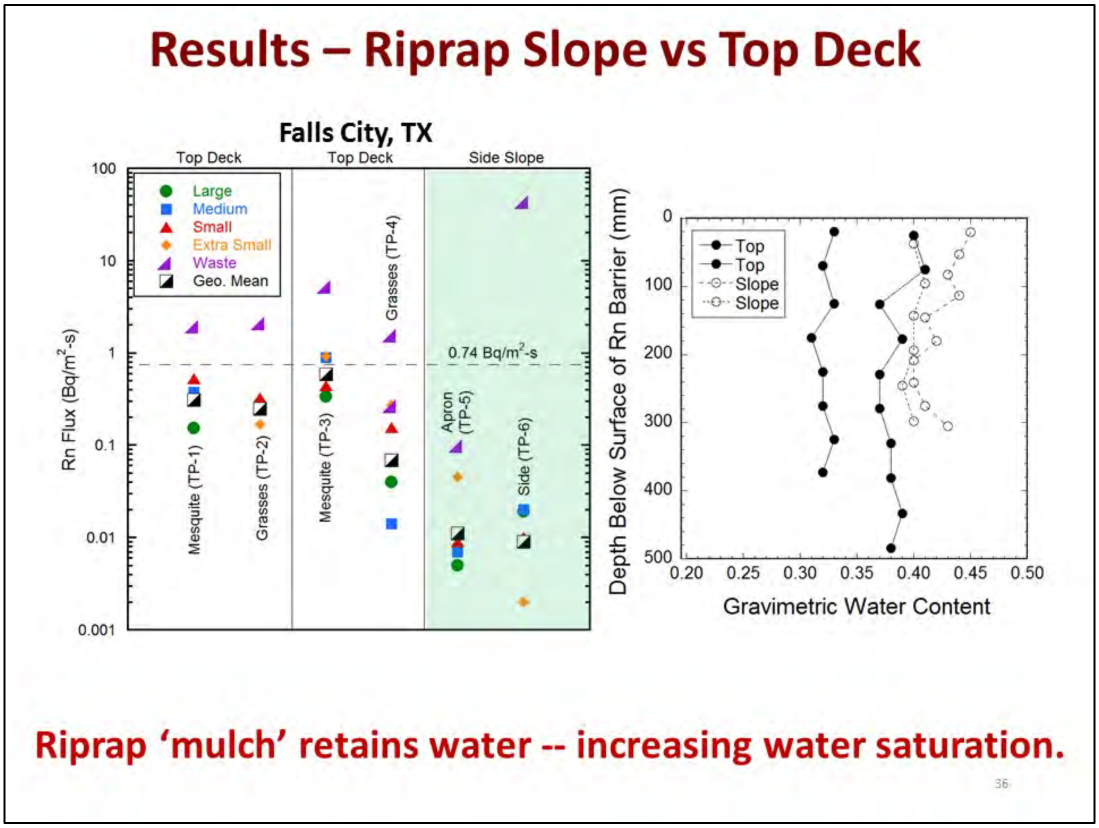


Fluxes at Ant Mound

Ant mound yields lower water saturation -- passive venting. Macrostructure contribute?

Results – Riprap Slope vs Top Deck

Falls City, TX

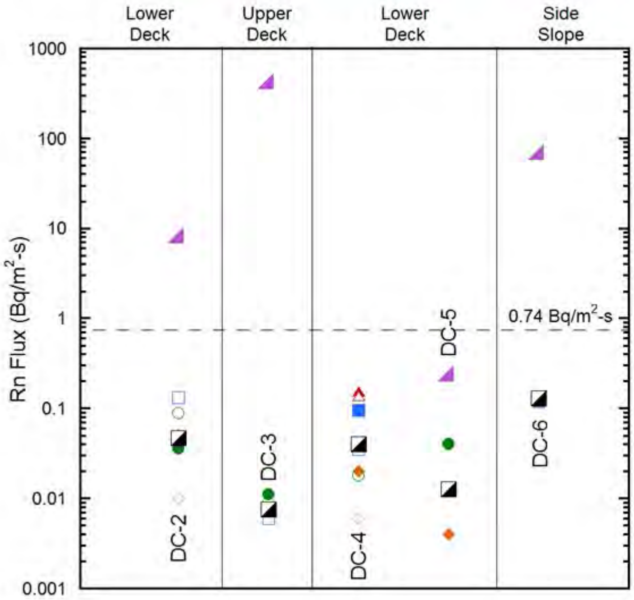


Results – Riprap Slope vs Top Deck

Falls City, TX

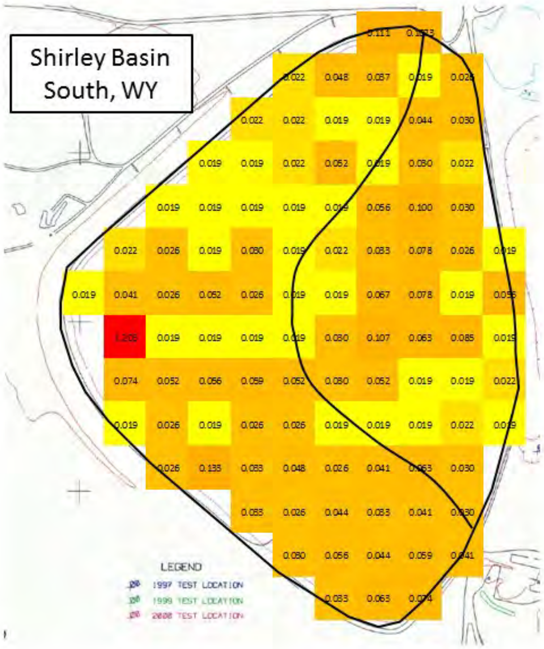
Riprap ‘mulch’ retains water -- increasing water saturation.

Fluxes at Shirley Basin South



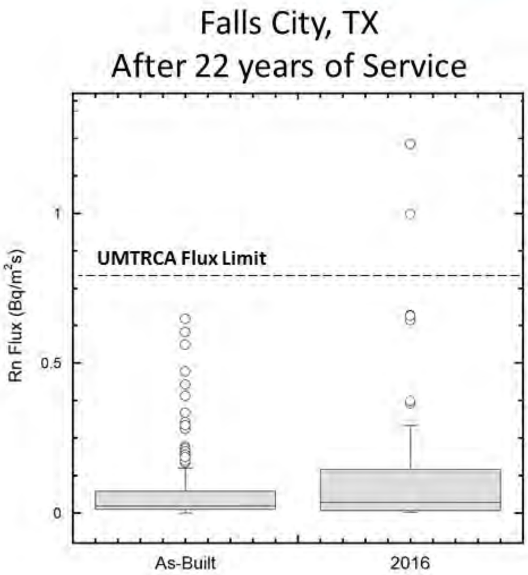
- Very low Rn flux at site.
- High flux from tailings.
- Rn barrier is performing very well.

As-Built Flux Data



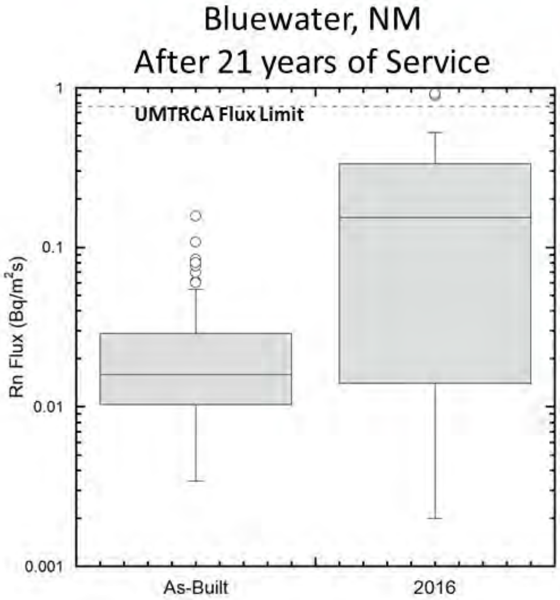
- Post construction of Rn barrier.
- 100 ft grid pattern.
- AC in small flux chamber.

Falls City, Texas


Falls City, TX
After 22 years of Service

- Greater flux in 2016
- 4x as-built.
- Highest on top deck.
- Flux on riprap slope similar to as-built.
- Average below limit.

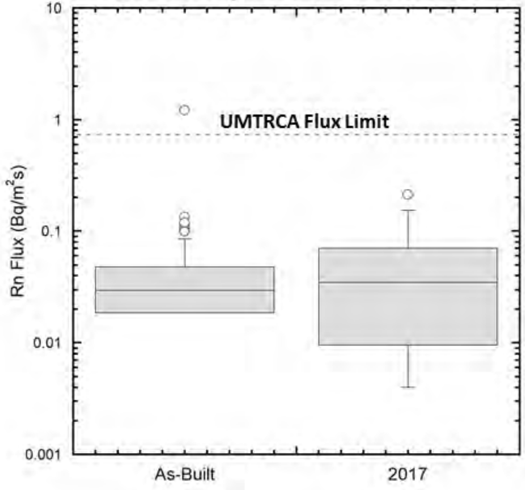
Bluewater, NM As-Built Comparison


Bluewater, NM
After 21 years of Service

- 2016 fluxes slightly greater than as-builts.
- Decrease in w% since construction, vegetation, animal burrowing.
- Two values above limit.
- Average still below limit.

Shirley Basin As-Built Comparison

Shirley Basin South, WY
After 17 years of Service



- 2017 fluxes similar to as-builts.
- Rn barrier nearly saturated with limited soil structure.
- Average flux much lower than UMTRCA limit.

Lessons Learned

- Fluxes below regulatory requirement, but higher than as-built (4-10x). What is long-term condition?
- Fluxes higher below features that contribute to lower water saturation (ant mound, salt bush). Can we control long term?
- No apparent scale effect – similar fluxes with large-scale and smaller flux chambers.

2.7 Radon Diffusion Coefficients

Presented by Mark Fuhrmann
Mark Fuhrmann[1], Alex Michaud[2], Nicholas Stephani[2]
[1]U.S. Nuclear Regulatory Commission, [2]University of Wisconsin—Madison

2.7.1 Abstract

Excavations were made into radon covers at four uranium mill tailings disposal sites to expose the upper surface of the radon barrier and the upper surface of the underlying mill tailings waste. Radon flux measurements were taken at the top of the radon barrier and at the top of the waste as described in Benson et al. (2017) at each location. From these pairs of fluxes and the local thickness of the barrier, effective diffusion coefficients were calculated using the RAECOM model (see NUREG/CR-3533, “Radon Attenuation Handbook for Uranium Mill Tailings Cover Design,” issued April 1984; NUREG/CR-2765, “A Mathematical Model for Radon Diffusion in Earthen Materials,” issued October 1982; and NRC Regulatory Guide 3.64, “Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers,” issued June 1989). The RAECOM code is available at the Wise Uranium Project Web site (http://www.wise-uranium.org/ctch.html). This code can also perform one-dimensional, steady-state radon diffusion calculations for a multilayered system that can be defined as needed, giving steady-state fluxes and concentrations at defined locations within the barrier profile. It can estimate diffusion coefficients from the thickness, moisture, and porosity data based on an empirical relationship from Rogers and Nielson (1991).

For this work, calculations of effective diffusion coefficients (D) for radon were based on the measured inlet flux at the bottom of the radon barrier and the exit flux measured at the top of the barrier. The inlet (bottom) flux from the waste and the barrier thickness were entered into the RAECOM code and the diffusion coefficient was iterated until a top flux was obtained that was close to that observed at the site. Using that diffusion coefficient, results were calculated in terms of a flux profile through the thickness of barrier material, giving fluxes at the depths defined in the model. These fluxes, along with the measured fluxes at the bottom of the barrier (top of the waste) and the top of the radon barrier, were plotted against depth in the barrier. They were also were used to calculate modeled Pb-210 profiles [see Section 2.9]. Travel times for radon moving through the barrier were estimated based on the diffusion coefficient and barrier thickness and are expressed both as days and as the number of Rn-222 half-lives needed to traverse the barrier.

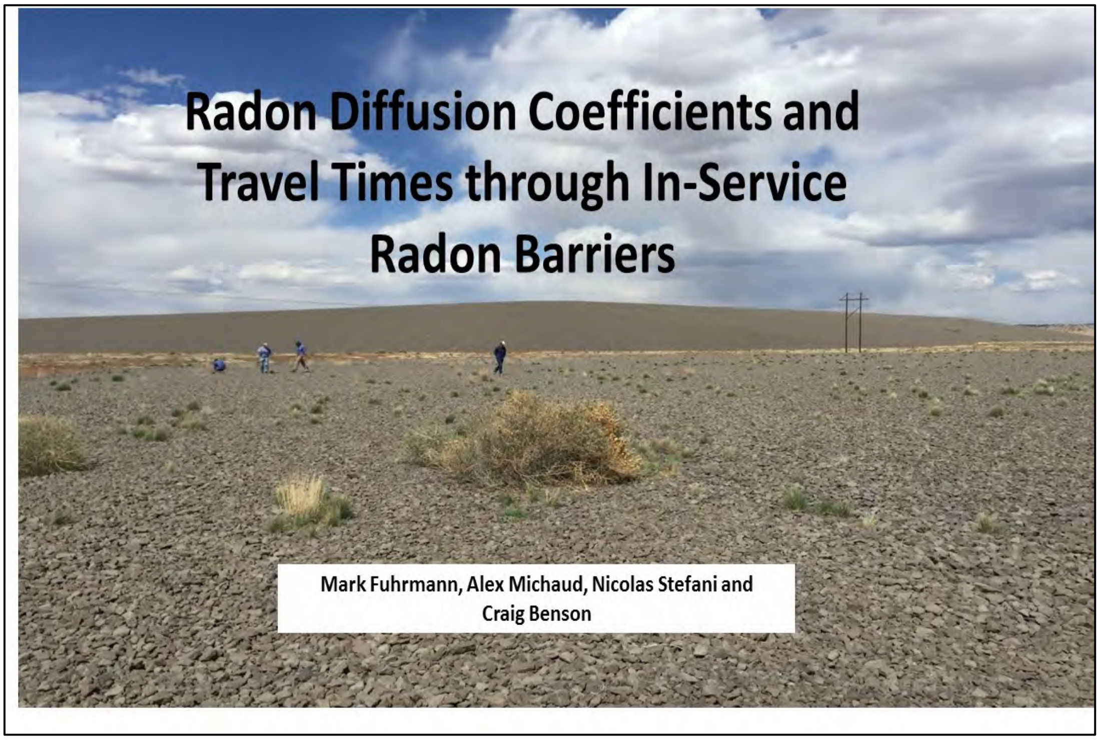
At Falls City, the average effective diffusion coefficient is 2.6×10^{-7} (m^2/s) on the top deck, which is vegetated; the number of half-lives needed to traverse the barrier is about 5.5. This suggests that about 2 percent of radon generated from the waste reaches the top of the barrier before it decays. The lowest fluxes are found at Pit 6 on the rock-covered side slope, where radon would need about 63 half-lives to cross the barrier. At that transport rate, no Rn-222 would exit the cover, all of it decaying within the radon barrier.

At the Shirley Basis South, site diffusion coefficients range from 1.1×10^{-7} to 6.1×10^{-9} m^2/s, with an average of 2.6×10^{-8} m^2/s for 20 measurements. Transport times, expressed as the number of radon half-lives, indicate that at least 10 and as many as 96 half-lives are needed to traverse the barrier. Most pits had high bottom fluxes (pit 3 was very high); this allows good confidence in the calculation of D. The barrier retains radon well. This site had especially low radon transport rates due to the smectite-rich cover material and its retention of moisture.

At the Bluewater site, fluxes and diffusion coefficients varied substantially. For example, at Pit 4 A and B, the effective diffusion coefficient averaged 5.4×10^{-8} m^2/s, with an average travel time of 15.3 half-lives for eight measurements. In contrast, at Pit 5 A and B, the effective diffusion coefficient averaged 1.8×10^{-6} m^2/s, giving a travel time of about 0.5 half-life. Very little radon retention takes place at Pit 5, while essentially no radon is lost from Pit 4. Even within a single pit, there can be notable variability. For example, at Pit 3, one measurement resulted in a diffusion coefficient of 1.4×10^{-7} m^2/s, giving a travel time of 4.6 half-lives. Only a meter or two away, a diffusion coefficient of 4×10^{-8} m^2/s was determined, with a travel time of 16 half-lives.

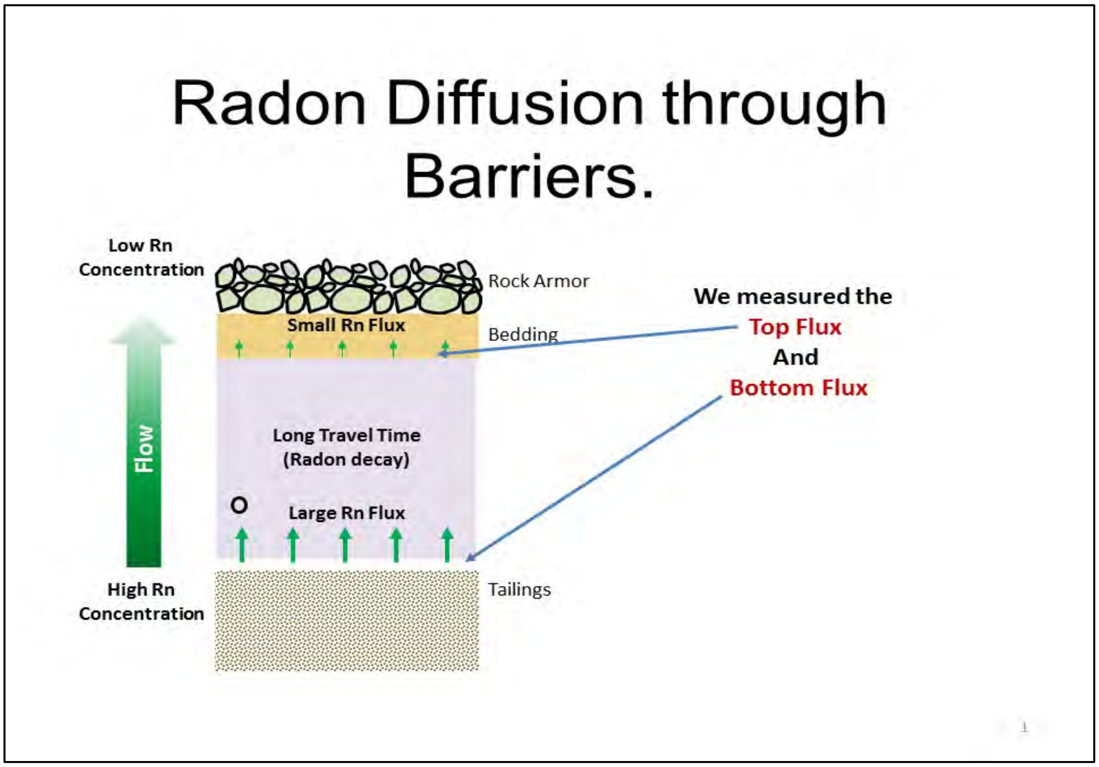
For the Lakeview site, the measurement of fluxes, even fluxes from the waste, was problematic due to the very low radon counts. Effective diffusion coefficients ranged from 3×10^{-6} to 7×10^{-8} m^2/s, with most being around 5×10^{-7} m^2/s, and travel times of less than one half-life.

2.7.2 Presentation



Radon Diffusion Coefficients and Travel Times through In-Service Radon Barriers

Mark Fuhrmann, Alex Michaud, Nicolas Stefani and Craig Benson



Radon Diffusion through Barriers.

Low Rn Concentration

Flow

High Rn Concentration

Rock Armor

Small Rn Flux

Bedding

Long Travel Time (Radon decay)

O

Large Rn Flux

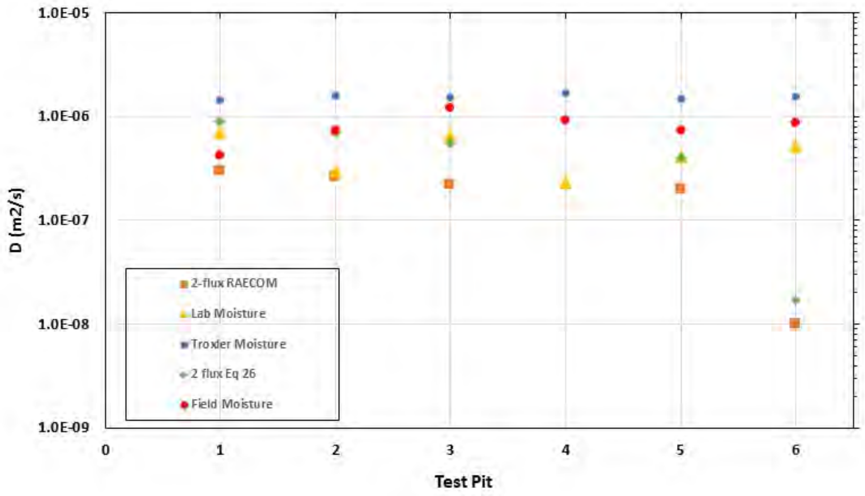
Tailings

We measured the **Top Flux** And **Bottom Flux**

Approaches to Estimate Diffusion Coefficients from Site Data

- 2-flux method using RAECOM to model diffusion (using measured **top and bottom** fluxes),
- 2-flux method using equation 26 from IAEA report 474,
- Moisture and porosity method using lab analysis of samples, empirical formula by Rogers and Nielson, 1991
- Moisture and porosity method using Troxler gauge measurements from the field.
- Moisture and porosity method using In-situ probe measurements.

Falls City: D calculated with Various Methods



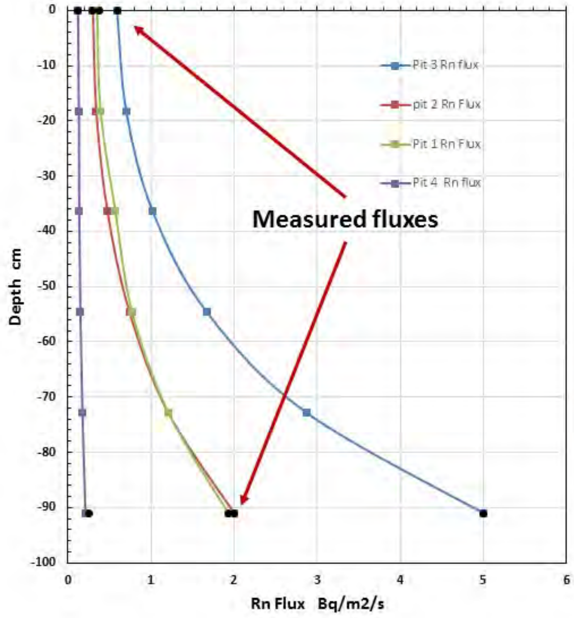
RAECOM Code

- Used for diffusion calculations to build radon barriers.
- Documented in NRC Regulatory Guide 3.64 (1989), NUREG/CR-2765 (1982), NUREG/CR-3533 (1984).
- Originally written on clay tablets, now Javascript.
- Input: flux from tailings, barrier thickness, layers, moisture, porosity.
- or flux from tailings and diffusion coefficient
- Output is steady-state D & Rn concentration in each layer.

Averaged Data for Falls City Barrier

Pit #	Location	Dry density g/cc Lab	Field dry density Troxler gauge g/cc	water % gravimetric	moisture saturation fraction	total porosity fraction
1	Top-deck	1.18	1.05	27.6	0.596	0.547
2	Top-deck	0.96	1.04	35.6	0.541	0.632
3	Top-deck	0.99	1.03	36.8	0.588	0.620
4	Top-deck	1.12	1.08	38.2	0.754	0.569
5	Apron	1.02	0.96	40.3	0.679	0.608
6	Slope	0.95	1.02	42.4	0.629	0.638
average		1.04	1.03	36.8	0.595	0.603

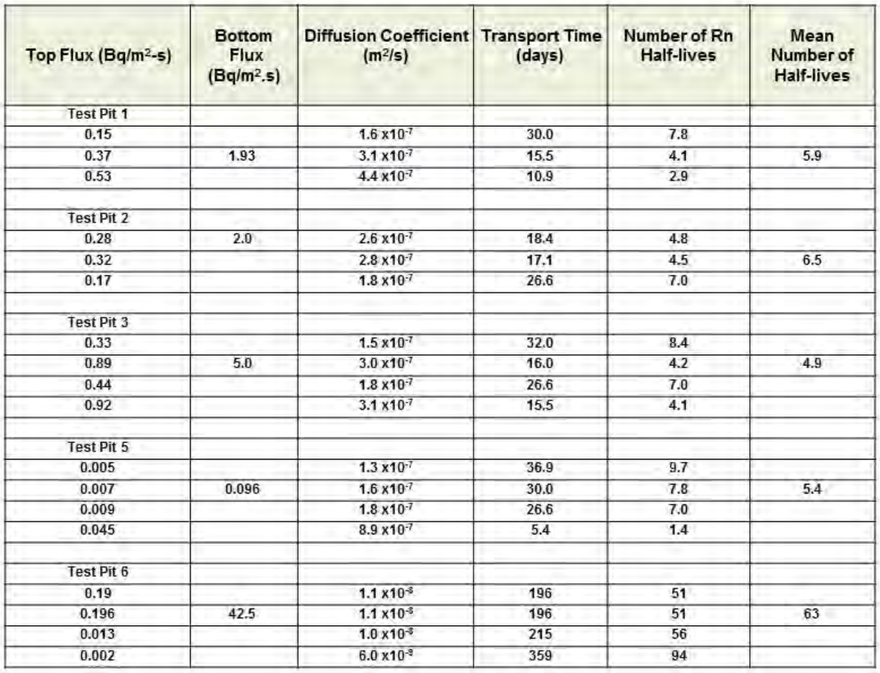
Falls City Rn Barrier Fluxes
Top Deck Pits



Input:
Measured bottom flux
Barrier thickness
Moisture content
Porosity

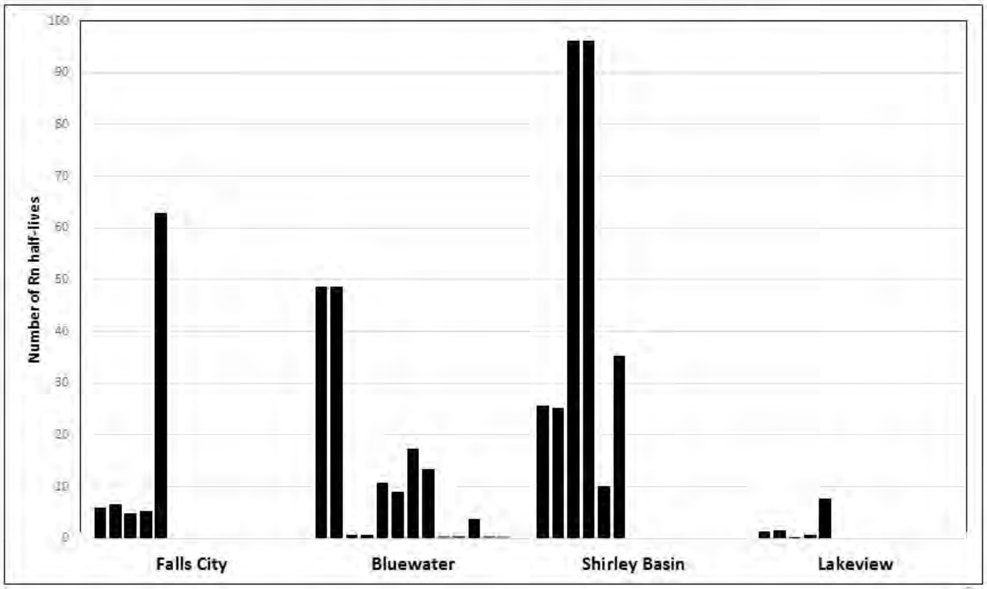
Output:
Diffusion coefficient
Rn fluxes from layers
Rn concentration in layers
Then
Adjust D to meet measured top flux

Falls City: Radon Fluxes, Diffusion Coefficients, and Transport Times

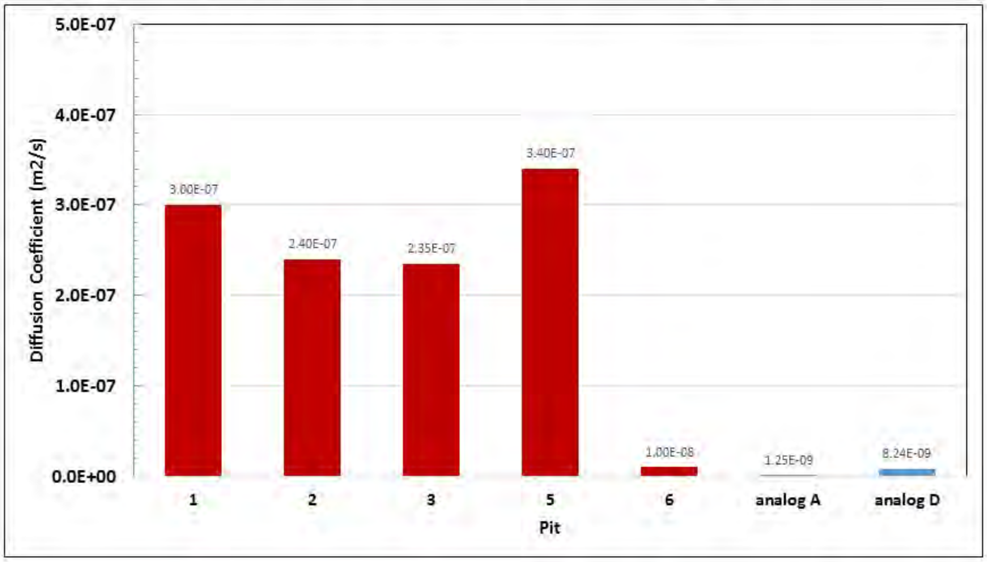


Top Flux (Bq/m^2-s)	Bottom Flux (Bq/m^2.s)	Diffusion Coefficient (m^2/s)	Transport Time (days)	Number of Rn Half-lives	Mean Number of Half-lives
Test Pit 1					
0.15		1.6 x10^{-7}	30.0	7.8	
0.37	1.93	3.1 x10^{-7}	15.5	4.1	5.9
0.53		4.4 x10^{-7}	10.9	2.9	
Test Pit 2					
0.28	2.0	2.6 x10^{-7}	18.4	4.8	
0.32		2.8 x10^{-7}	17.1	4.5	6.5
0.17		1.8 x10^{-7}	26.6	7.0	
Test Pit 3					
0.33		1.5 x10^{-7}	32.0	8.4	
0.89	5.0	3.0 x10^{-7}	16.0	4.2	4.9
0.44		1.8 x10^{-7}	26.6	7.0	
0.92		3.1 x10^{-7}	15.5	4.1	
Test Pit 5					
0.005		1.3 x10^{-7}	36.9	9.7	
0.007	0.096	1.6 x10^{-7}	30.0	7.8	5.4
0.009		1.8 x10^{-7}	26.6	7.0	
0.045		8.9 x10^{-7}	5.4	1.4	
Test Pit 6					
0.19		1.1 x10^{-8}	196	51	
0.196	42.5	1.1 x10^{-8}	196	51	63
0.013		1.0 x10^{-8}	215	56	
0.002		6.0 x10^{-9}	359	94	

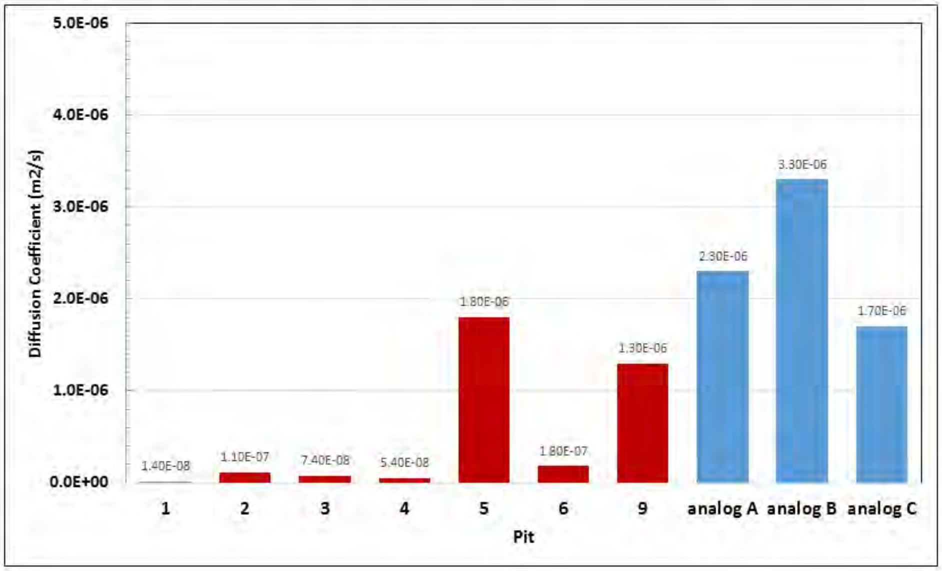
Number of Rn-222 Half-Lives for Transport through Radon Barriers



Falls City: Diffusion Coefficient for Disposal Cell and Analog Site



Bluewater: Diffusion Coefficient for Disposal Cell and Analog Site



Diffusion Coefficients

- Calculated for all flux measurements using RAECOM and the 2-flux method
- Allow estimate of transport times of Rn through barrier
- Allow comparison of D for the radon barrier and for analog sites.

2.7.3 Question and Answer Session for: Field Evaluation of Radon Fluxes from Radon Barriers at In-Service Uranium Mill Tailings Disposal Facilities, and Radon Diffusion Coefficients

Question. We know moisture content is very important for radon flux. Could you use geophysical methods to scan the whole site and get an overall average for moisture content?
Reply. You probably could use DOE/EM's electrical resistivity method or radar to create a map of water content.
Comment. Actually, those methods are really difficult in high-clay-content materials.
Comment. We know the relationship between radon flux and moisture content—the wetter the better. We know the moisture content as-built—they wet the material as much as possible to get optimum compaction. They measured moisture content as they built so they could continue building the barrier. They did not let the material dry out. So the question is how representative are the as-built measurements, without any structure development, to long-term conditions. Mark Fuhrmann has shown us how long it takes for radon to diffuse through the barriers. If you measure radon flux right away, the radon may not have enough time to come into equilibrium. So there is some question about how representative those as-built flux values are of initial conditions.
Comment. If you look at the construction specifications, these barriers are built in layers, and builders have to show that moisture and compaction requirements are met. That is the easiest way to control the quality of the radon barrier. So you should have a pretty good record.
Reply. Our whole construction quality assurance/quality control system has completely evolved. The whole focus was on compaction. In the old system, QA/QC was highly variable. Today, it is a different story—very predictable that you meet construction specifications.
Comment. When they were building these sites, as shown in the completion reports, there were sometimes well over 1,000 measurements of moisture and bulk density reported as different lifts were put on. That was to show optimized water content for compaction. If, as Jody Waugh was saying, they go immediately to radon flux measurements, after adding moisture, that will bias flux measurements low. We might have biased high.
Comment. But the flux is still within the flux criteria, so that tells me that there is a lot of margin built into the barrier.
Comment. Yes, and if you compare our bulk density and moisture content values for some of these sites, I think Falls City is one of them, our measurements are darned near the same as the as-built values.
Reply. Another point that Jody brought up is that the flux measurements were made as soon as the radon barrier was done, so that they could continue putting on other layers of the cover. The radon barrier is probably not in equilibrium with the flux of radon coming up from the waste, so the flux measurements may be biased low. Looking at the as-built test results, there are a lot of questions and methods have changed, yet our measurements and the as-built values are pretty much the same, which is really remarkable.
Comment. There is a regulatory requirement to perform that radon measurement within a certain amount of time, maybe 90 days.

Question. Did you measure the radium-226 content of the tailings? The emanation factor can differ significantly, depending on moisture conditions.
Reply. No, we were not allowed to touch the tailings. The completion reports typically have numbers for the emanation factor that were determined experimentally. I don't know how that relates to emanation in current conditions. At Shirley Basin South, the waste is pretty coarse grained and well drained.
Comment. On many of these sites, the barrier was not put directly on the tailings. There was a lot of very low-activity material, like windblown material, that they gathered up and put on top of

the tailings. So there was low-activity material above the tailings, and then the radon barrier was put over that.
Comment. That is why the Shirley Basin South site was so different. The radon barrier was directly on top of the tailings ponds. So we actually got to the surface of the waste, and it was visually different than the barrier material.

Question. Was an assumption about compaction built into the regression equation for the estimate of the diffusion coefficient? Didn't the equation assume a value like 95-percent compaction?
Reply. No, this equation is from Rogers and Nielson (1991), and they gathered a lot of data for it. Their relationship involves porosity and percent water saturation.

Question. The hydraulic properties change over time as the site is aging. The percolation rate probably goes back to what it was in the natural environment. Radon appears to be a different story. Although the site is changing, flux appears to be close to the way it was in the beginning. What further investigations do you need to do to verify that?
Reply. It is not what we expected. We expected that if we see changes in hydrology, we should see changes in flux. One fluid changes, so we should see similar changes in the other fluid too. That is not what we saw. This was a relatively small sample size of four sites, but with very different climates, construction methods, and cover profiles. There is some change in flux, but it is not as dramatic as changes in hydraulic properties. Maybe the range over which the diffusion coefficient varies over the practical range of moisture content is not the same as the range of hydraulic properties. Flux varies over two orders of magnitude, but hydraulic properties vary over six orders of magnitude. That probably has something to do with it.
Comment. Thinking of pore size distribution and connectivity of pores, maybe the saturated conductivity does not reflect changes in storability of the soil unit. If you attempt to make an impermeable barrier, it is in a state that is not happy with the environment. Perhaps nature is changing it in such a way that there are changes in saturated conductivity that are significant, but the changes in resistance to gas diffusion are much smaller.
Reply. That is valid. These are two different processes. One is a gas diffusion process, and the other is advection. Radon diffusion is controlled largely by water saturation and the saturated conductivity is controlled by the largest pores—different mechanisms.
Comment. Does some portion of the moisture characteristic curve potentially correlate to the radon diffusion coefficient?
Reply. You could look at shape changes to possibly pick up changes in radon diffusion coefficient.

Question. If saturated conductivity increases, does that translate to higher moisture content, which would mean a lower diffusion coefficient of radon?
Reply. Yes, sometimes, but it should drain more readily.
Comment. You might have to factor in vegetation and ET. ET drives most release of moisture.
Comment. Conductivity doesn't indicate levels of moisture content but only how fast moisture can move through.
Comment. Yes. If the barrier is more permeable, then a wetting front moves in more quickly, but it also will drain more quickly.

Question. The graph of hydraulic conductivity seems to indicate that, except for Shirley Basin South, it appears that changes are not yet finished. The deeper layers of the radon barrier did not seem to have changed yet. For the other three sites, it seems like the top layer of radon barrier had changed to values that you recommended, but some of the deeper ones had not.

Reply. This is most clear at Bluewater—we have one profile that is 2.5 meters deep, and we took five block samples. The trend is beautiful. [Editor’s note: see Section 2.5 p. 2-101]

Comment. If the bottom layer of radon barrier is close to its as-built condition, that will have an effect on the radon flux. Change has not extended to that depth.

Comment. Some of the Pb-210 data may speak to that.

Comment. This goes to the whole issue of the effect of changes stopping at a certain depth or extending deeper with more time.

Comment. This is the beauty of the analog studies. Looking at these analog sites may be able to tell us what is not a steady-state condition in the same material. Could the analogs inform the ultimate depth of structure formation?

Comment. The comparison of the natural analogs vs. the engineered barrier is of interest. There must be some differences; the barrier is put in with some machine, soil structure is destroyed, and then you assemble the soil as a barrier. The natural analog is untouched for thousands of years. Is there a point of disconnect where the analog part gets shaky?

Comment. Great point. Our analog sites are limited to the four DOE sites. They are in or near the disposal cell property. Considerable opportunity exists to explore natural analog sites regardless of whether they are on the property or not.

Comment. We need to grow the catalog. It would be nice to be able to go to the catalog and just pick one, or one that is close, when we are doing a performance assessment review.

Comment. Ideally, we should go to the same borrow area as was used for the barrier material.

Comment. We did that, but there is debate about it. In some instances, there are disadvantages to limiting your search to the borrow area.

2.8 A Survey of Soil Morphology and Process with Implications to Long-Term Performance at Four UMTRCA Sites

Presented by Morgan Williams
Ph.D. Candidate, Applied Soils Laboratory, University of California at Berkeley

2.8.1 Abstract

One of the primary uncertainties associated with the long-term success of geotechnical designs is the dynamic nature of soil condition over space and time. As part of an ongoing DOE/LM and NRC study that seeks to determine the impact of soil change on the performance of engineered cover systems in the UMTRCA portfolio, we have characterized the morphology of soils across the disposal cells in Bluewater, NM; Falls City, TX; Shirley Basin South, WY; and Lakeview, OR. Comparisons between as-designed and current radon barrier morphology indicate that patterns of soil change not only differ among the four sites studied but also across individual locations surveyed on the Bluewater and Lakeview sites. Herein, we highlight several key contributors to observed soil morphological conditions, including original barrier system design and present surface conditions. We give special emphasis to the decadal emergence of soil and root morphology at lateral distances away from individual surface features, including squirrel trail grass, bitterbrush, saltbush, rabbitbrush, and harvester ant mounds at the Bluewater and Lakeview sites. Although morphological relics of manufacturing (such as individual lift events) and visually striking heterogeneity in clay mineral composition are evident, we find, with few annotated anomalies, that emergent soil architecture within radon barriers across the individual profiles observed at the Falls City and Shirley Basin South sites are generally uniform, with the exception of small variations in very fine root development. Detailed diagrams and annotated photographs are provided that map soil morphology under dozens of surface features across the four sites surveyed, offering a unique window into commonly abstracted subsurface conditions of in-service radon barrier systems. A first-order effort to connect measured hydraulic performance (K_{SAT}) against a soil morphological development index is presented for the Bluewater site. We find that the emergence of soil architecture controls saturated hydraulic conductivity (K_{SAT}) at Bluewater, which results in the co-emergence of soil microbial food webs with potential implications for the long-term stabilization and maintenance of K_{SAT} regulating soil architecture. The talk concludes with a discussion on efforts to estimate the rates and qualities of soil change that are expected to occur over radon barrier design lifetimes (of 200–1,000 years) through the careful selection and study of adjacent natural analog sites. Such sites capture the cumulative imprint of earth surface processes on soil architecture under shared site and material factors, offering our best estimates of long-term soil condition and engineering performance of radon barrier systems through space and time.

2.8.2 Presentation

A SURVEY OF SOIL MORPHOLOGY & PROCESS

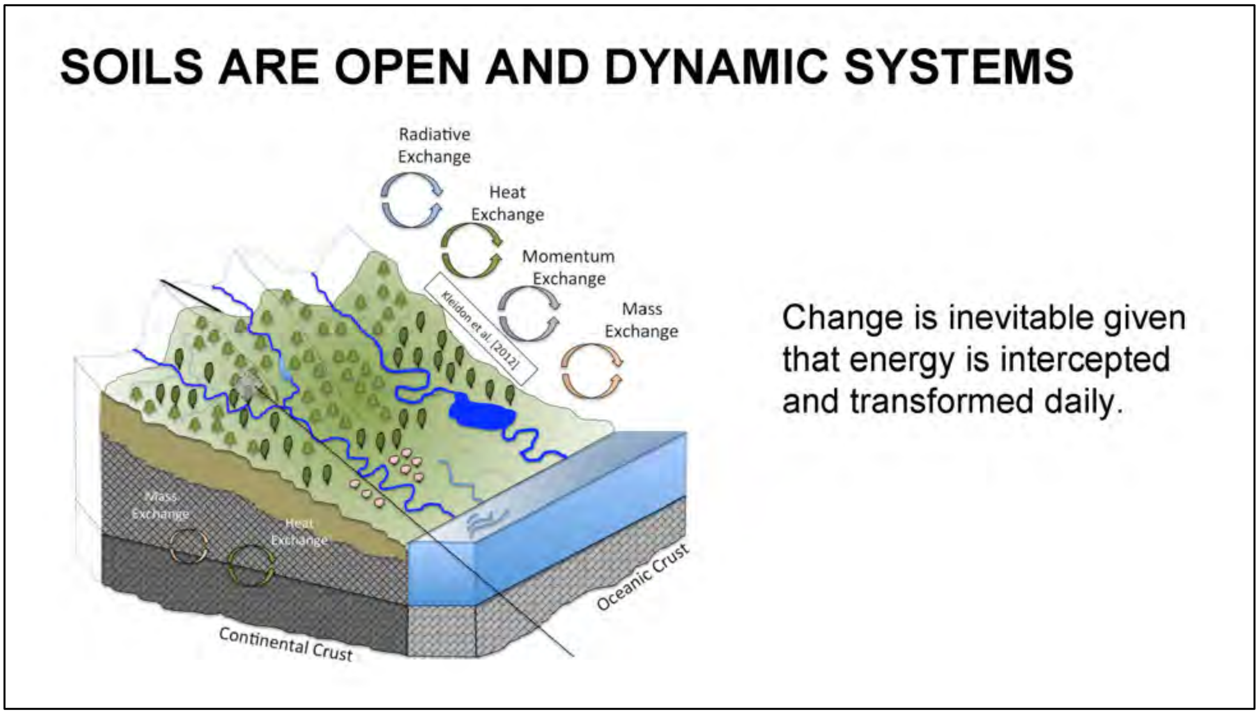
WITH IMPLICATIONS TO LONG TERM PERFORMANCE

Morgan M Williams
July 25th 2018

morgan.williams@berkeley.edu

NRC RADON BARRIER MEETING

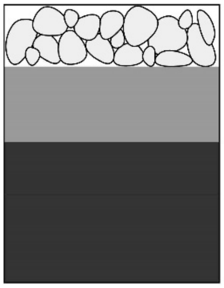
Berkeley
UNIVERSITY OF CALIFORNIA



SOILS ARE OPEN AND DYNAMIC SYSTEMS

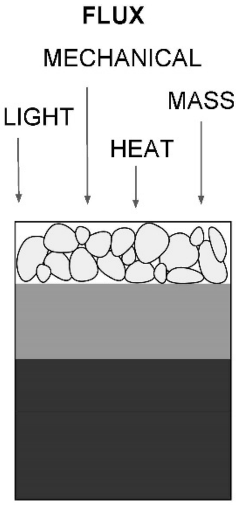
Change is inevitable given that energy is intercepted and transformed daily.

SOILS ARE OPEN AND DYNAMIC SYSTEMS



TIME = 0

SOILS ARE OPEN AND DYNAMIC SYSTEMS

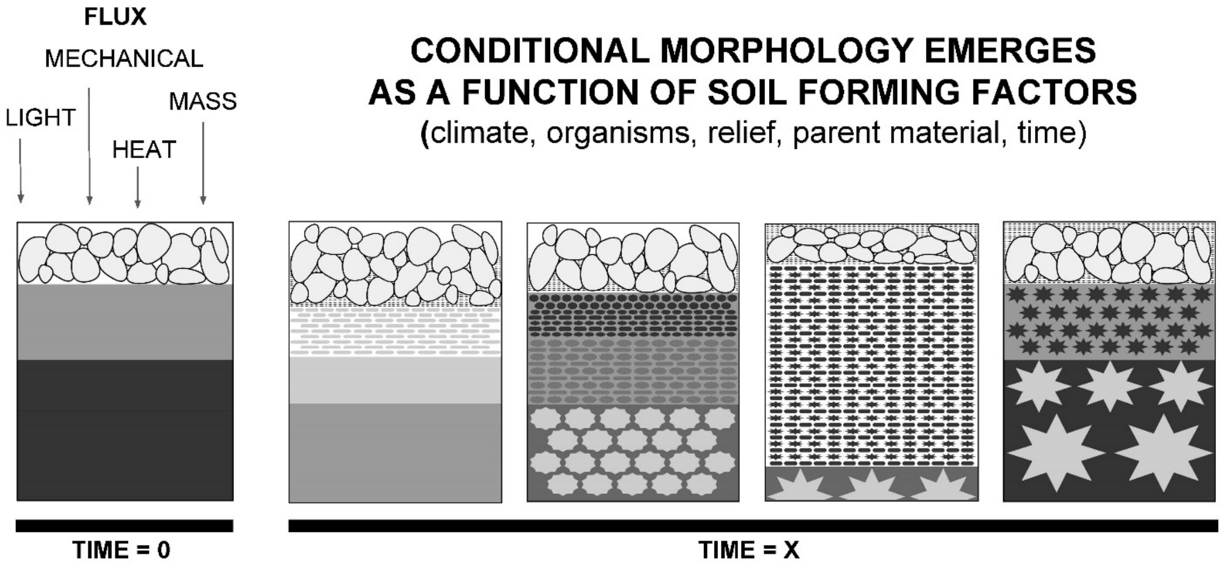


TIME = 0

SOILS ARE OPEN AND DYNAMIC SYSTEMS

CONDITIONAL MORPHOLOGY EMERGES AS A FUNCTION OF SOIL FORMING FACTORS

(climate, organisms, relief, parent material, time)



FLUX

MECHANICAL

LIGHT

MASS

HEAT

TIME = 0

TIME = X

WHAT DOES THIS MEAN FOR ENGINEERED SOILS THAT WERE DESIGNED TO PERFORM REGULATED TASKS OVER TIME?

Center For Land Use Interpretation

JOINT AGENCY RADON BARRIERS PROJECT

U.S. DEPARTMENT OF ENERGY LEGACY MANAGEMENT	UNIVERSITY of VIRGINIA ENGINEERING	College of Engineering UNIVERSITY OF WISCONSIN-MADISON	DRI Desert Research Institute	UNITED STATES NUCLEAR REGULATORY COMMISSION
Jody Waugh	Craig Benson	Bill Likos Xiadong Wang Nick Stefani Alex Michaud	Bill Albright	Mark Fuhrmann

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A TOUR OF SOIL MORPHOLOGY AND PROCESS ACROSS FOUR UMTRCA SITES

SITE SOIL SURVEYS

LOCATIONS STUDIED

- FALLS CITY, TX
- BLUEWATER, NM
- SHIRLEY BASIN, WY
- LAKEVIEW, OR

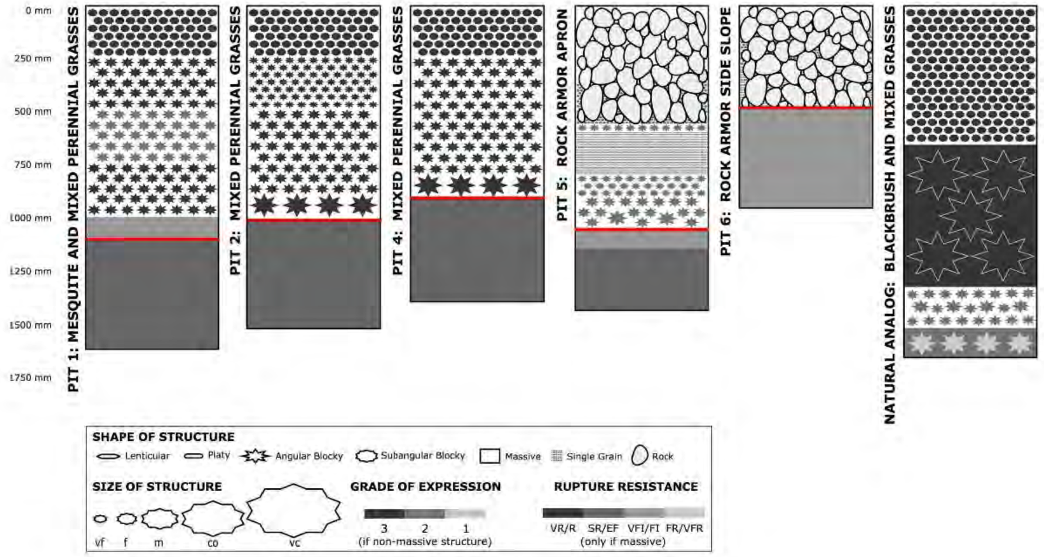
SITE SOIL SURVEYS

METRICS OF FOCUS

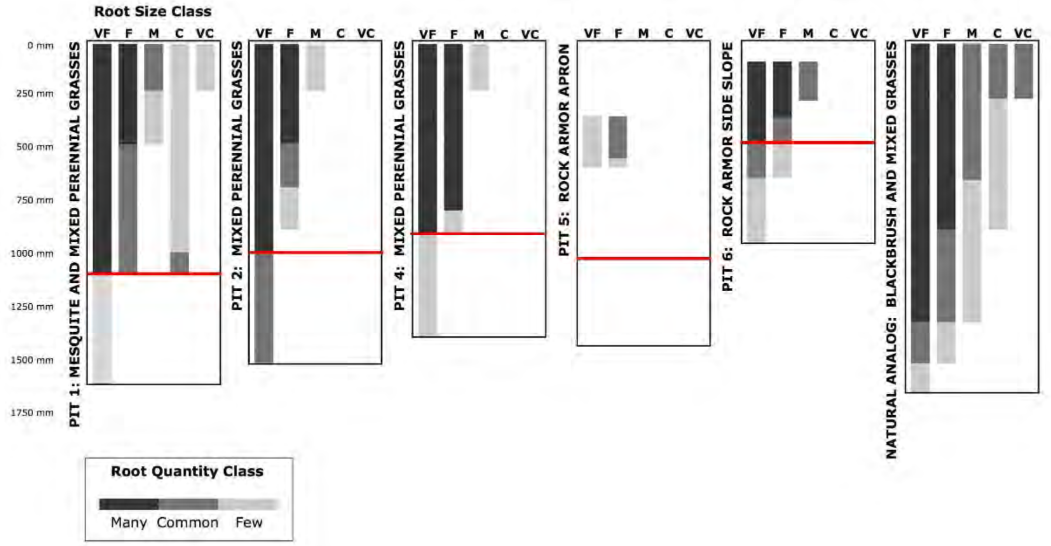
1) SOIL STRUCTURE
   (CLASS, SIZE, AND GRADE)
2) ROOT MORPHOLOGY
   (SIZE AND QUANTITY)
3) SOIL CHEMISTRY
   (C, N, CO3, pH, EC …)
4) SOIL BIOLOGY
   (NEMATODES, BACTERIA…)
5) ANOMALIES
   (CONSTRUCTION RELICS…)

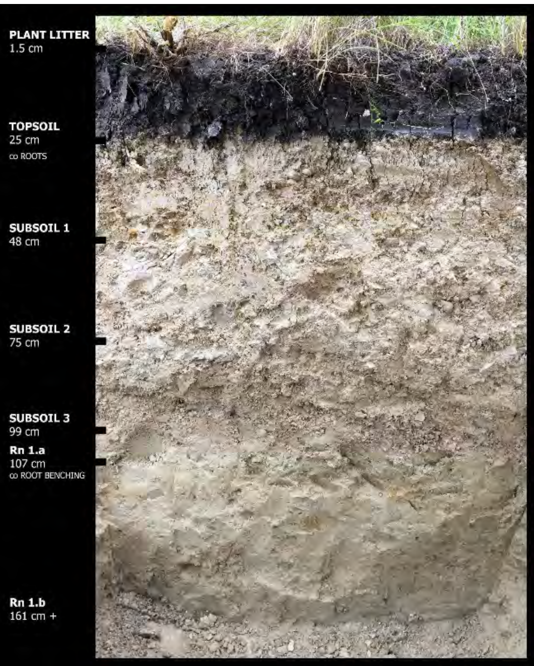
FALLS CITY, TEXAS

FALLS CITY, TX : SOIL ARCHITECTURE



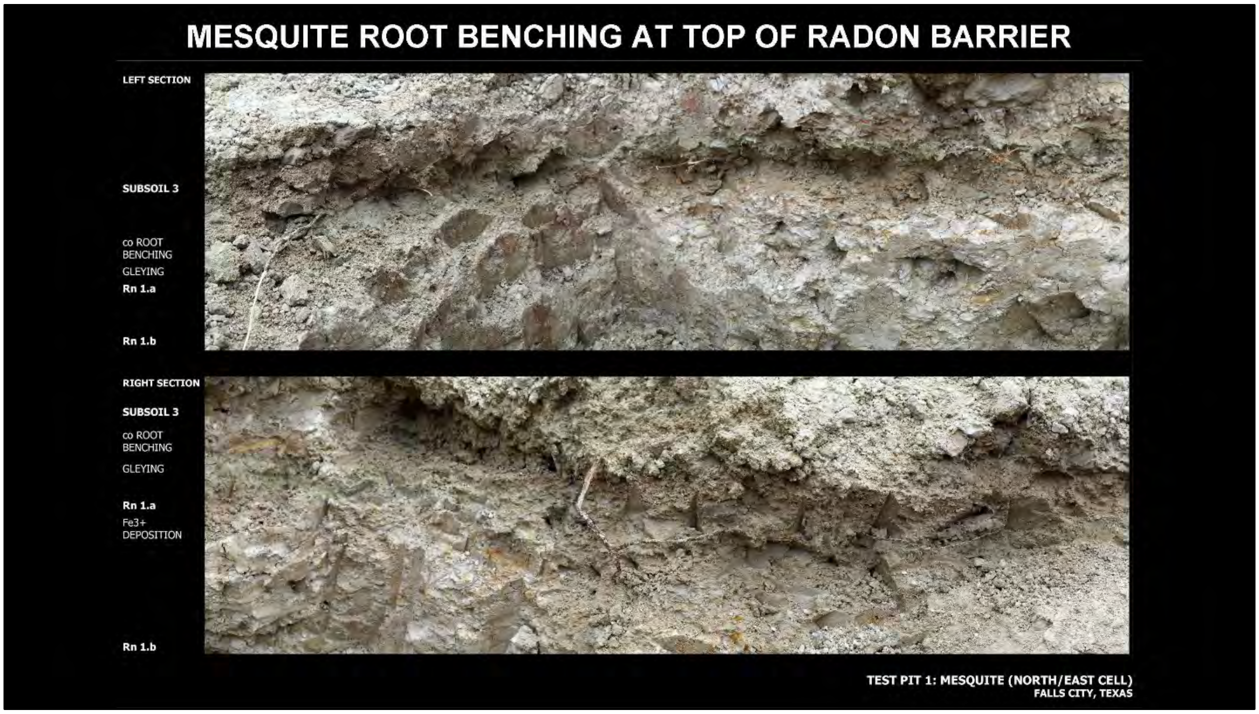
FALLS CITY, TX : ROOT MORPHOLOGY





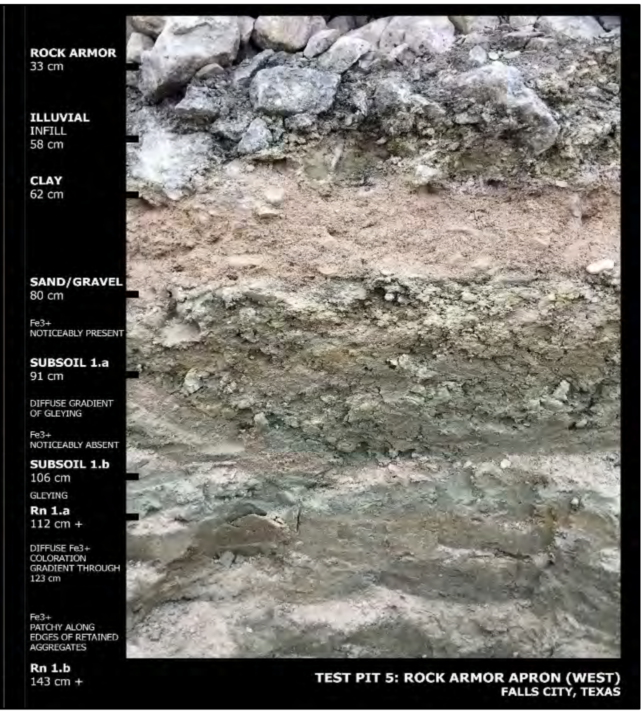
TEST PIT 1: MESQUITE (NORTH/EAST CELL)
FALLS CITY, TEXAS

TEST PIT 2: MIXED PERENNIAL FORAGE GRASSES
FALLS CITY, TEXAS



TEST PIT 1: MESQUITE (NORTH/EAST CELL)
FALLS CITY, TEXAS

TEST PIT 6: ROCK ARMOR SLOPE (WEST)
FALLS CITY, TEXAS

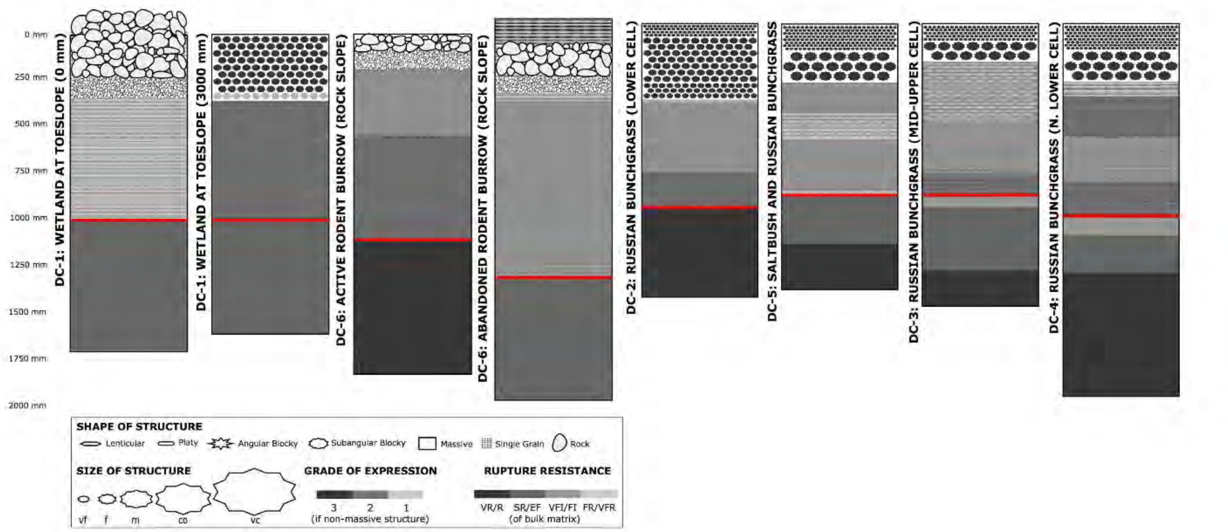


TEST PIT 5: ROCK ARMOR APRON (WEST)
FALLS CITY, TEXAS

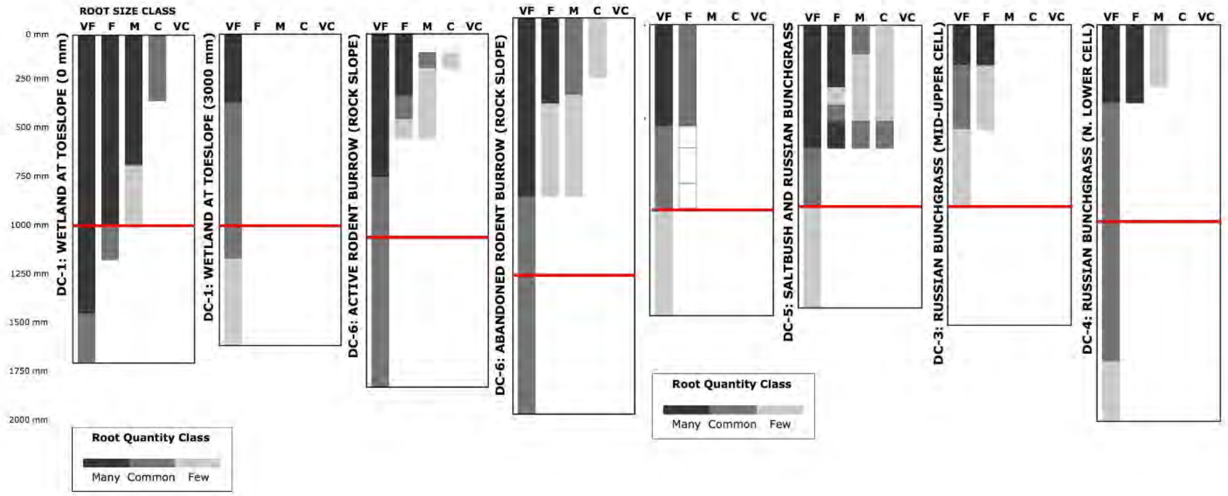
KEY OBSERVATIONS

- Relatively even soil morphology in radon barrier
- Some anomalies with rooting depth and density
- Horizontal root benching (mesquite) on top of barrier
- Barrier was very moist (and redox features plentiful)
- Rock slope was a distinct system
    - (barrier depth, rooting, moisture, redox)

SHIRLEY BASIN, WYOMING

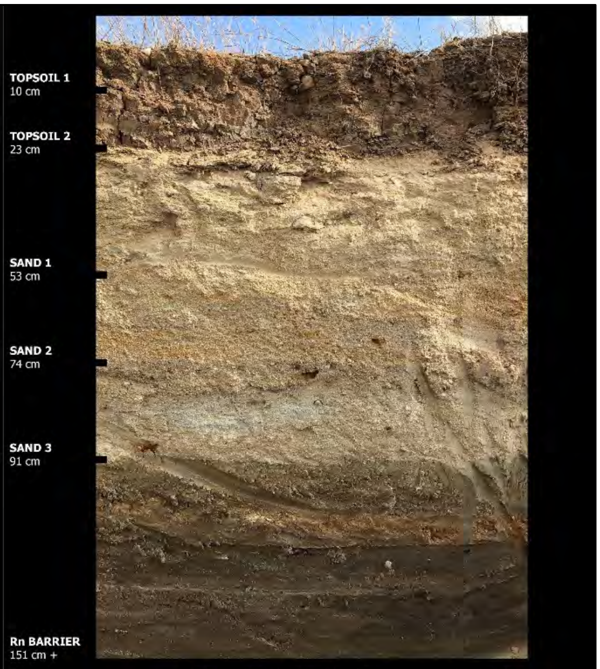


SHIRLEY BASIN, WY : SOIL ARCHITECTURE



SHIRLEY BASIN, WY : ROOT MORPHOLOGY

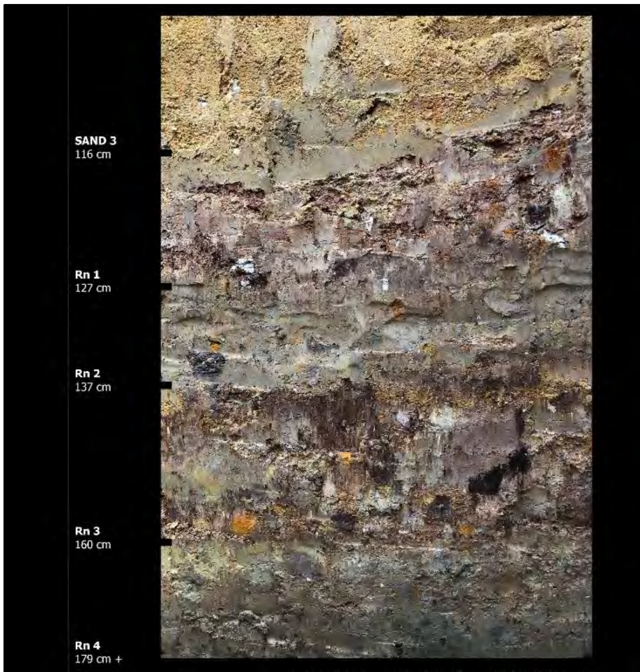
DC-5: SALTBUSH - SOUTH LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING



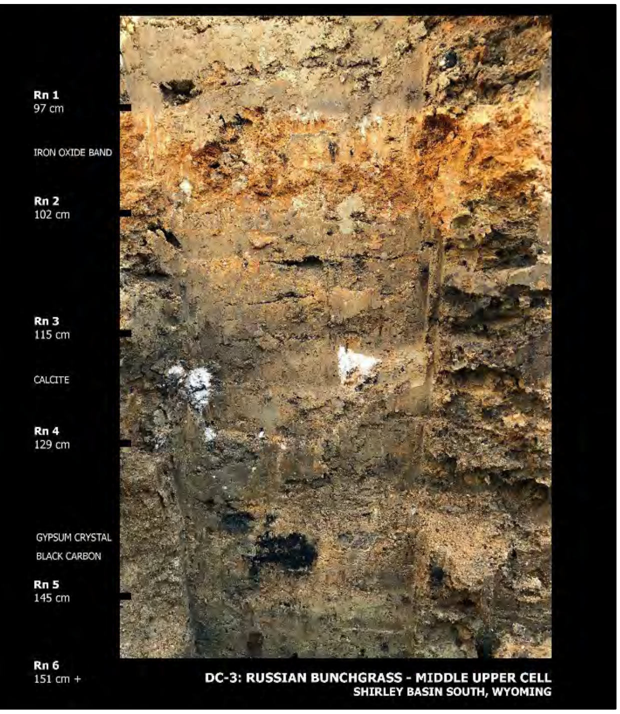
DC-3: RUSSIAN BUNCHGRASS - MIDDLE UPPER CELL
SHIRLEY BASIN SOUTH, WYOMING

DC-4: RUSSIAN BUNCHGRASS - NORTH LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING

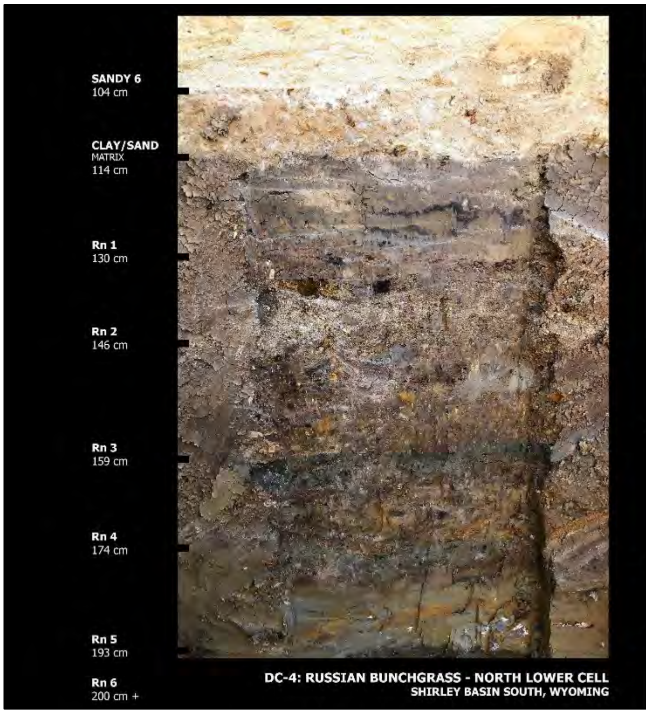
DC-2: RUSSIAN BUNCHGRASS - BOTTOM LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING



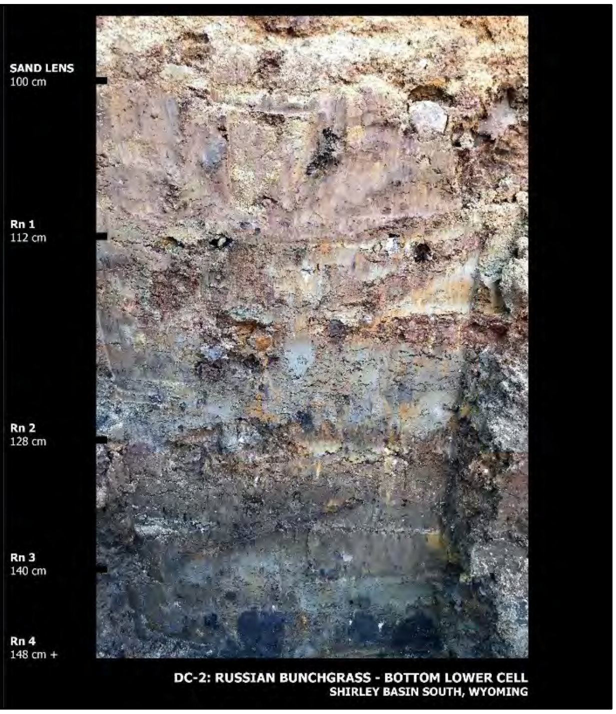
DC-1: WETLAND GRADIENT - TOESLOPE 0 cm
SHIRLEY BASIN SOUTH, WYOMING



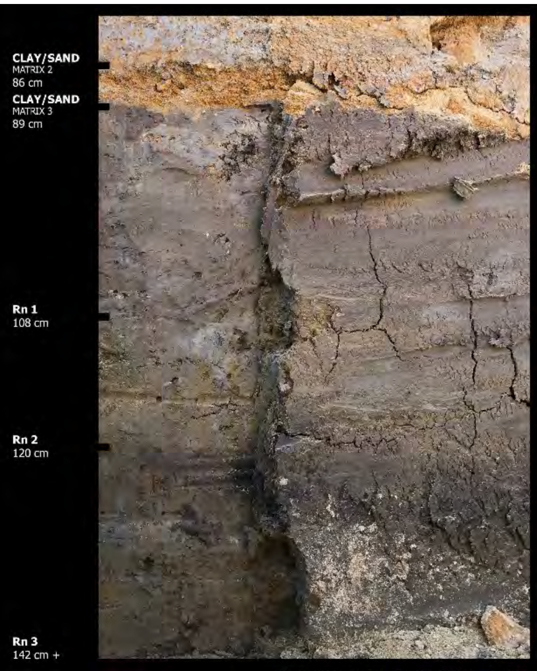
DC-3: RUSSIAN BUNCHGRASS - MIDDLE UPPER CELL
SHIRLEY BASIN SOUTH, WYOMING



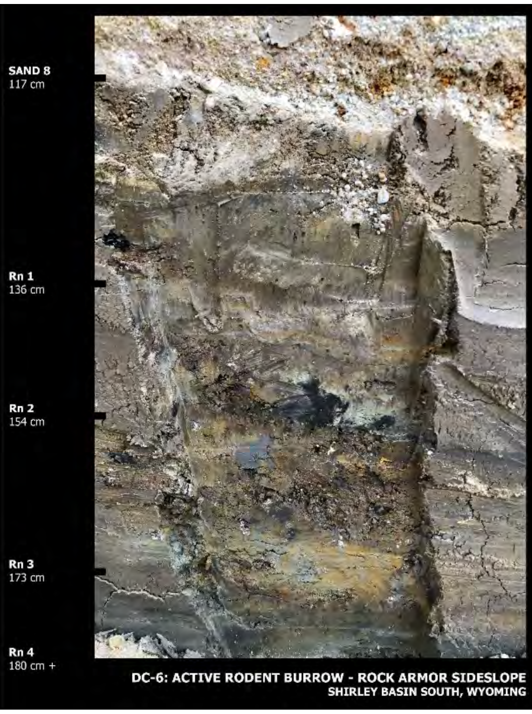
DC-4: RUSSIAN BUNCHGRASS - NORTH LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING



DC-2: RUSSIAN BUNCHGRASS - BOTTOM LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING



DC-5: SALTBUSH - SOUTH LOWER CELL
SHIRLEY BASIN SOUTH, WYOMING



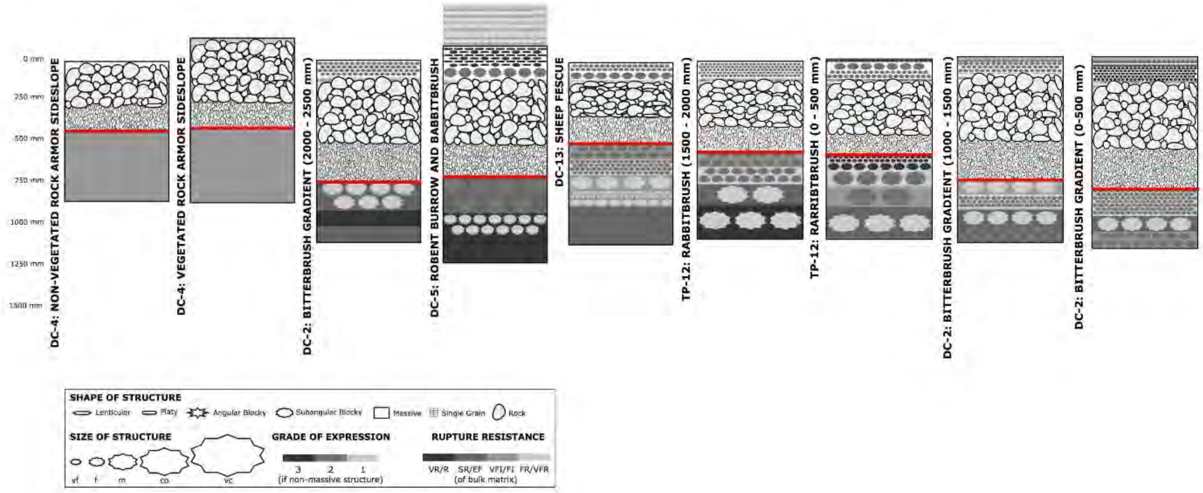
DC-6: ACTIVE RODENT BURROW - ROCK ARMOR SIDESLOPE
SHIRLEY BASIN SOUTH, WYOMING

KEY OBSERVATIONS

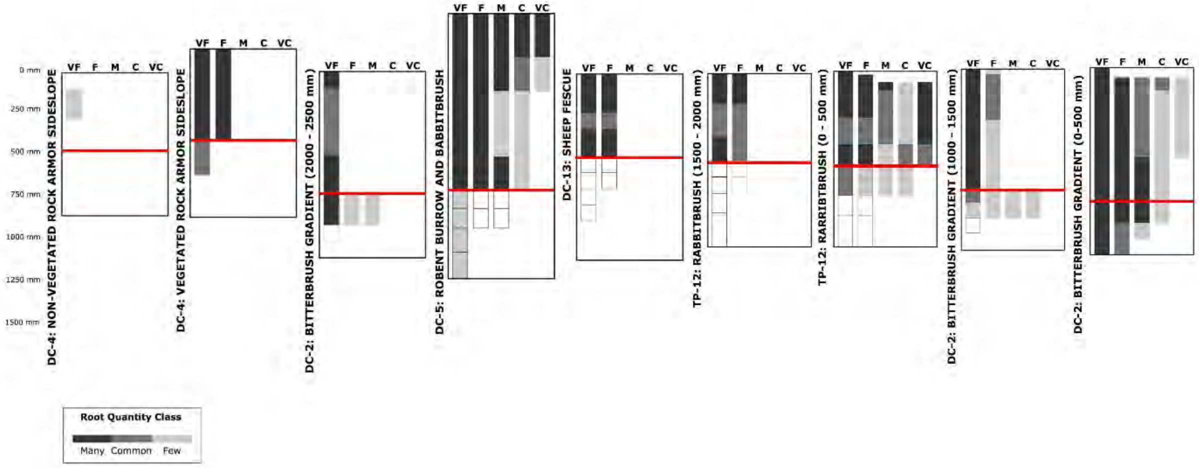
- Relatively even morphology in radon barrier
- Some anomalies with rooting depth and density
- Anomalies in sandy overburden thickness and composition
- Considerable anomalies in radon barrier construction morphology
- Barrier was very moist (and redox features plentiful)

LAKEVIEW, OREGON

LAKEVIEW, OR : SOIL ARCHITECTURE

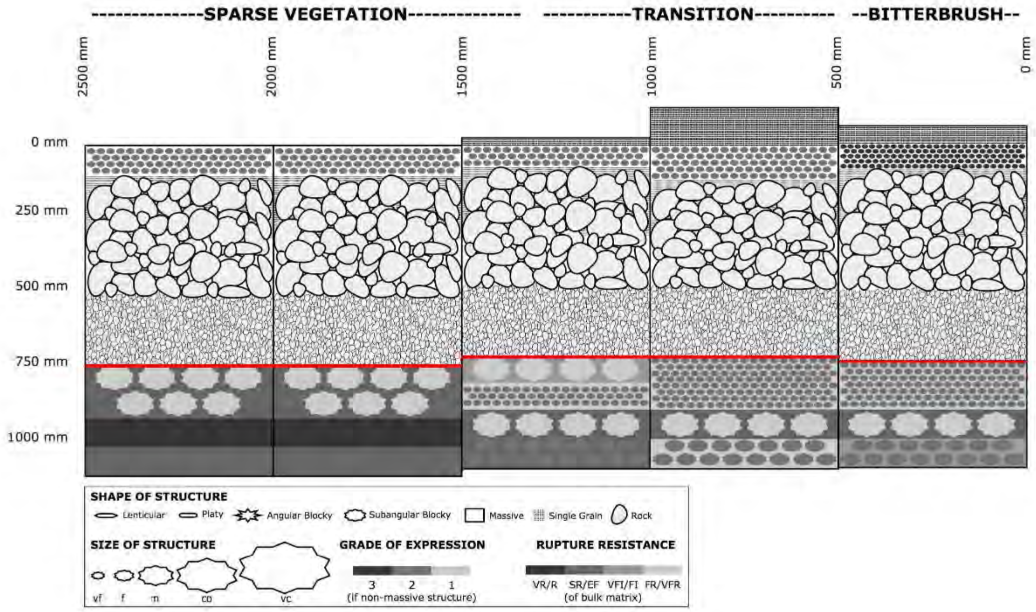


LAKEVIEW, OR : ROOT MORPHOLOGY

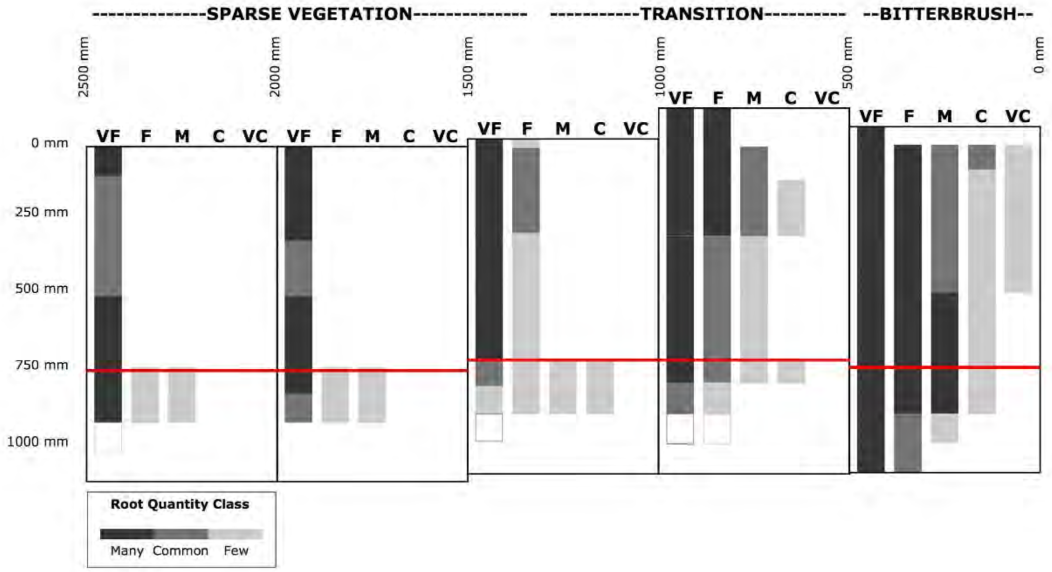


DC-2: BITTERBRUSH IMPACT GRADIENT
LAKEVIEW, OREGON

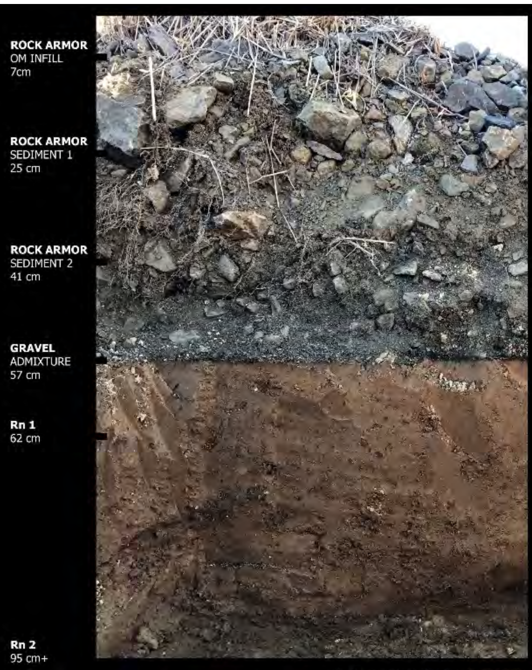
DC-2: BITTERBRUSH - SOIL ARCHITECTURE



DC-2: BITTERBRUSH - ROOT MORPHOLOGY



DC-12: RABBITBRUSH IMPACT GRADIENT
LAKEVIEW, OREGON



DC-4: ROCKSLOPE VEGETATED
LAKEVIEW, OREGON

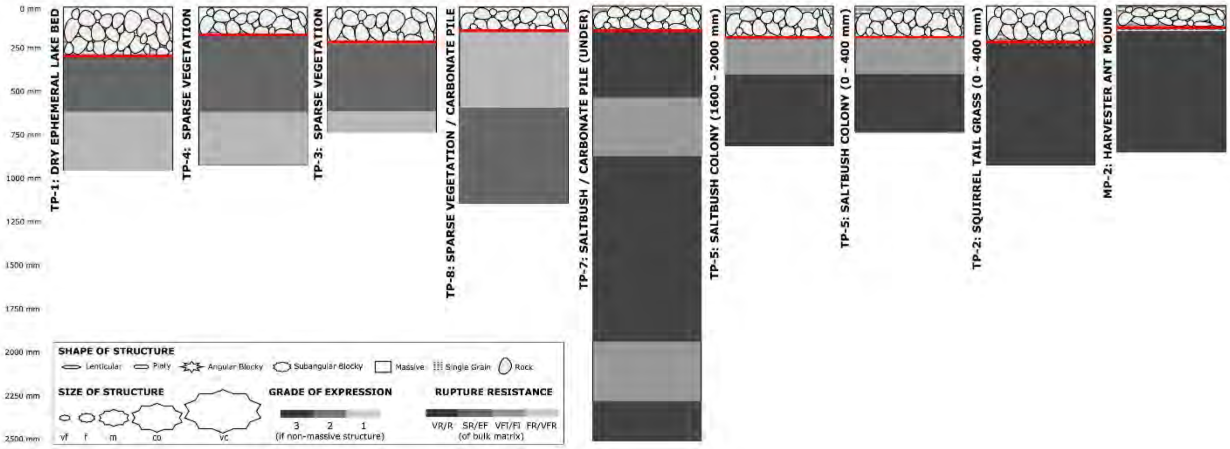
DC-4: ROCKSLOPE VEGETATED
LAKEVIEW, OREGON

KEY OBSERVATIONS

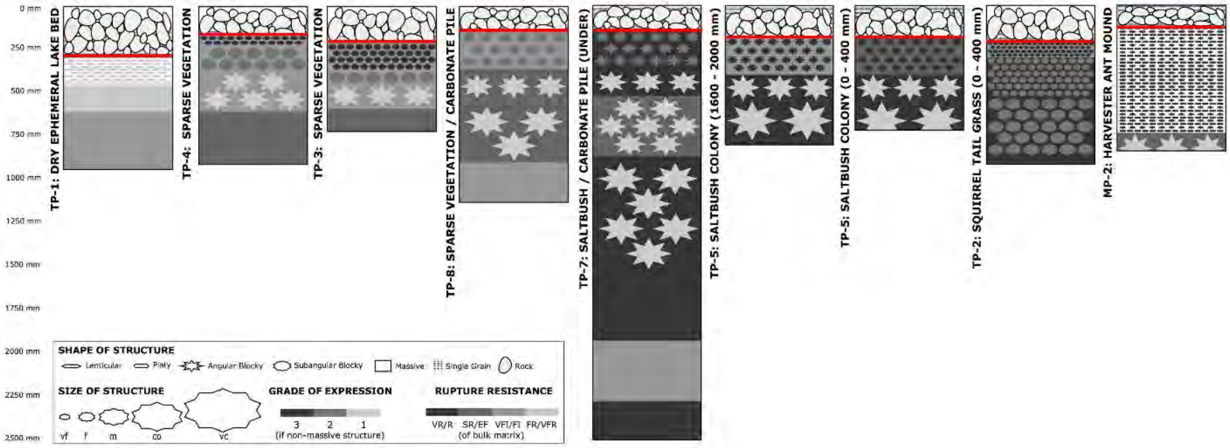
- Emergence of impact gradients
- Surface feature(s) influence soil morphology of radon barrier (ped and root structure)
- Some anomalies in radon barrier construction morphology
  - Texture of lift events
- Rock slope was a distinct system
  - (barrier depth, vegetation, moisture)

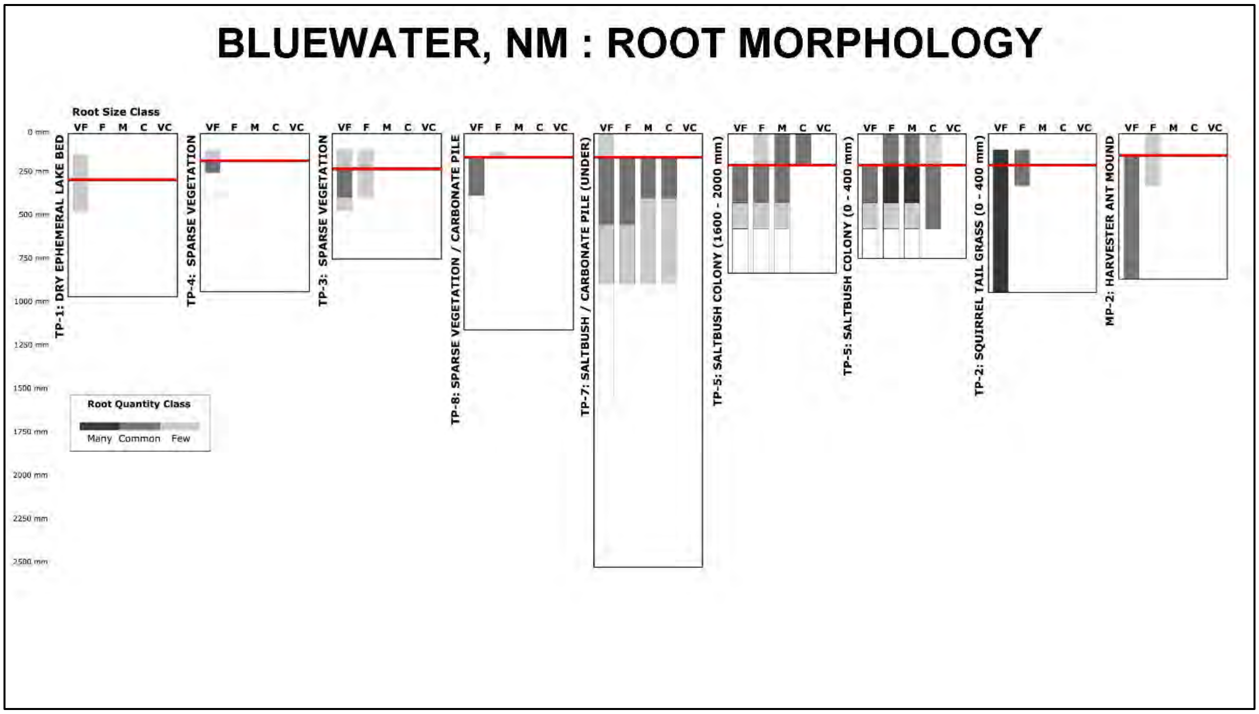
BLUEWATER, NEW MEXICO

BLUEWATER, NM : SOIL ARCHITECTURE
(HYPOTHETICAL AT CONSTRUCTION)



BLUEWATER, NM : SOIL ARCHITECTURE

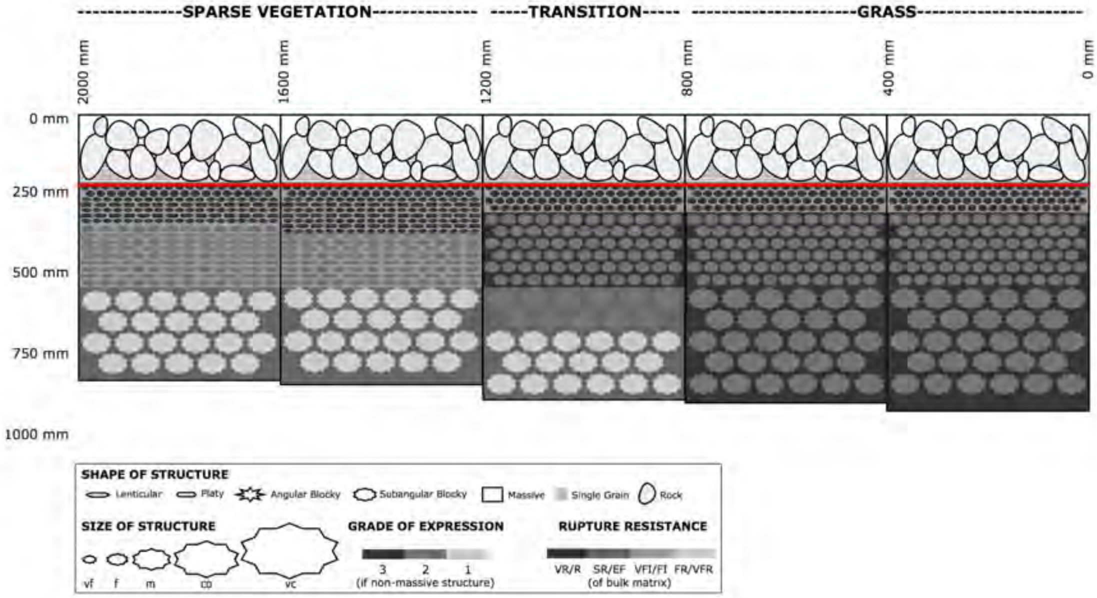




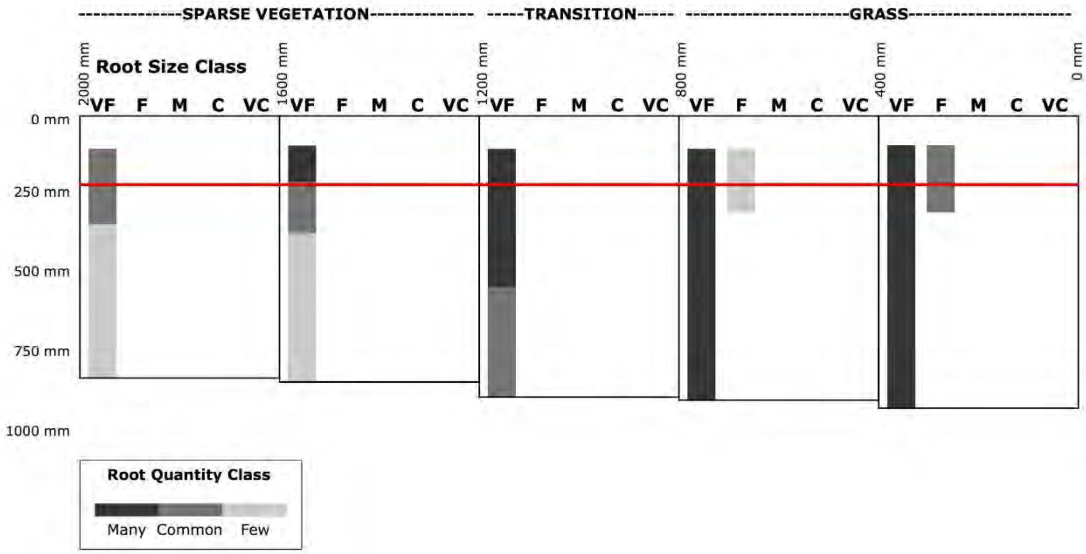
BLUEWATER, NM : ROOT MORPHOLOGY

TP-4 : SPARSE ANNUAL VEGETATION (UPPER CELL / SANDY TAILINGS)
BLUEWATER, NEW MEXICO

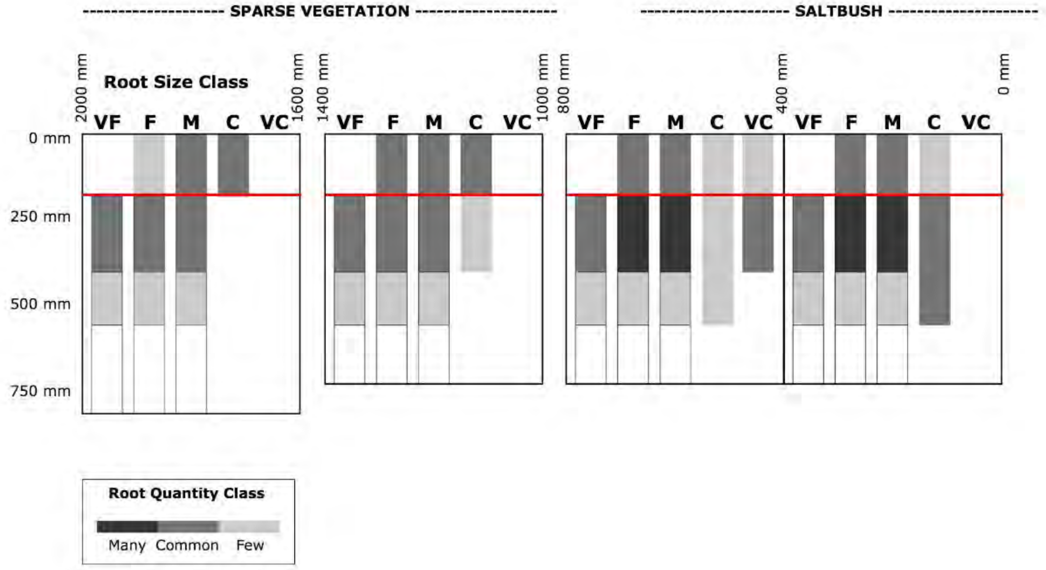
TP-2: SQUIRREL TAIL GRASS - SOIL ARCHITECTURE



TP-2: SQUIRREL TAIL GRASS - ROOT MORPHOLOGY

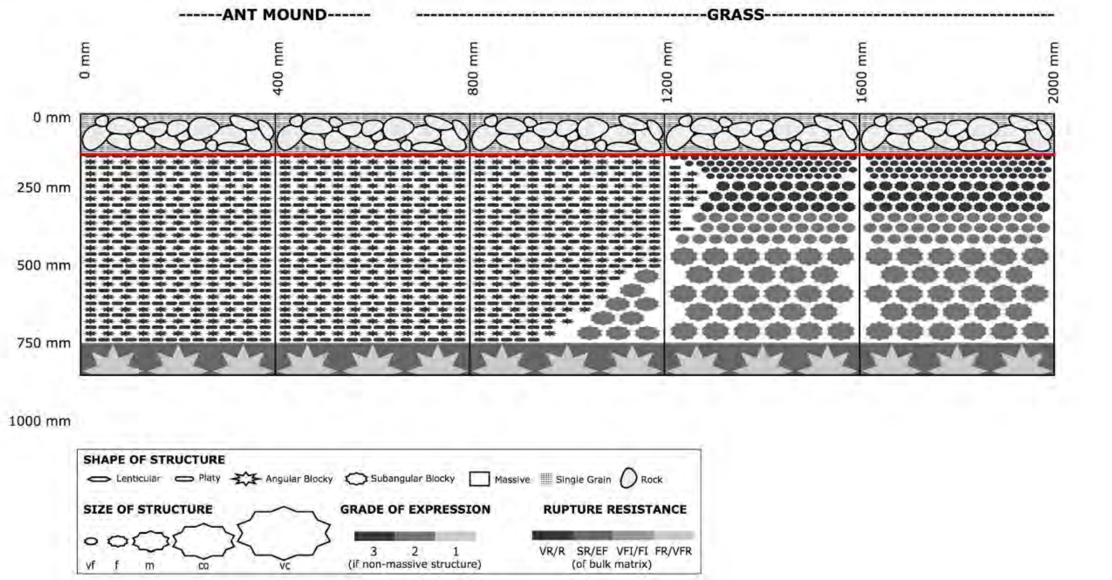


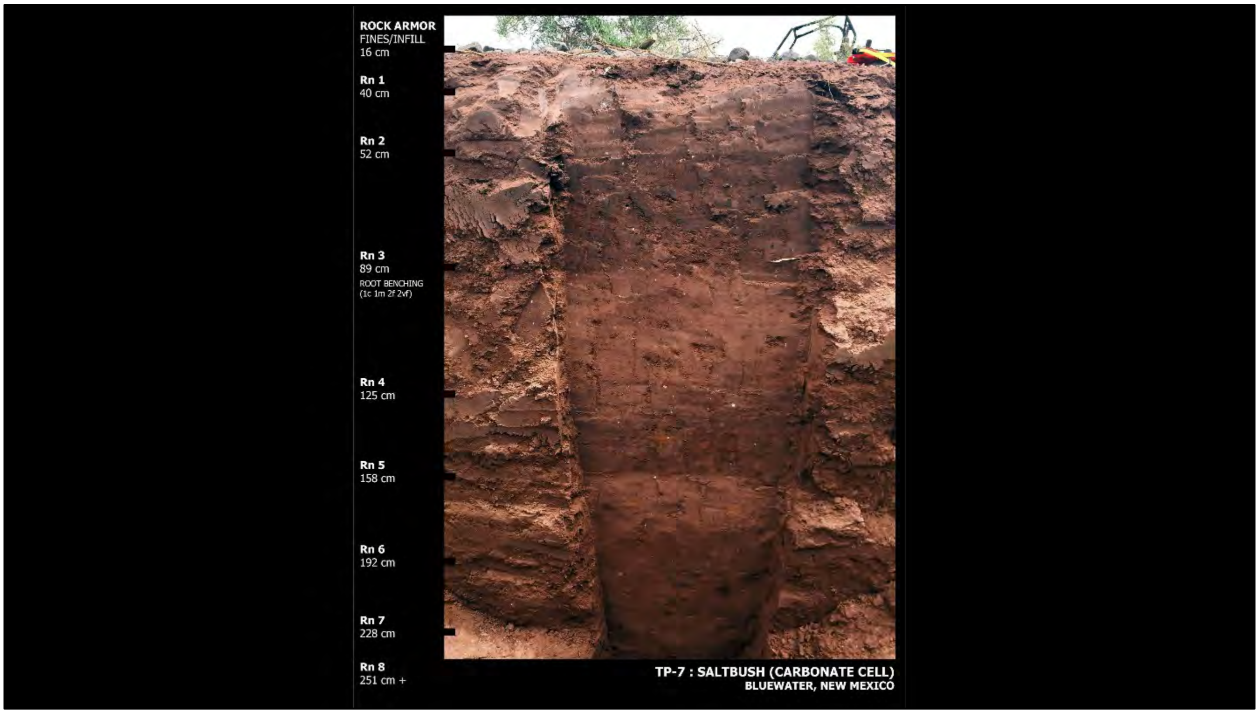
TP-5: SALTBUSH - ROOT MORPHOLOGY

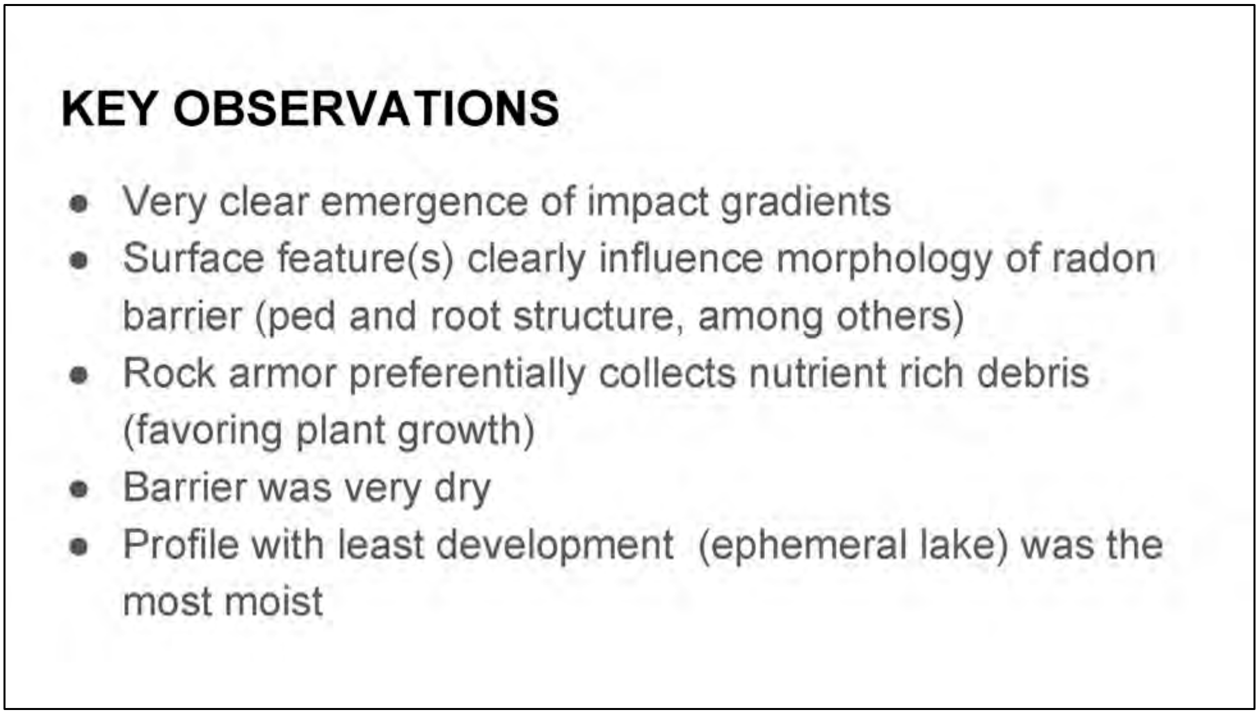


MP-2: HARVESTER ANT MOUND (MID-UPPER CELL / SANDY TAILINGS)
BLUEWATER, NEW MEXICO

MP-6: HARVESTER ANT MOUND - SOIL ARCHITECTURE







KEY OBSERVATIONS

- Very clear emergence of impact gradients
- Surface feature(s) clearly influence morphology of radon barrier (ped and root structure, among others)
- Rock armor preferentially collects nutrient rich debris (favoring plant growth)
- Barrier was very dry
- Profile with least development (ephemeral lake) was the most moist

HOW DOES OBSERVED SOIL MORPHOLOGY INFLUENCE HYDRAULIC CONDUCTIVITY?

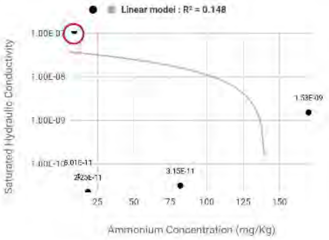
- Focus on Bluewater and Shirley Basin Ksat data
    - Falls City and Lakeview still in process
- Bluewater = shallow, rock barrier
- Shirley Basin = deep, planted barrier

SHIRLEY BASIN, WYOMING

POSSIBLE PREDICTORS FOR HYDRAULIC CONDUCTIVITY

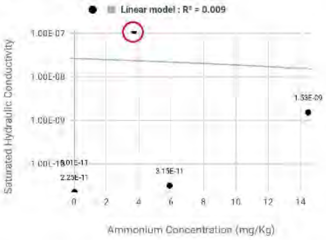
AMMONIUM CONCENTRATION (mg/Kg)

n=5



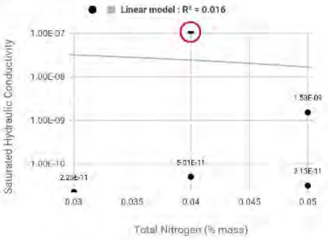
NITRATE CONCENTRATION (mg/Kg)

n=5



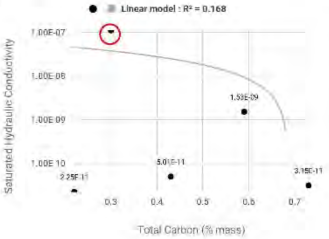
TOTAL NITROGEN (% mass)

n=5



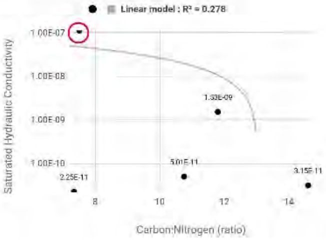
TOTAL CARBON (% mass)

n=5



CARBON:NIRTOGEN (ratio)

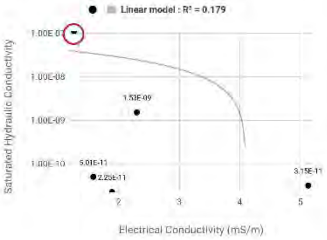
n=5



POSSIBLE PREDICTORS FOR HYDRAULIC CONDUCTIVITY

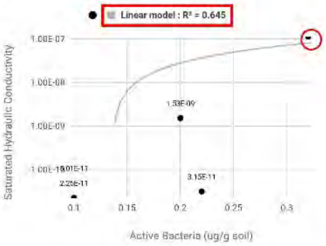
ELECTRICAL CONDUCTIVITY (mS/m)

n=5



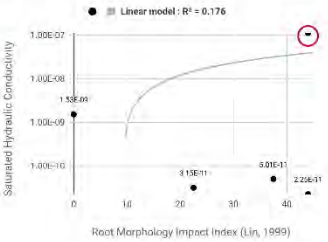
ACTIVE BACTERIA (ug/g soil)

n=5



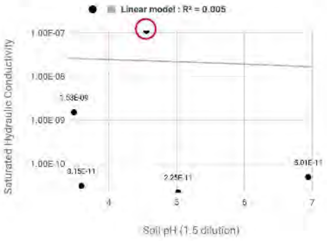
ROOT MORPHOLOGY (point conversion; Lin, 1999)

n=11



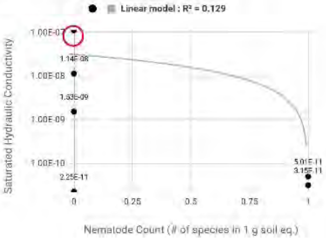
SOIL pH

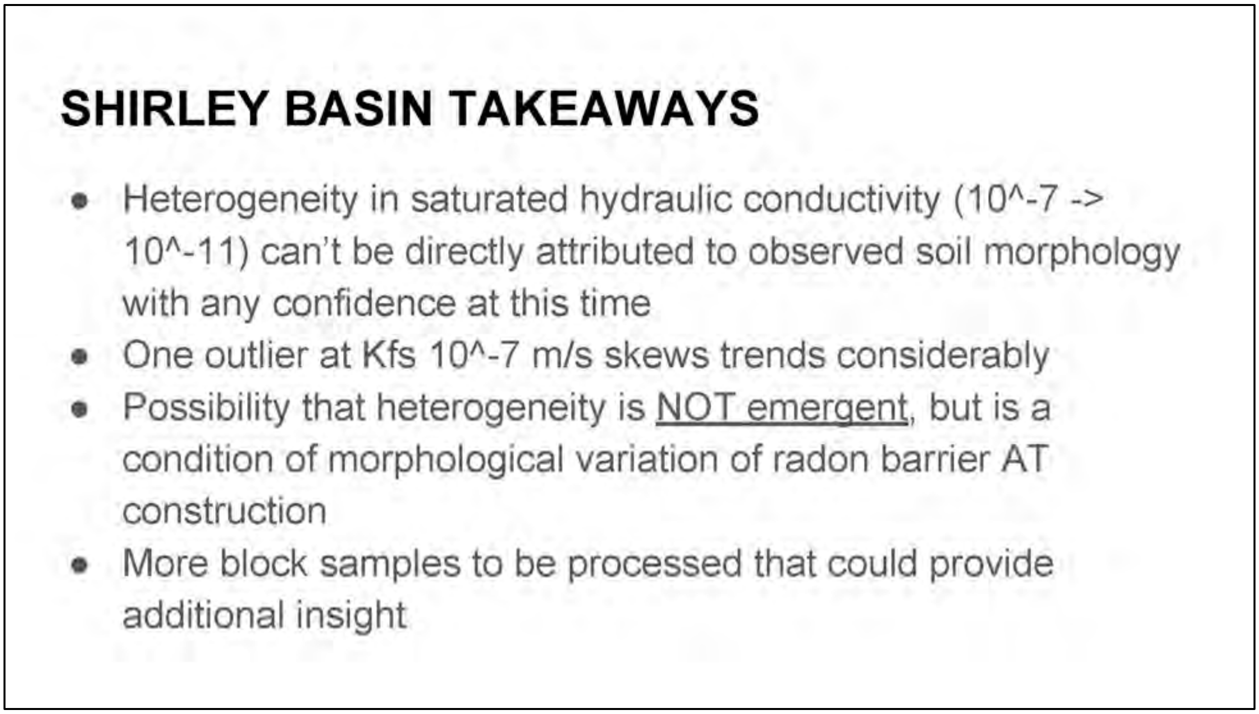
n=5



NEMATODE SPECIES COUNT (# of species)

n=5





SHIRLEY BASIN TAKEAWAYS

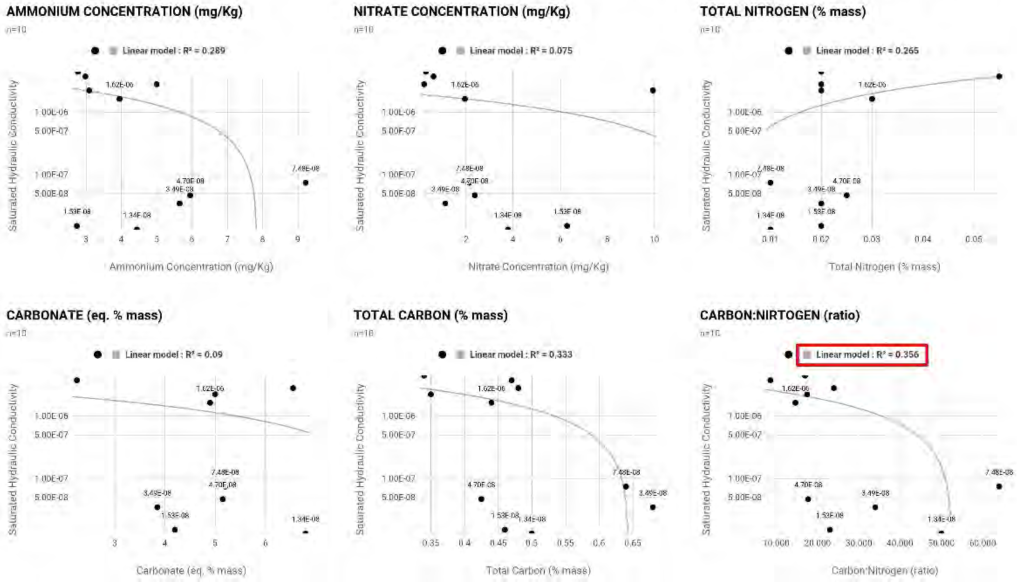
- Heterogeneity in saturated hydraulic conductivity (10^-7 -> 10^-11) can't be directly attributed to observed soil morphology with any confidence at this time
- One outlier at Kfs 10^-7 m/s skews trends considerably
- Possibility that heterogeneity is NOT emergent, but is a condition of morphological variation of radon barrier AT construction
- More block samples to be processed that could provide additional insight

DC-1: WETLAND GRADIENT - TOESLOPE 0 cm
SHIRLEY BASIN SOUTH, WYOMING

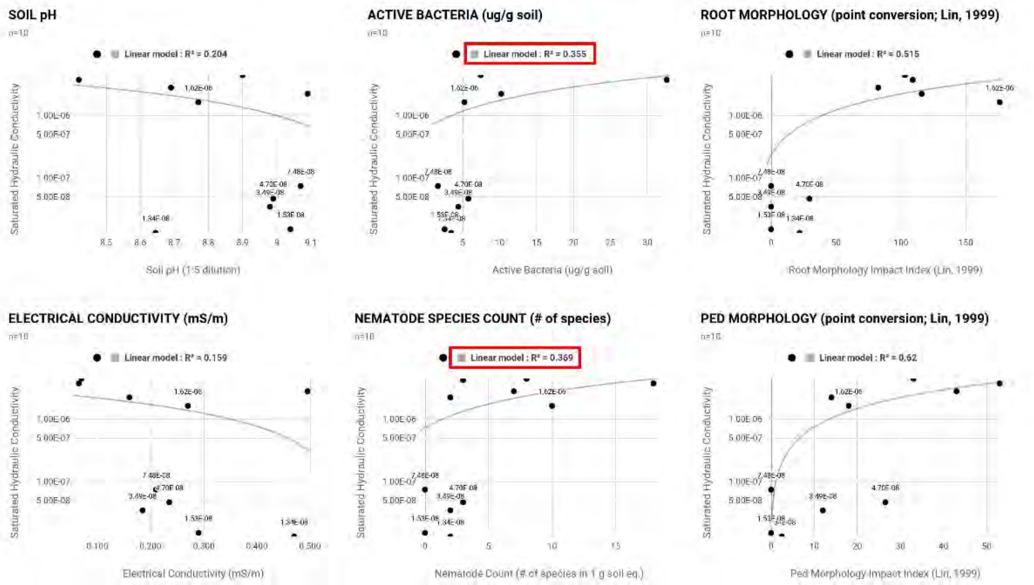
DC-3: RUSSIAN BUNCHGRASS - MIDDLE UPPER CELL
SHIRLEY BASIN SOUTH, WYOMING

BLUEWATER, NEW MEXICO

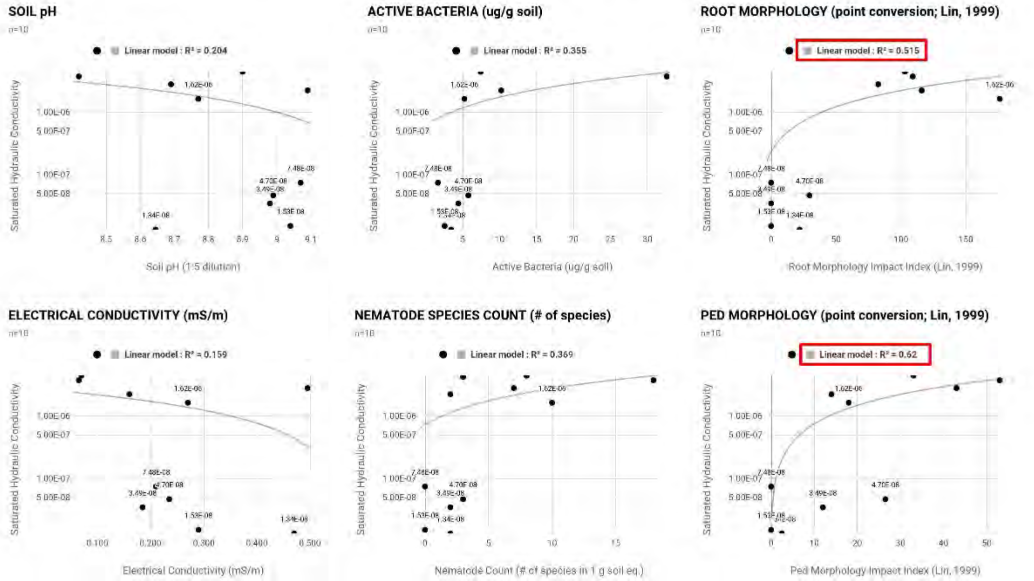
POSSIBLE PREDICTORS FOR HYDRAULIC CONDUCTIVITY



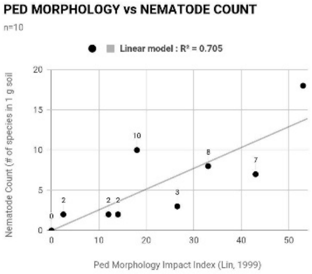
POSSIBLE PREDICTORS FOR HYDRAULIC CONDUCTIVITY



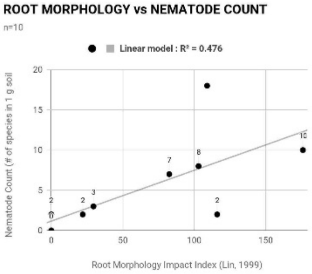
POSSIBLE PREDICTORS FOR HYDRAULIC CONDUCTIVITY



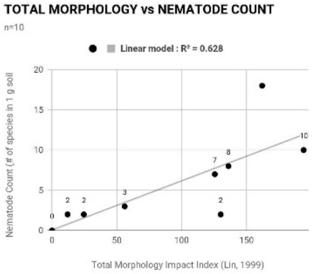
POSSIBLE PREDICTORS FOR NEMATODE DIVERSITY


PED MORPHOLOGY vs NEMATODE COUNT

n=10

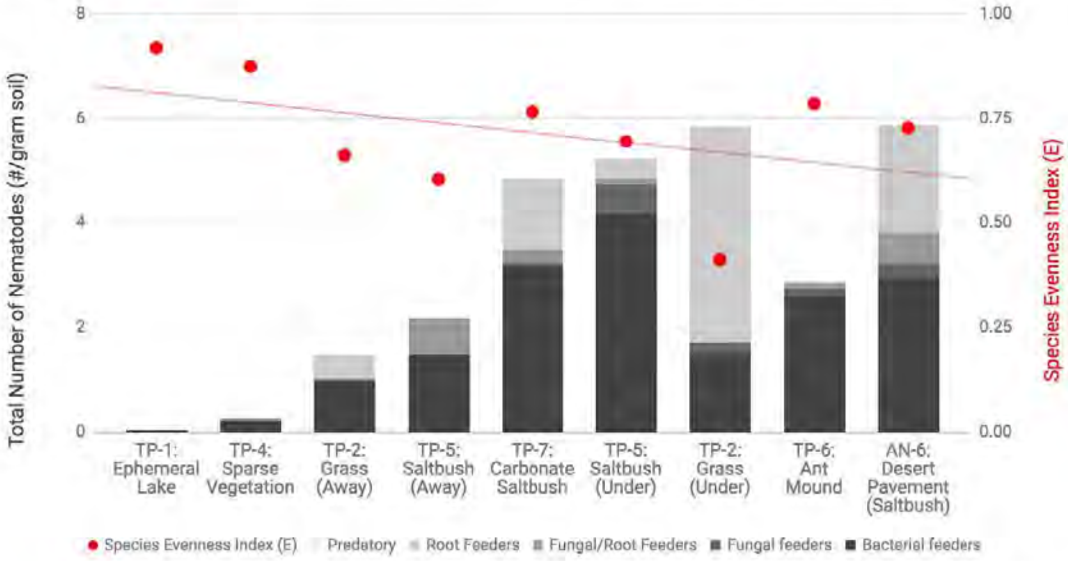

ROOT MORPHOLOGY vs NEMATODE COUNT

n=10

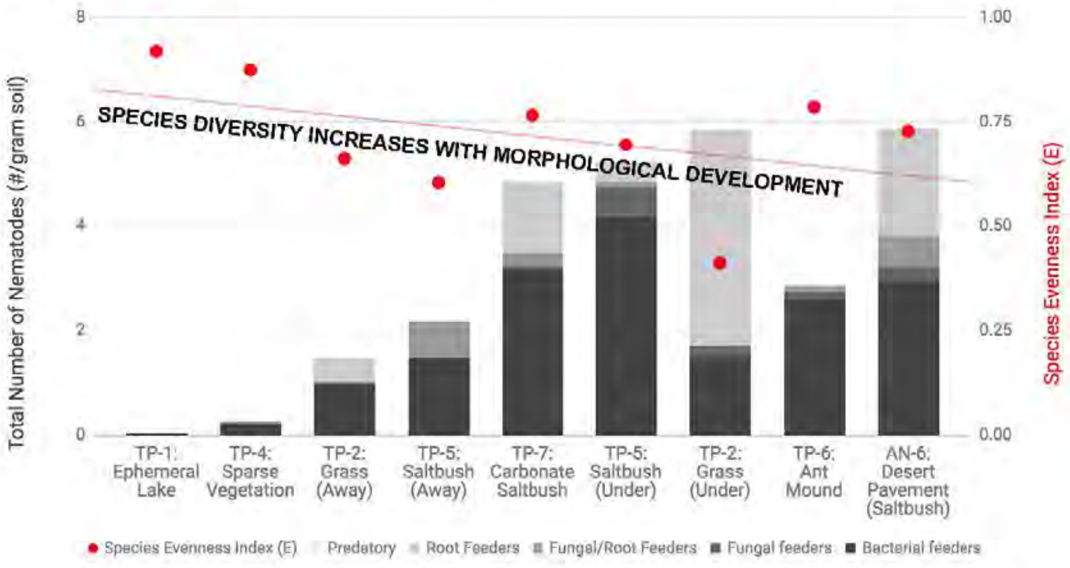

TOTAL MORPHOLOGY vs NEMATODE COUNT

n=10

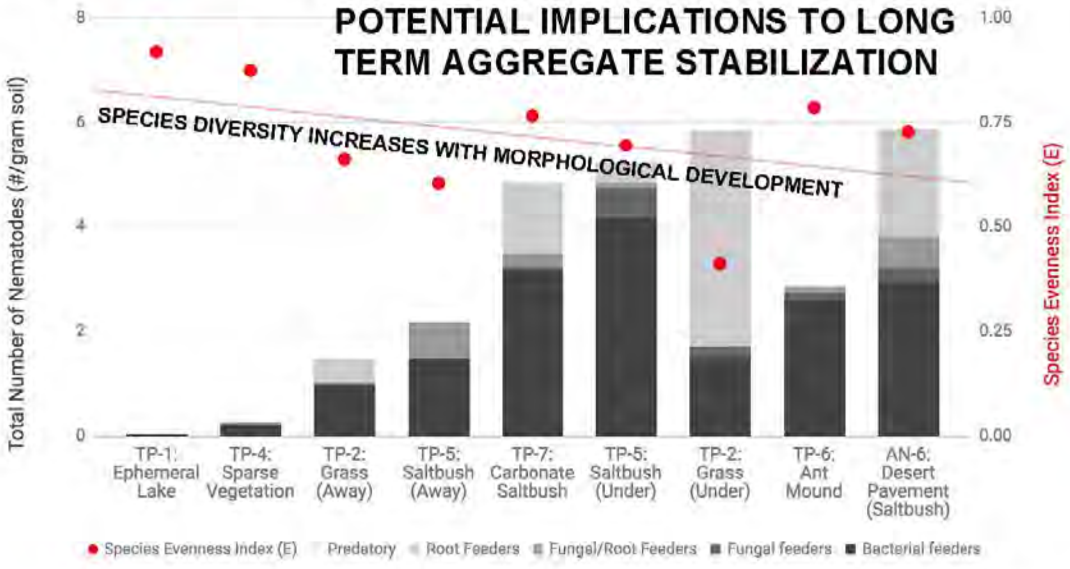
NEMATODE SPECIES COMPOSITION UNDER DIFFERENT SURFACE FEATURES



NEMATODE SPECIES COMPOSITION UNDER DIFFERENT SURFACE FEATURES

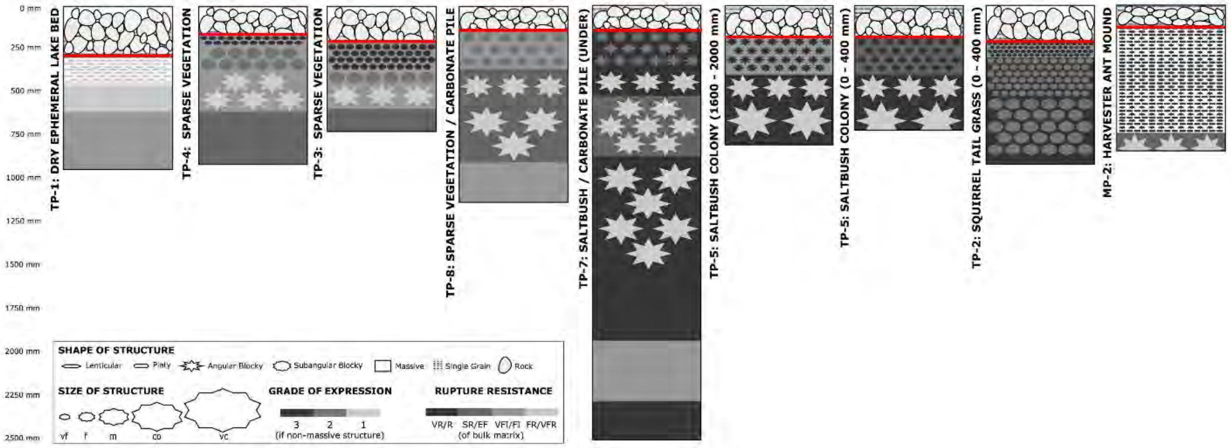

SPECIES DIVERSITY INCREASES WITH MORPHOLOGICAL DEVELOPMENT

NEMATODE SPECIES COMPOSITION UNDER DIFFERENT SURFACE FEATURES


POTENTIAL IMPLICATIONS TO LONG TERM AGGREGATE STABILIZATION

SPECIES DIVERSITY INCREASES WITH MORPHOLOGICAL DEVELOPMENT

BLUEWATER, NM : SOIL ARCHITECTURE

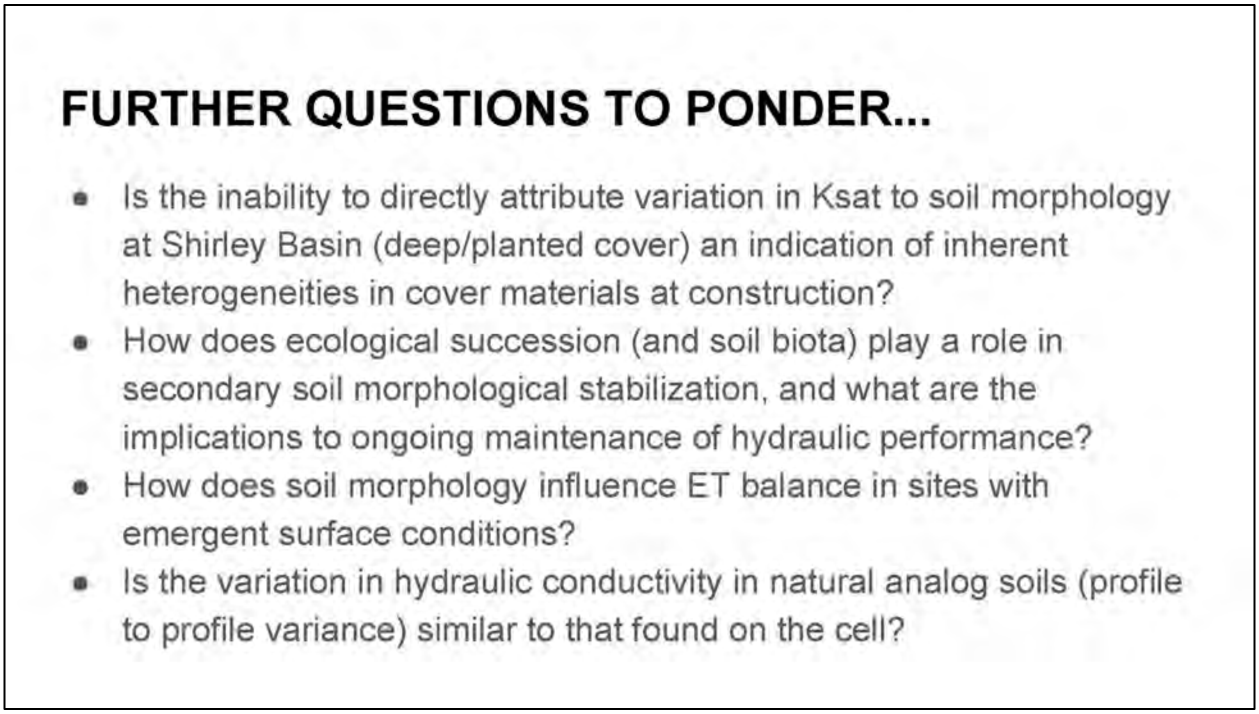


BLUEWATER - TAKEAWAYS

- Hydraulic conductivity is most controlled by

  SOIL PED > PLANT ROOTS > SOIL BIOTA (byproduct of)

- Incidence of impact gradients is striking
- Presence and diversity of soil biota (nematodes and bacteria) may have long term implications to <u>stabilization and maintenance</u> of emergent soil architecture
- Ants and grasses increase soil structure the most (thus Ksat)
- If ecological succession is moving in the direction of grass, cover will have higher potential Ksat (barring ET balance)



FURTHER QUESTIONS TO PONDER...

- Is the inability to directly attribute variation in Ksat to soil morphology at Shirley Basin (deep/planted cover) an indication of inherent heterogeneities in cover materials at construction?
- How does ecological succession (and soil biota) play a role in secondary soil morphological stabilization, and what are the implications to ongoing maintenance of hydraulic performance?
- How does soil morphology influence ET balance in sites with emergent surface conditions?
- Is the variation in hydraulic conductivity in natural analog soils (profile to profile variance) similar to that found on the cell?

2.8.3 Question and Answer Session for: A Survey of Soil Morphology and Process with Implications to Long-Term Performance at Four UMTRCA Sites.

Question. What can you tell us about the animal burrows?
Reply. There were several types of animal burrows. We saw field mouse burrows at one site. There were ground squirrel burrows at Lakeview and ants at Bluewater. At Lakeview, the squirrels did not get through the rock material. But in the natural analog site, without rocks, they go down a meter. We also observed ant mounds at the Bluewater and Falls City sites. We excavated several ant mounds at Bluewater, and found that they extended through the depth of the barrier and to a lateral distance of roughly 125 cm from the center of the mound. We didn't excavate the ant mound in Falls City.

Comment. The evidence about the rock barrier being effective against intrusion is particularly important to substantiate that design. We design the biointrusion barriers, but often we don't know how well they function. Actually, the design is pretty empirical; could we take block samples that contain these former burrows?
Reply. I took four block samples in this profile and they were all next to each other, so yes, the top block sample will have relics of burrows.

Question. The animal burrows look like they were filled. Were there voids or was there backfill material in them?
Reply. There was one burrow with an open void and that was an active burrow at a depth of about 40 centimeters. The rest were backfilled. They were abandoned, and surface flow redistributed sediment into them over time. That is why they have a dark color. They are filled with top soil that was moved into the subsurface. We also saw evidence of in-filled insect (possibly beetle) burrows at Bluewater occurring to a depth of 50 cm under the Saltbush profile.

Question. Does vegetation ever find these abandoned burrows?
Reply. It is pretty hard to say. The roots go everywhere. They look for moisture. It is just a function of how hard they need to work for it. This is pretty loosely consolidated material, and there was no preference for roots to move along abandoned burrows.

Question. How natural are the natural analogs? Are the distribution and number of plant species what we think has been there the last 1,000 years or are they what you see after grazing or some other impact?
Reply. At Shirley Basin South, the landscape is pretty denuded from grazing. The surface ecology is not perfect for an analog site. When choosing an analog, you would like an ecology that mimics the cell itself. Managers would never allow the cell to be as degraded as the analog site we were able to find there. However, long-term soil development that disturbed only goes back a few hundred years. The majority of that soil morphology at Shirley Basin South has been formed in the Holocene in post-glacial outwash.

Comment. Bluewater is a very intact ecosystem. The analog area was limited from grazing because it was on the mill property. So for 80 years, that has been an intact environment. That landform has been stable for the last 2,000 to 3,000 years. It is on an alluvial terrace. At some point it was more active, but over the last several thousand years it has been stable. Finding the correct analog that shares physical and biological conditions with the engineered cover, at relevant timescales is a challenge, but very informative.
Comment. The area at Falls City is grazed quite a bit. There probably would be a lot more black acacia and mesquite. It has been pretty thinned out as it was grazed. Lakeview is another site where the ecology is fairly advanced with some late seral ecology. There are a

couple of old western junipers growing there; their presence shows that the land has not been disturbed for a long time. The sagebrush, bitterbrush, and rabbitbrush association we see at Lakeview is late seral, so it probably is a good analog site. The landscape development varies from site to site and can depend on how the area was managed over the decades.

Question. How much does recent land management matter?
Reply. We have a really good understanding of range land management and the impact of overgrazing on soil structure and degradation of soil quality over a 2- or 3-year period. However, the subsurface morphology, which is what we expect the radon barrier to deviate toward, may be more resistant to degradation over a short period. However, if shifts of the surface ecological conditions happen over a long-enough time, will that impact the subsurface? It is very hard to tease that effect out. For selection of the right analog, you should have good information that goes back 500 years into the past, at least.
Comment. The ideal analog site is right next to the borrow area for the disposal cell. At Bluewater, that was late successional vegetation, so it was a good site. At Falls City and Shirley Basin South, the analog sites were heavily disturbed by grazing for decades.
Comment. On the time scale of a couple of decades, especially with root growth, if grazing impacts the plant distribution, that would impact root growth with respect to subsurface properties.
Reply. It could. Once soil architecture is developed, how is it maintained over time? Vegetation may create aggregate structure and also stabilize that structure. Because of its biological activity, exuding hydrophobic compounds coat the peds, making the soil structure resistant to shrinking and swelling events and stabilizing the structure. Changing from sagebrush steppes to grassland, some of these processes are not known on the decade scale. Pedology on the time scale of UMTRCA covers is an emerging field with more opportunities to explore.

2.9 Can Lead-210 Be Used to Indicate Long-Term Radon-222 Transport in Radon Barriers?

Presented by Mark Fuhrmann
Mark Fuhrmann[1], Alex Michaud[2] and Michael Salay[1]
[1]U.S. Nuclear Regulatory Commission, [2]University of Wisconsin—Madison

2.9.1 Abstract

The long-term behavior of engineered earthen covers for UMTRCA sites has prompted research by DOE and the NRC to assess changes in properties of four covers that are each about 20 years old. One design criterion is intended to provide reasonable assurance that the Rn-222 release flux will not exceed 20 pCi/m^2-s (0.74 Bq/m^2-s) for a period of 1,000 years to the extent reasonably achievable and in any case for at least 200 years. Radon flux measurements are typically conducted for 24 hours and are subject to substantial short-term impacts of changing moisture content and barometric pressure. Our hypothesis is that profiles of Pb-210, a daughter of Rn-222 with a 22.3-year half-life, within radon barriers will provide an indicator of where Rn-222 decayed and therefore its transport within the barrier over long times. The concentration of Pb-210 will increase for about 250 years, until the two radionuclides come into secular equilibrium.

Samples of radon barrier materials from four in-service sites have been analyzed for Pb-210. In all cases, Pb-210 was detectable, often was substantially above background values, and had higher concentrations at the bottom of the radon barriers where much of the Rn-222 lingers and decays as it moves up from the tailings. In some profiles, Pb-210 was found to decrease to background partway through the barrier, indicating that all Rn-222 had decayed before reaching the surface; in these cases, radon fluxes at the top of the barrier were generally at background. In other cases, Pb-210 concentrations were greater than background toward the surface of the barrier. In these locations, measured radon fluxes at the top of the radon barrier were elevated, indicating radon migration through the entire radon barrier and long-term release of a small fraction of radon that entered the barrier from the waste.

To relate Pb-210 concentrations to radon flux, we used the RAECOM code to model diffusive transport of radon (NUREG/CR-3533, Regulatory Guide 3.64). This code was originally used to estimate thicknesses of the barriers prior to construction, but it can also be used to estimate diffusion coefficients from measured top and bottom fluxes, as well as to provide calculations of radon flux and steady-state concentration at defined depths within the barrier profile. A spreadsheet model was developed to convert Rn-222 flux profiles from RAECOM to Pb-210 concentrations and to calculate the ingrowth of Pb-210 as the barrier ages.

We observed two types of Pb-210 profiles within the barrier material. The first is a curve that continually decreases with distance from the waste until it reaches the background Pb-210 concentration. From that point, the Pb-210 concentration remains constant as the surface of the barrier is approached. Calculated Pb-210 values based on the modeled radon flux, from our top and bottom flux measurements and the age of the barrier, correspond with the measured Pb-210 results quite well. The second type of profile shows a more complex pattern in which Pb-210 increases from the bottom of the barrier to a maximum 5 or 10 cm up from the bottom. Then the Pb-210 concentration drops rapidly but does not attain background concentrations; it remains elevated as the top of the barrier is approached. This type of profile seems to conform to the moisture saturation profile of the barrier material and was observed at only two locations at the

Shirley Basin South site; it is unclear whether these locations represent an unusual set of controls on Rn-222 transport/Pb-210 deposition. Approaches to modeling this type of profile are being discussed.

Findings from this work indicate that Pb-210 profiles are promising for quantifying long-term Rn-222 transport in radon barriers. Two approaches to better understanding long-term transport in radon barriers are suggested; the first is the use of detailed Pb-210 profiles to define Rn-222 transport mechanisms within the barrier as a means of testing assumptions about transport mechanisms used in models as well as the impacts of moisture content and preferential pathways. The second is a monitoring approach that uses samples from the upper portion of the barrier (perhaps the top 25 cm taken by Geoprobe) to determine whether Pb-210 is elevated compared to the background concentration. Our data strongly suggest that Pb-210 concentrations greater than background in the upper portion of the barrier are an indicator of elevated radon flux from the top of the barrier.

2.9.2 Presentation

Can Pb-210 be used to indicate long-term Rn-222 transport in Radon Barriers?

Mark Fuhrmann RES/NRC
Mike Salay, Alex Michaud, Craig H. Benson,
William H. Albright, William J. Likos, Nicolas Stefani, Kuo Tian,
W. Joseph Waugh, and Morgan M. Williams

Hydraulic conductivity measurements

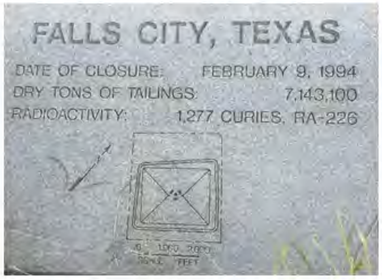
Radon Flux Measurements at top of Rn barrier

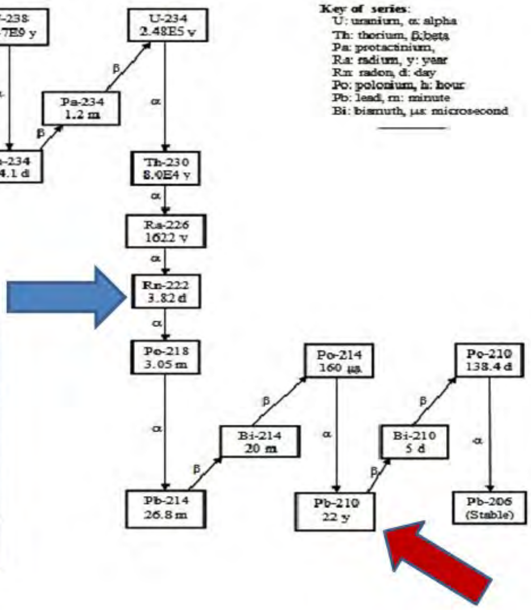
How can we estimate long-term Rn-222 transport in radon barriers?

We are interested in performance of these barriers over decades to hundreds of years. However....

- **Available measurements of Rn Flux from barriers are short term (24 hrs).**
- **These short-term flux measurements provide little information about long-term processes. They can be influenced by processes even shorter than the measurement.**

U-238 Decay Chain





Hypothesis; Pb-210 distribution/profiles can be used to evaluate long-term Rn transport in radon barriers.

Can we detect Pb-210 in radon barrier material?

Can we observe Pb-210 profiles in radon barriers that are the result of Rn-222 migration from the tailings?

Do the results make any sense?

Can we relate measured Pb-210 to Rn-222 generated by the tailings? Can we model Rn distribution and compare that to Pb-210 profiles?

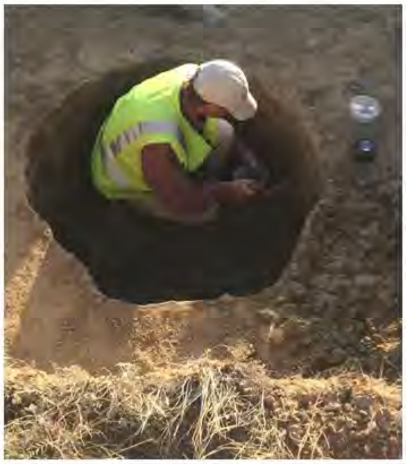
We measured Pb-210 profiles in Barrier Material at multiple locations at four uranium mill tailings sites.

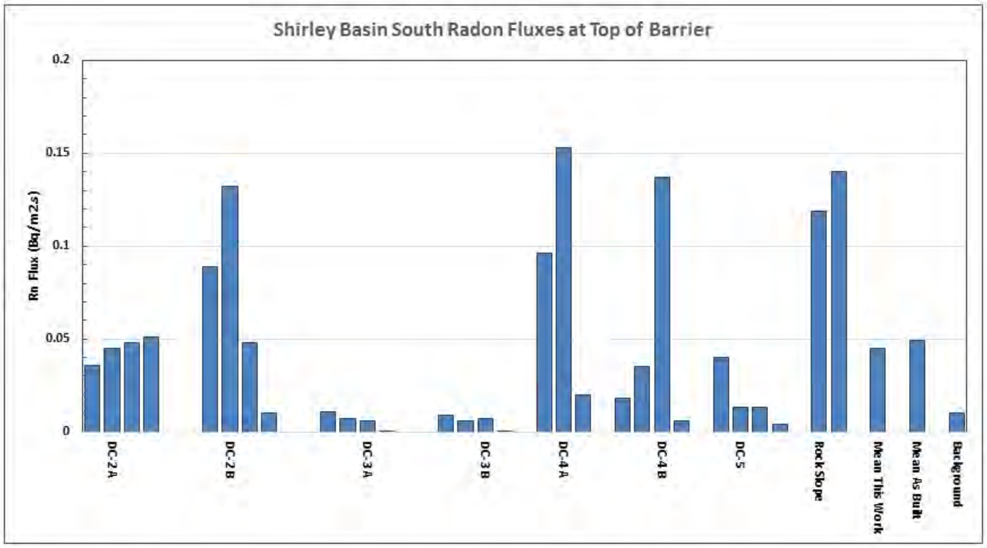
Pb-210 Methods

Barrier materials sampled at measured depths.

Samples sent to Eberline for analysis. EML Pb-01. Pb-210 is isolated from most interferences. Its progeny Bi-210 is separated from Pb-210, and the β activity is measured radiometrically after ingrowth.

Minimum Detected Activity = 0.02 Bq/g
2-Sigma Standard Error = 0.02 to 0.033 Bq/g

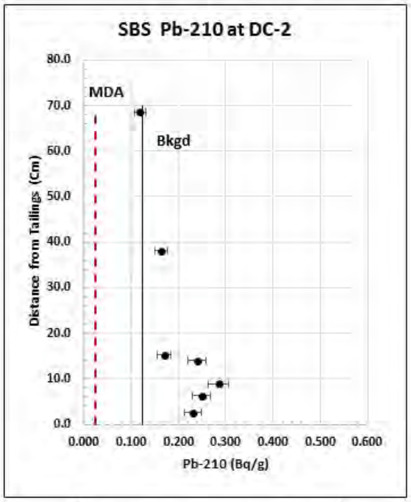


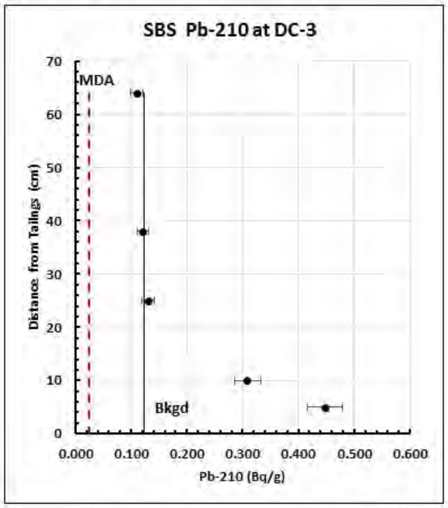


Rn fluxes measured at experiment pits at Shirley Basin South vary substantially. Note the background flux on the far right. Can Pb-210 profiles within the barrier material tell us about long-term transport of Rn?

Measured Pb-210 in the Shirley Basin South Barrier Material

2-Sigma Error Bars, MDA, and Background

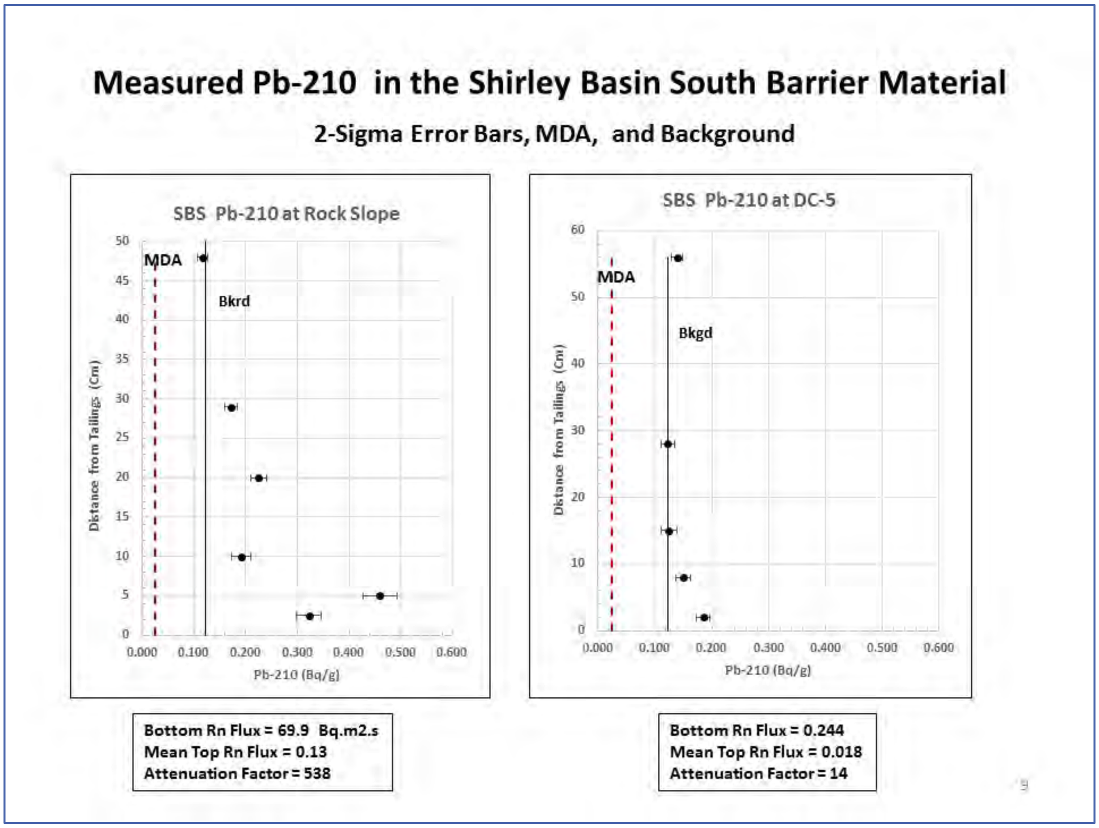




Bottom Rn Flux = 8.39 Bq/m2.s
Mean Top Rn Flux = 0.057
Attenuation Factor = 147

Mean Bottom Rn Flux = 370 Bq/m2.s
Mean Top Rn Flux = 0.006
Attenuation Factor = 6170

Background was determine two ways; modeled Ra-226 content of material and Pb-210 measured in stockpiled barrier material away from tailings.

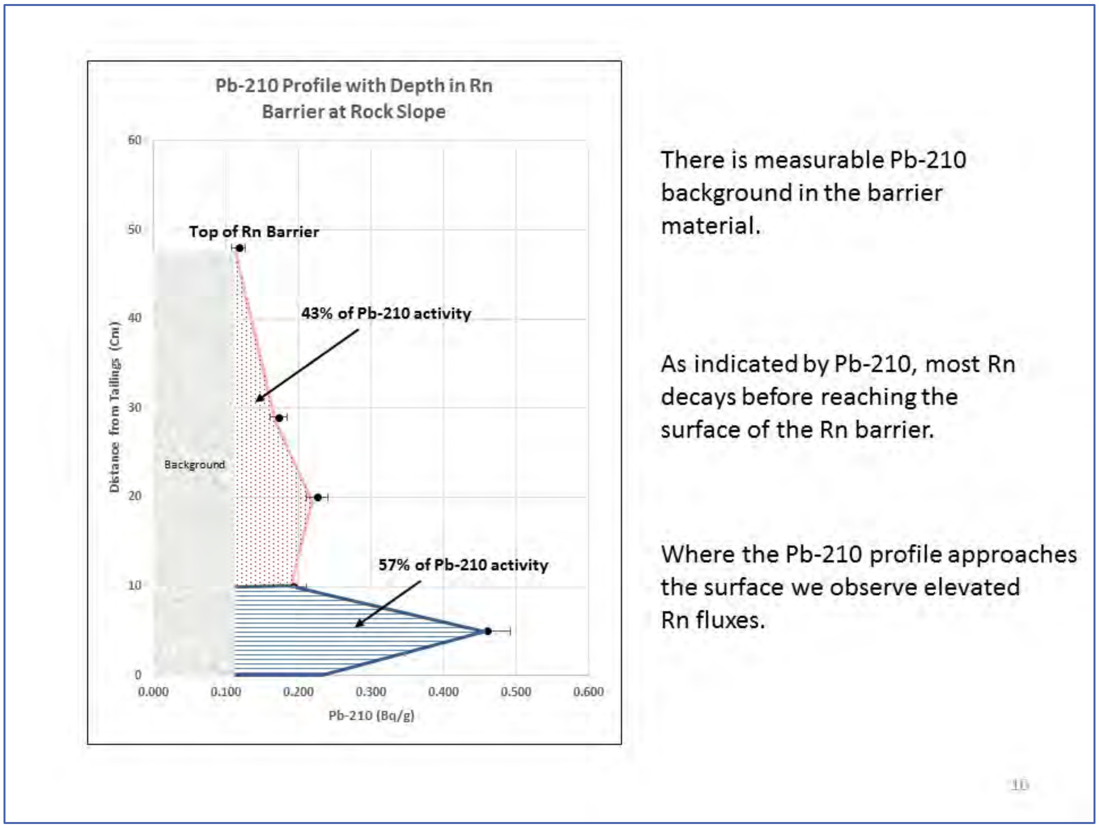


Measured Pb-210 in the Shirley Basin South Barrier Material

2-Sigma Error Bars, MDA, and Background

Bottom Rn Flux = 69.9 Bq.m2.s
Mean Top Rn Flux = 0.13
Attenuation Factor = 538

Bottom Rn Flux = 0.244
Mean Top Rn Flux = 0.018
Attenuation Factor = 14

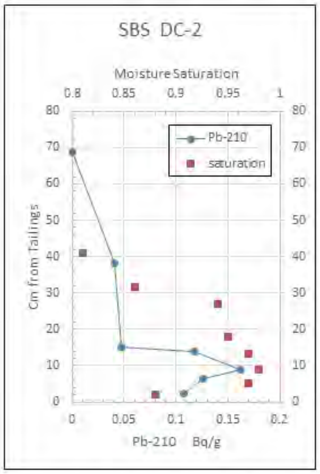


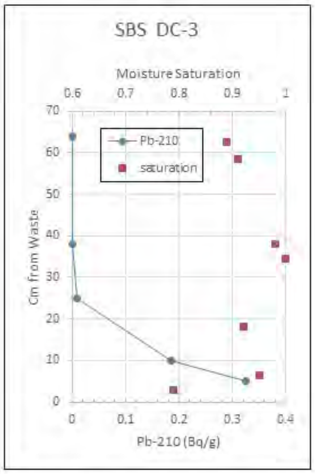
There is measurable Pb-210 background in the barrier material.

As indicated by Pb-210, most Rn decays before reaching the surface of the Rn barrier.

Where the Pb-210 profile approaches the surface we observe elevated Rn fluxes.

Impact of Moisture Saturation on Pb-210 Distribution





Bottom Flux = 8.39 Bq/m2.s
Mean Top Flux = 0.057 > Bkrd

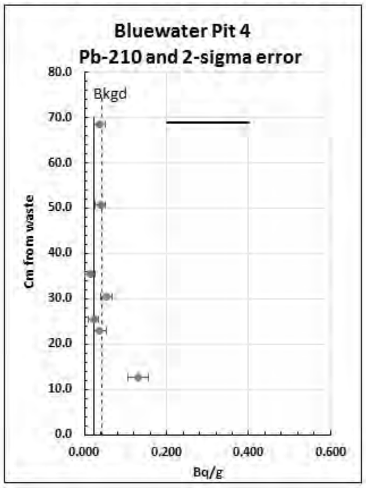
Bottom Flux = 370 Bq/m2.s
Mean Top Flux = 0.006 = Bkrd

Pb-210 is background subtracted

Measured Pb-210 in the Bluewater Barrier Material

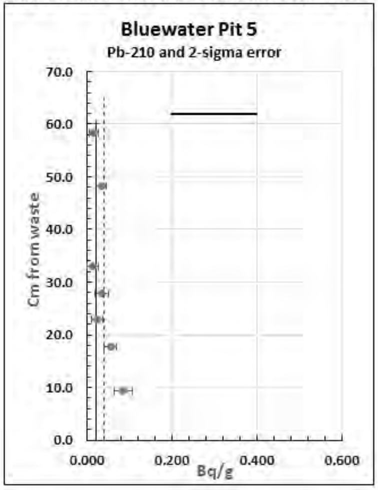
2-Sigma Error Bars, MDA, and Background

Top Rn flux is not elevated and Pb-210 is background



Bottom Flux = 11.9 Bq/m2.s
Mean Top Flux = 0.011 Attenuation Factor = 1080

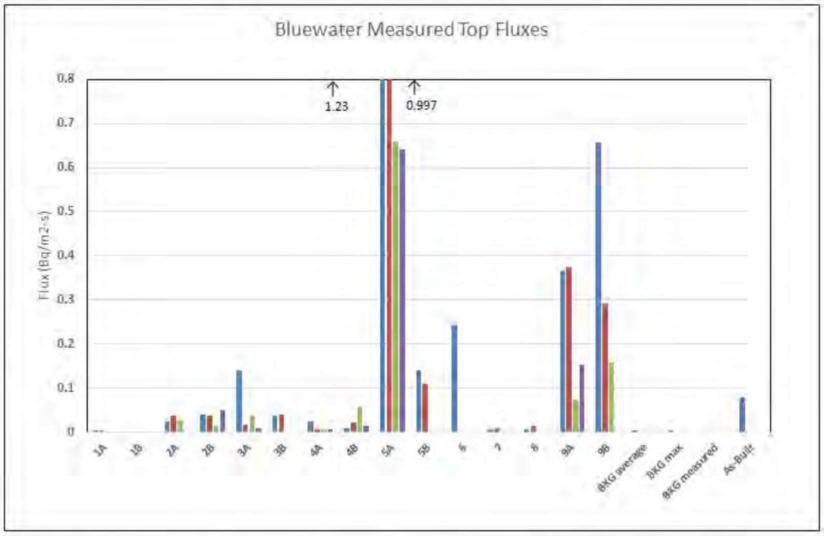
Top Rn Flux is elevated but Pb-210 is background



Bottom Flux = 1.85 Bq/m2.s
Mean Top Flux = 0.882 Attenuation Factor = 2.1

Dashed red line is the Minimum Detected Activity and the black line is background Pb-210.

Rn Fluxes measured at Bluewater

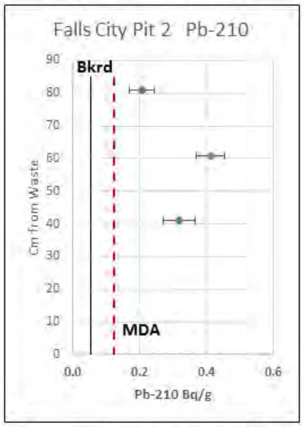


Pit 4 fluxes are very low and are consistent with observed Pb-210 profile being at Background.
Pit 5 fluxes are substantially elevated and are not consistent with Pb-210 profile.

Measured Pb-210 in the Falls City Barrier Material

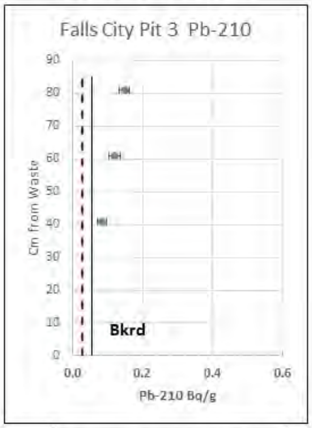
2-Sigma Error Bars, MDA, and Background

Top Rn Flux was elevated



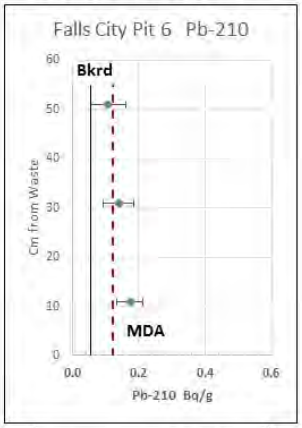
Bottom Flux = 2.06 Bq/m2.s
Mean Top Flux = 0.30
Attenuation Factor = 6.9

Top Rn Flux was elevated



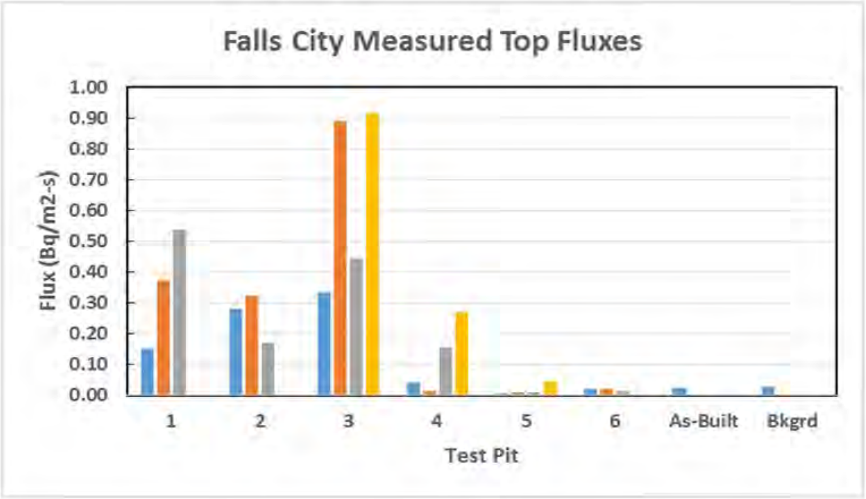
Bottom Flux = 5.15 Bq/m2.s
Mean Top Flux = 0.60
Attenuation Factor = 8.6

Top Rn Flux was background



Bottom Flux = 42.5 Bq/m2.s
Mean Top Flux = 0.013
Attenuation Factor = 3270

Red dashed line is the Minimum Detected Activity and the black line is background Pb-210.
All samples are from Shelby tubes and only from the upper portion of the barrier.
Pb-210 in pits 2 and 3 is substantially above MDA and background, indicating
Rn movement through the barrier. For Pit 6 Pb-210 is at MDA and suggests little or no
radon moving through the barrier.
Note Pb-210 MDA for Pits 2 and 6 are higher than Pit 3 because a different method was used.

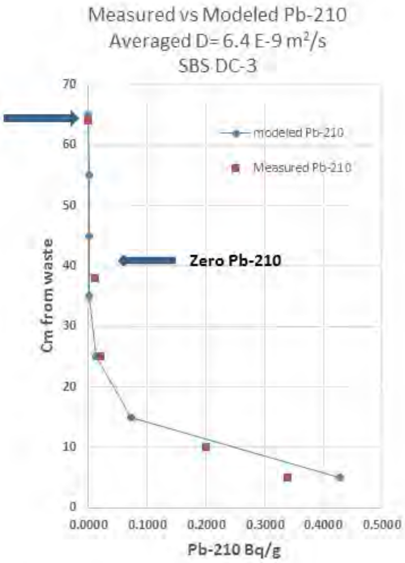


Rn fluxes at barrier surface for pits 2 and 3 are consistent with elevated Pb-210 profiles.

Rn Fluxes at pit 6 were consistent with Pb-210 profile which was essentially at MDA.

Can we compare measured Pb-210 profiles in barrier material to modeled Pb-210 based on Rn-222 generated by tailings?

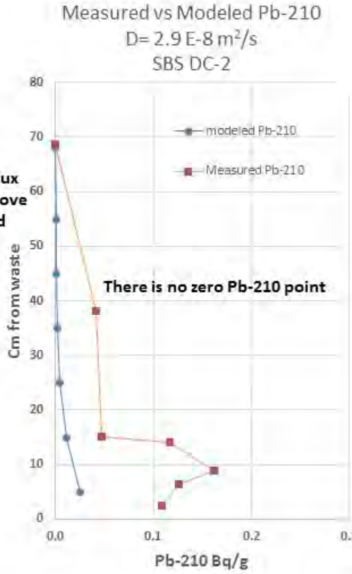
- **Modeled Pb-210 Methods**
  - **Measure top and bottom Rn-222 fluxes and maximum Rn-222 concentrations with Flux Chambers and Rad-7**
  - **Measure moisture, density, porosity, and Ra-226 of barrier material**
  - **Using RAECOM and 2-flux method calculate Rn Diffusion Coefficient (D)**
  - **Using moisture-porosity relationship calculate Rn Diffusion Coefficient**
  - **RAECOM calculates steady state concentrations and fluxes of Rn within barrier profile**
  - **Convert Rn flux to Pb-210/g and allow for in-growth time (age of the barrier).**



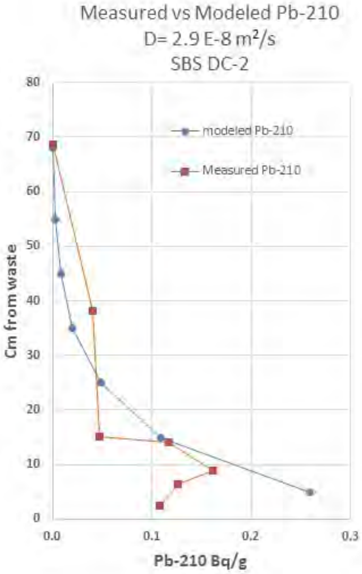
Measured Rn flux at top Is background

Pb-210 is background subtracted. D was average of all chambers with 2-flux method.
Measured Rn source: 3.71E6 Bq/m^3 Model source : (3.71E6)/0.6 = 6.18E6 Bq/m^3 MIC = 0.6

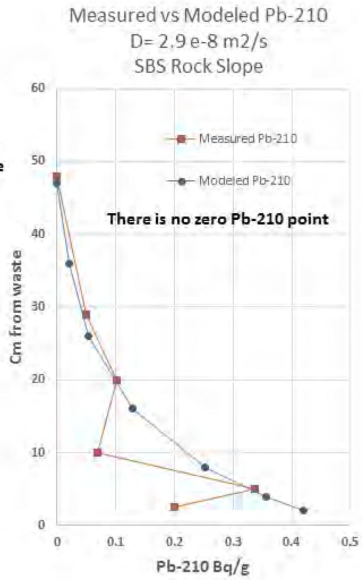
Observed flux At top is above background



Modeled Pb-210 is from observed source concentration and averaged D. Background subtracted.



Modeled Pb-210 with source concentration increased 10x and averaged D. Area under both curves is similar. Simple diffusion model does not work and source needed is higher than observed.



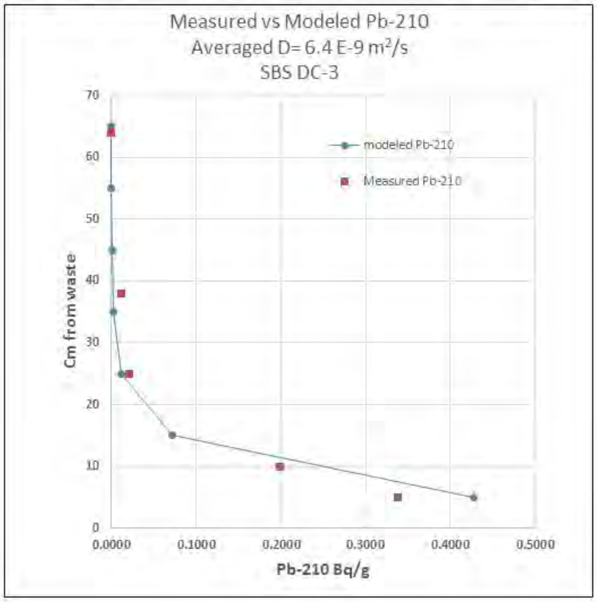
Measured vs Modeled Pb-210
D= 2.9 e-8 m2/s
SBS Rock Slope

Observed flux at top is above background

There is no zero Pb-210 point

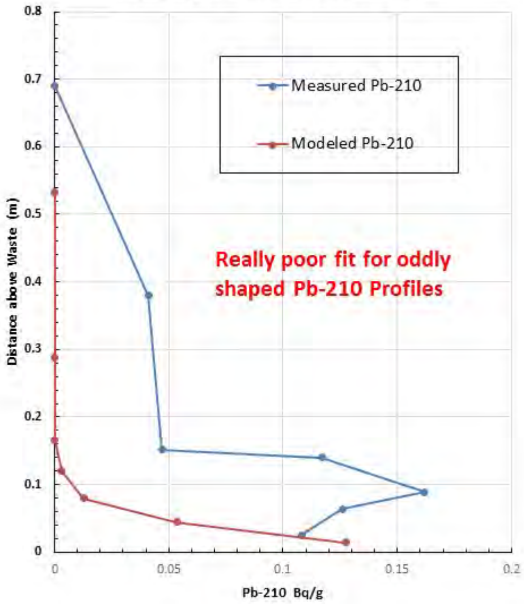
Pb-210 modeled with observed source concentration and averaged D

Pb-210 profile and model match well when transport is simple diffusion in a homogenous median



Measured vs Modeled Pb-210
Averaged D= 6.4 E-9 m^2/s
SBS DC-3

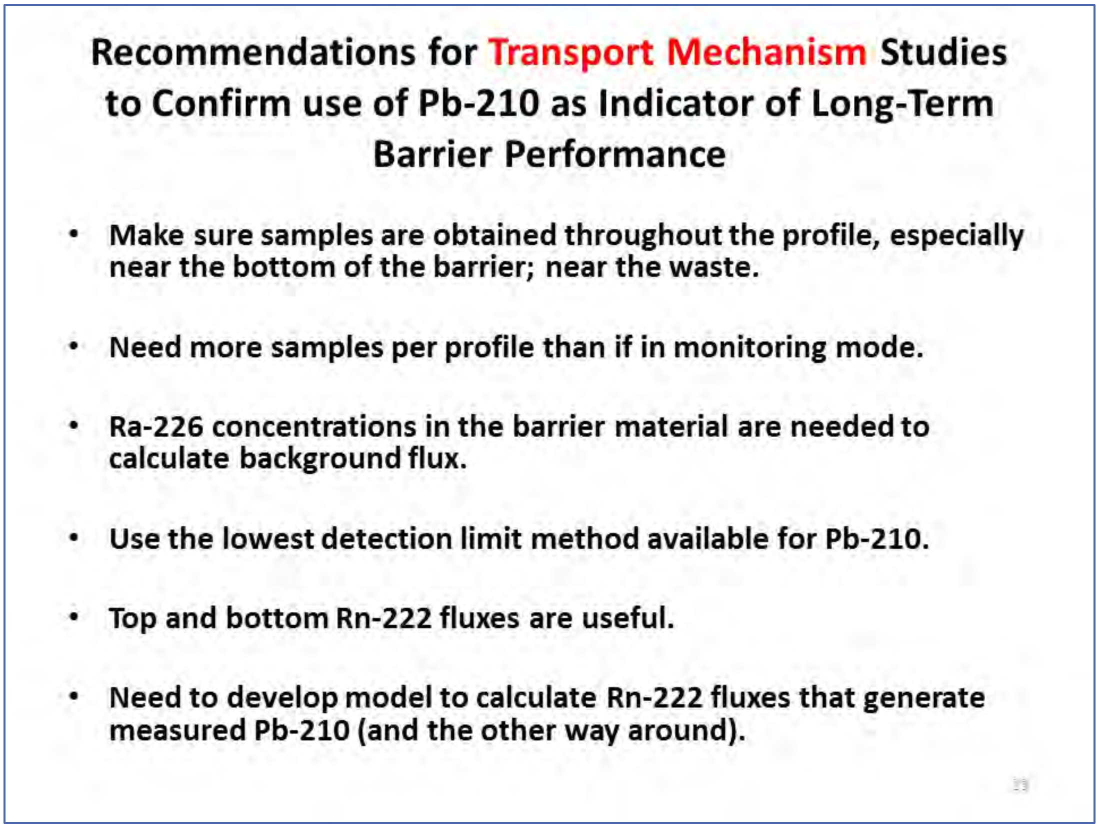
Modeled and Measured Pb-210 SBS DC-2
D calculated with measured moisture and
porosity for each RAECOM layer



Really poor fit for oddly
shaped Pb-210 Profiles

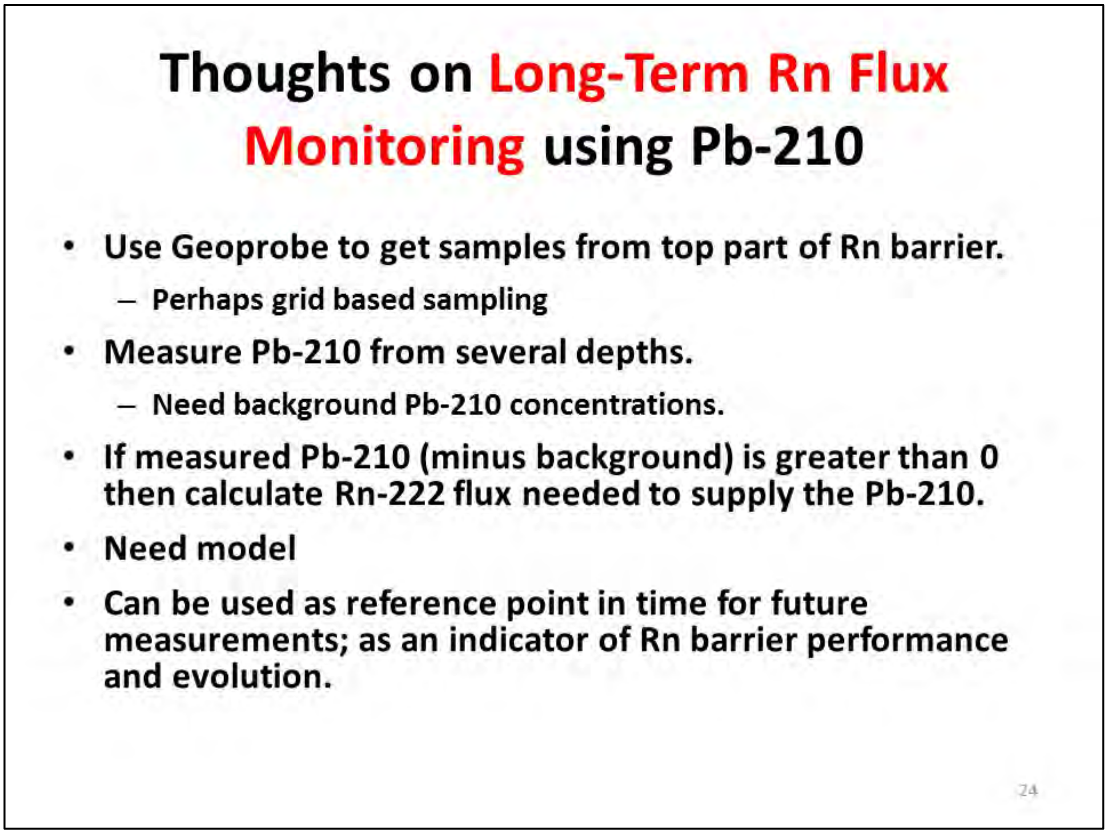
Observations

- Pb-210 concentrations can be measured and they often show systematic variation within the thickness of the barrier.
- Pb-210 is generally elevated near waste and decreases toward the top of the barrier.
- In some locations Pb-210 indicates all Rn decays away before diffusing through the barrier. At these locations Rn flux at the top of the barrier is background.
- At other locations Pb-210 indicates a small fraction of Rn diffuses through the barrier. Rn fluxes are elevated at top of the barrier. Preferential pathways?
- Comparison of Pb-210 distributions with moisture saturation profiles suggest strong small-scale control of Rn transport within barriers.



Recommendations for Transport Mechanism Studies to Confirm use of Pb-210 as Indicator of Long-Term Barrier Performance

- Make sure samples are obtained throughout the profile, especially near the bottom of the barrier; near the waste.
- Need more samples per profile than if in monitoring mode.
- Ra-226 concentrations in the barrier material are needed to calculate background flux.
- Use the lowest detection limit method available for Pb-210.
- Top and bottom Rn-222 fluxes are useful.
- Need to develop model to calculate Rn-222 fluxes that generate measured Pb-210 (and the other way around).



Thoughts on Long-Term Rn Flux Monitoring using Pb-210

- Use Geoprobe to get samples from top part of Rn barrier.
  - Perhaps grid based sampling
- Measure Pb-210 from several depths.
  - Need background Pb-210 concentrations.
- If measured Pb-210 (minus background) is greater than 0 then calculate Rn-222 flux needed to supply the Pb-210.
- Need model
- Can be used as reference point in time for future measurements; as an indicator of Rn barrier performance and evolution.

2.9.3 Questions and Answers Session for: Can Lead-210 Be Used to Indicate Long-Term Radon-222 Transport in Radon Barriers?

Comment. It would be really interesting to overlay your lead concentration plots on the photos, like you did with the density, moisture, and depth diagrams.
Reply. We started doing that with the moisture content. There's more that we can do to tease out information.
Comment. I would argue you want a conceptual site model for each one of those. How do you calculate diffusion, and what model would you use for that? You brought up clay and the sorption of Pb-210 on clay, and the other issue is the moisture content. It would be a very good performance indicator if you could overlay data with regard to Pb-210, but you have to have that conceptual site model and the effective mathematical model describe what's going on with Rn-222 and the lead.
Comment. It would be interesting to also look at root counts versus moisture and Pb-210.
Reply. Good idea.

3 NEXT STEPS

Discussion Led by Craig Benson
Dean of Engineering, University of Virginia

3.1.1 Presentation

What's Next?

What do we want?

- Meet near term goals: construct, operate, close
- Meet long-term goals: maintain, sustain
- Meet requirements: satisfy regulations

What do we need?

- Flexible cost-effective design based on managing risk
- Resilient design – functions well and sustainable in perpetuity (stable state design)
- Confidence in ability to design, construct, & monitor

How Do We Get There?

- Categorize our facilities in terms of type of risk, climate, and form
- Seek out and characterize natural sustainable systems that provide long-term isolation with minimal intervention.
- Develop methods to replicate natural and sustainable containment systems.
- Develop simple and cost effective techniques for surveillance that confirm functions

3.1.2 Discussion

Craig Benson. I was thinking about the different stakeholders we have here. We have folks from DOE/EM who are more on the design construction operation side, and people from DOE/LM who work on the long-term management stewardship of the sites. And then we have folks from the NRC who are on the compliance side. So we all have a different role in this, and oftentimes those roles don't overlap. Yet we would like to have something that is congruent between what the NRC would want in terms of a system in which you have a high degree of confidence to meet your goals for meeting regulatory requirements. For EM, you would like to have something that's cost effective to build and that you can build, operate, and permit in a practical way. You also want something that LM can manage and maintain in perpetuity without an extraordinary amount of effort or resources, something that LM has a high degree of confidence will last. How do we bring those three different goals together? Those are the challenges we can think about as we direct our work going forward. How do we go about doing that?

One of the things that we talked about last night is that a lot of our design work now is around a uniform set of criteria that we apply to every site. The risk is different depending on the site. Certainly, a mill tailings site has different risks than the saltstone disposal facility or the HLW tanks at Hanford; they all pose different risks and they are in different environments with different receptors. The emissions from those sites have different impacts and potential effects. We need to be able to create a process by which we are really focusing on managing risk. When creating facilities, our approach to design, maintenance, and permitting should be around managing the risks as opposed to managing the process. It’s really a more flexible approach. We need to think about how we can create resilient designs that fit in with that function well, that are sustainable in perpetuity, and that meet the performance goals. Finally, how can the NRC have confidence that we actually can build the facility and have some confidence that it's going to work over a very long period of time?

How can we create a resilient stable-state design that represents the long-term condition, not only when we build it but 1,000 years from now? This means design, construction, and monitoring so that we really understand the processes involved and how they're going to affect the system. We need to be sure the design is resilient enough so that it functions in the context of those processes. For example, if we have an anthill ingress into a facility, that design needs to still function in the context of that type of disruption. They are all kind of big-picture ideas, but then how do you get there?

We just started to make some notes on how to get there [editor's note: see slide 2 of the presentation, Section 3.1.1, page 3-2]. These are just ideas meant to start a conversation. First of all, we think about the types of risk that we have. These are different types of factors that affect how we would go about designing a facility and the type of approach we want to take, given the risks. There is climate. Where do our facilities sit? The climate is very different for Burrell than it is at Bluewater, versus that at the Savannah River Site, versus out at Hanford. These are very different climates and very different settings.

The second item is to start to better understand natural sustainable systems. We engineer things and then nature changes them. I guess we're better at that than we were 30 years ago, when we started really working in containment systems. That's really the essence of trying to get out a resilient design—look at what nature tells us. The big force that we're dealing with is nature trying to take the system in a certain direction, and entropy is going to push it to a longer term stable state. We need to try to get to that stable state from the beginning. We are looking for these natural sustainable systems that provide long-term isolation with minimal intervention.

Jody talked about this last night. There are debris flows on the western slope in Colorado that are essentially natural riprap deposits that have been in place for millennia. They provide great examples for us of a natural system that will function for thousands of years. They are essentially undisturbed in the context of disruptive environments. We can characterize them, understand them, and then understand how we can translate those into engineering designs. We can then develop methods to replicate these natural and sustainable systems so we can have a higher degree of confidence in their performance. In this way, a regulator can actually believe we know what we're doing, and the regulator can be confident that we can design a facility with a high degree of reliability.

Can we develop simple and cost-effective techniques for surveillance to confirm the function? I think what Mark Fuhrmann is doing in terms of Pb-210 fits that perfectly, and it is something that others can also do. A process that involves digging gigantic holes, taking samples, and doing all kinds of neat analysis is expensive and slow. We did four sites in 3 years. If we had a technique where we get a lot of samples with a Geoprobe like Mark has suggested, and if we take 20 samples in a day and perform the analyses in a month, we could have an idea of how that system is functioning. It may not be in great detail, but it might tell us whether the system is functioning, or it might give us more detail. Can we develop these kinds of simple and cost-effective techniques for surveillance to allow us to confirm function? DOE/LM could use such a technique to check on sites periodically and report back to DOE and the NRC to demonstrate that the function is meeting the goals.

Jody Waugh. I think there may be really practical questions on how we're managing these sites. There are three questions that are related to legacy sites that we manage. One is that the long-term surveillance plan right now requires us to spray herbicides to kill the vegetation. It's a very practical question; do we have to continue spraying or can we let the vegetation grow? If we spray, does this mean we are going to spray herbicides for 1,000 years? How does the risk associated with 1,000 years of herbicides compare to the risk associated with the radon?

Then, how do we manage the sites going forward? In some cases, vegetation growing at a site may be beneficial. Transpiration may control the water balance and prevent percolation. But there are tradeoffs. We've shown that vegetation tends to dry out the radon barrier, create root channels, and enhance structure development, therefore increasing radon flux. For example, at Bluewater, we have a ground water contamination plume that's moving away from the site toward an area where the local farmers pumped water for irrigation. As a result, at that site, maybe the risks are greater associated with ground water contamination than they are from an increase in radon flux.

Thinking of another site, Shirley Basin South is a mining area and the subsurface is just full of uranium. Natural uranium in the ground water is high, so maybe what the tailings contribute really doesn't matter.

Next, is there a way to do risk-informed performance monitoring? We start out with an unfocused one-size-fits-all approach, but maybe we should move to more risk-informed performance monitoring. Even coming out of the 2010 workshop on engineered barrier performance (NUREG/CP-0195), we asked this question. This leads to the third question that Craig has already alluded to—how should we go about monitoring? Do we have the technologies available currently to monitor? Is there a simple, inexpensive way over time to monitor or estimate radon flux using Pb-210? Similarly, is there a method to monitor and estimate whether we're getting percolation flux for sites where the risks are greater with ground water contamination?

Those three questions are key. We need to decide whether to spray or not. We need to know whether ET and controlling the water balance or whether controlling the radon fluxes is the higher priority. We need to be able to monitor if we go to risk-informed performance monitoring.

Craig Benson. The risk defines the monitoring priorities.

Jody Waugh. The last item is how do we prioritize sites and allocate resources to address the previous three questions?

Tom Nicholson. How do you interact with EPA?

Jody Waugh. I'm a DOE/LM contractor. I'm not a policy person and so I don't really interact with EPA. I'm sure LM does, but I'm on the applied science side of LM as a contractor, and I really can't speak to these policy aspects.

Tom Nicholson. We have risk to public health and risk to the environment. If I were EPA or the States, I would ask that LM give me an indication over the long term of how well these systems are going to operate with regard to public health and the environment.

Jody Waugh. In the past, we have done ecological risk assessments at some of these sites, and I think it's something we could build on moving forward. We haven't done those types of assessments in a while. The focus has been on compliance with UMTRCA.

Craig Benson. Sherri, as the chair of LFRG, what is DOE/EM's perspective?

Sherri Ross. We use models to predict how the facilities are going to perform, and we recognize uncertainty and variability in them. We try to prioritize additional research and information needs, and we conduct annual reviews of our operations and facilities. Our models are living documents that need to be maintained and current. There is both compliance monitoring and performance monitoring of facilities. We use our models to try to predict and give reasonable assurance so we can authorize the operations to proceed, but our models are considered living documents. We do additional research and development to maintain those as current and factor in new information as we go, including performance monitoring and separate compliance monitoring. Typically, we will hopefully not run into compliance issues early on. For CERCLA facilities, it is a three-agency approval process to operate, involving DOE, EPA and the State. Typically, the remedies are reviewed by the agencies on 5-year frequency, where they specifically look at what data you have accumulated. Is new information in sync with your model? Do you need additional information? The reviews look at ground water samples and air monitoring, and there's a frequency for monitoring. You do want to focus on those barriers and the performance of the barriers that are really needed. What's the major risk for the facility, depending on what you're disposing there and on operations?

Tom Nicholson. You brought up the word "remedy." So after 5 years of collecting data and doing good analysis, what causes you to want to use a remedy? What is the indicator that says something has to be done or that it's fine for 5 more years, and we'll look again after another 5 years wait? What are the indicators that say remediation has to be implemented?

Sherri Ross. It's the requirements. There are the regulations, and you look at your risk assessment so you know what contaminants are there. What is the risk they imposed? Does an action need to be taken? Those are typically three-agency decisions, and they evaluate those questions together. They look at proposed options and then select an action collectively. The three agencies will agree to the proposed remedy, implement it, and perform 5-year reviews. The agencies agree to what data are being collected and evaluate them. The agencies may decide 10 years down the road that they need to consider a different parameter. For example, the agencies might say that they know they do not have a lot of uranium here or that they do need to better evaluate radon performance. Then they might want to monitor for Pb-210 in the subsurface. It's an evolving process that does not start with all the answers at once. They evaluate and see whether additional actions are needed. DOE/EM does that at its operating disposal facilities. On an annual basis, DOE/EM needs to know what it disposed of last year. Typically, DOE/EM is under CERCLA, and those are 5-year remedy reviews by all three agencies, so it's very similar to the questions you're posing here under LM. We will also install closure caps, but a lot of ours are mixed waste. There's a liner so I don't think that's directly applicable.

Ming Zhu. I would like to add, as Sherri mentioned, DOE has been using the risk-informed approach in all phases, from design, construction, and operation to site closure. As Sherri alluded to, DOE Order 435.1 guides the use of performance assessment to support all those three phases. Using the LFRG process for disposal facilities and even for high-level liquid waste when we go through tank waste closure, we will follow a similar process for closure. In addition, for remedy actions there's discussion about when you can turn off pump and treat and the criteria we should use to make that decision. That's part of the 5-year review that we do under the EPA requirements. There's active discussion on the need to come up with some kind of formal guidance to make that decision a little more robust. That's part of the reason why we stood up the Performance and Risk Assessment Community of Practice, to share information, develop consensus, and hopefully document the group consensus as guidance to our sites. Craig is one of the leaders in that group and is developing one key piece for the performance assessment—how to predict the long-term performance of engineered structures. Roger Seitz is another key player in that group who has already developed a white paper on how to manage uncertainties given all the factors that need to be taken into account in the final decision. The point I want to drive home is we are using the risk-informed approach—although maybe it's not formally called that—but consensus seems to be in recent years to make decisions a little more robust.

Craig Benson. Perhaps elevating that idea would be really helpful. I think that group has come together a lot over the last few years and has really started to gel.

Hans Arlt. I really like what Jody spoke about. When I look at these uranium mill tailings covers, there are two issues. One is with the ground water being contaminated from the waste when the water filters through the cover. The other one is with the radon release. Right now there doesn't seem to be a problem with radon release, but there's an indication that there might be a problem in the long term. The biggest releases were from root systems and animals like ants. It seemed that the fauna and flora are not good for radon release. You're seeing the beginning of that at some of the sites, some more than others, so you had impacts from anthills and roots and those don't seem to repair themselves. In other words, once an anthill is there, it's there, and you have that problem for a long time. Once you have that root system there and it loosens up the soil, that's there even if the plant dies. So it seems like you have the beginning of a potential problem, and you have 170 years or so to go. I think a lot of these covers are 30 years old. I would think somehow that one may be able to model long-term impacts so if you have a certain rate for how many anthills develop at a site and how many plants are there. These rates are changing. Shirley Basin South seems to have really fantastic compacted clay, even though it has really high sources. I would guess that if you modeled that site, even after hundreds and hundreds of years, you're not going to have a problem, although you might eventually have a problem at some point if roots develop.

Jody Waugh. Yes, that gets back to something I introduced yesterday during the presentation when we talked about starting with a conceptual ecological succession model. We are starting with as-built conditions. There's no ecology; we call this primary succession. It's like a rock surface that eventually turns to soil, but what we're starting with is the engineered as-built site. Then, we're trying to define this dynamic end state—potential natural vegetation or late seral stage. I had a cartoon up there trying to illustrate this seral stage concept [editor's note: see Section 2.4.2, page 2-65]. We'd like to develop these models for each site, at least conceptual successional models, and then be able to define where we are currently in this progression, that is, this trajectory that we are projecting. So we define where we currently are and how much more ecological change we would anticipate. Then, because that seems to be the key driver, we need to define the soil morphological changes in response to the ecological change and, most critically, the changes in engineering properties.

Hans Arlt. I was talking about modeling what happens if you just leave the system alone, as it keeps on doing what it is doing. It seems to me DOE/LM may be thinking about changing some of these sites. You have the slide showing plowing in the riprap [editor's note: see Section 2.3.2, page 2-49]. You've been talking about that for a very long time and so I'm wondering—what's the decision there? When the decision is made, will you change the covers by plowing in the riprap, or do you plan on looking at that for another 10 or 20 years? There's no sense in modeling what happens if you leave the system alone if you're going to change the site.

Jody Waugh. Currently, we are looking at how Mother Nature is changing the sites. Particularly for arid sites, there's probably no need to try to pull soil up into the riprap if Mother Nature is depositing aeolian dust and filling that for us.

Hans Arlt. So your opinion is that DOE/LM is thinking maybe we shouldn't be so active? Maybe we should just leave it the way it is? Maybe stop the herbicide as the most active thing, and then one could just model what one has and then see whether there is potentially a problem. Models, of course, have a lot of uncertainty, but maybe you can get kind of a ballpark idea of whether there will be a problem in 50 years or 70 years at some of these sites.

Jody Waugh. Yes, if the cover begins looking like the analog site within 170 years or 970 years, how will the cover perform with that morphological stage, that ecology, that water balance, and associated engineering properties?

Hans Arlt. It may be that the radon release is fine at some of the sites, even with a lot of vegetation and animals. However, you might have three or four sites where it is a problem and you can't let it continue going the way it is going—maybe we need to put in a geomembrane.

Jody Waugh. I get to look at sites individually, like comparing Shirley Basin South to Bluewater. In one case, maybe radon flux is a greater concern for risk, while at the other, percolation of water is probably the greater risk. We need to be able to screen, categorize, and prioritize all these sites as to the best way to manage a particular site moving forward. Should we let it transform into an ET cover or do we need to keep spraying? It's a tradeoff. The wetter the better for radon attenuation, but plants need to dry out the cover if we want to prevent percolation so tailings are not a continuing story.

Sherri Ross. I would like to see us apply what we've learned into the design. Most of these sites studied were arid sites, and, except for some of the plants that had deep, deep roots, plant roots will follow the water. If you design the top of your cover to be well above where radon decays, then you may not need long-term maintenance. One of the goals of DOE is to minimize long-term maintenance. If you know what plant life will grow on the covers, you can design for that so they don't actually degrade your barrier.

Jody Waugh. A lot of these covers were designed with a protective layer. You might remember the three designs we had at the beginning. The earlier ones just had rock right over the top of the radon barriers, the cover wasn't protected. Later, the covers had a protective layer. That protective layer is also a water storage layer, and we don't see the roots going down into the radon barriers below the protective layer very much. We're not in the design business, but if you design one that way, we would like to monitor that type of design.

Sherri Ross. For the purpose of the continuing living documents, what are you learning in your maintenance and monitoring? How can you apply that information? At a facility that already has a closure cap, it is difficult but you could install a top layer if you determined that it's necessary. However, the information could be applied when you do design the next facility closure cap.

Jody Waugh. When you are designing the cover, think about where it's going to go—where Mother Nature is going to take this cover. Earlier, Craig brought up looking at natural systems and natural analogues; this is really important, but we haven't developed it much. The glacial debris flow is a really good example. It's an analog site right near the Grand Junction disposal cell. During the Pleistocene, as the glaciers were melting on top of the Grand Mesa, basalt mixed with soil came down and basically armored the Mancos Shale. This is a really high-clay-content shale that was used to build a radon barrier. We have this natural analog with soil and rock armoring these slopes, and we're going to look at this to see how stable it is. Morphologically, the slopes have been stable for 10,000 years. We look at the water balance. The vegetation is growing. We can see calcium carbonate is forming in the soil. The water is not moving very deep so it's been stable. So I take engineers to that site and ask them to engineer that natural analog to use in the design for a disposal cell, because it's already proven to last for 10,000 years.

Mark Fuhrmann. For existing sites, your idea of using a succession model to get information on different stages of vegetation on that site over different times suggests that we need more detailed information on the impact of that type of vegetation on a very small scale because we see how patchy radon fluxes are. However, we don't know about water ingress on that scale. We know that about 40 centimeters is a good size for a measurement. We do know that the radon fluxes are somehow very patchy, but we are not sure why. If a vegetative system moves in such that you've got a large plant every 100 meters or so, you need to know more about how the radon and hydraulic conductivity are influenced around that plant on a granular-enough scale that you can then take your succession model and plug in these properties of flux over the whole site. This would then give you estimates of your radon fluxes at the boundary and your water transport through the cover, in order to be able to estimate how these things are behaving in 200 years.

Jody Waugh. We do have some evidence for water balance and water percolation, and how well vegetation may control that at the Monticello ET cap. It is a really good first example of where we enhanced establishment of late successional vegetation. I showed a photo yesterday [editor's note: see Section 2.3.2, page 2-43]. Instead of waiting for Mother Nature to put in sagebrush grass steppe vegetation, we planted it. We didn't wait for the natural succession to take place. Over the course of 20 years and at a site that is relatively wet and has a short growing season, ET has been adequate to cut percolation flux down to almost zero. Of course, it was designed as an ET cover. In the second example, and I talked a little bit about it yesterday, there is the test lysimeter facility that we've built at the Grand Junction disposal cell. As the disposal cell cover is being managed, we spray the vegetation, nothing grows, and we are monitoring the water balance. On the other part of the test cover, over the past 3 years, we've seeded it and we're allowing vegetation to come in. The percolation flux has dropped considerably. We need to keep monitoring, but there's evidence from these studies that this is a feasible approach. I think at some point we are going to have to apply water balance modeling to evaluate results.

Mark Fuhrmann. We seem to be able to understand the balance between radon flux and water transport processes, but how can you design around that tradeoff? Maybe there are ways to design the cover in layers that allow you to get both.

Jody Waugh. When we talk about the ecological succession as at the Grand Junction disposal cells, a good example is aeolian dust that's beginning to fill the rock. It's changing the plant habitat, whereas initially that rock was acting as a mulch and keeping the cover wet. Now, the dust has created habitat for deep-rooted plants. You saw the photographs that I showed yesterday [editor's note: see Section 2.3.2, page 2-41]. At these sites, we're beginning to see that the aeolian dust is filling spaces between the rocks, holding a lot of the moisture closer to the surface and increasing surface evaporation. Now we're seeing shallow-rooted grasses and forbs start to grow on that surface. Mother Nature may be starting an ET cover for us by depositing dust. Going back to Hans Arlt's questions, rather than ripping, maybe we just want to enhance that process. Maybe we want to fill the rock with fines so that it's not acting as a mulch, and so we have shallow-rooted plants and a more favorable water balance.

Tom Nicholson. In order to enhance performance, you have to understand the conceptual model of the site as it is today, and how those processes are working. We worked with the University of Arizona back in the high-level waste days, and we talked about conceptual model uncertainty and parameter uncertainty. The issue you've been bringing up with Mark now involves scenario uncertainty. You think you know the Burrell site or the Canonsburg site, but you have invasive species such as Japanese knotweed, which is adding nutrients, mulch, and all kinds of carbon. The argument is that you think you know the scenario you're building in as a succession, but now there are invasive species. The other issue is that nature often goes through cycles, and so therefore you could have a long-term drought or a fire. How will that change things? That has to be built into your scenarios.

Jody Waugh. On the slides I presented yesterday [editor's note: see Section 3.2.3, page 2-55], I ended with the uncertainties in climate going forward and invasive species, fire, drought, and so on.

Roger Seitz. With regard to this kind of design, a lot of our barrier designs include a bio-barrier that is basically cobbles. How durable will that be if it is going to fill in? How can we effectively develop a bio-barrier that's going to do its job for a long time to protect against intrusion by plants and critters? How do you design that?

Jody Waugh. We included a bio-barrier at Monticello, but it's not a surface rock, it is just above the capillary barrier interface at the ET cover at Monticello. Years ago at Pacific National Laboratory and also at Los Alamos, Tom Harkinson did some work looking at the turnover of soils by burrowing animals and different types of barriers needed for different types of burrowing animals. When we designed Monticello, we used these earlier studies to get a rock size and a rock spacing. We didn't want to change the storage or the flow of water. We just wanted to prevent, in the case of Monticello, prairie dogs from getting down to the capillary interface.

Roger Seitz. From what we're seeing, animals and plants are what create problems for radon. The other point goes back to Tom Nicholson asking, what triggers a change? We started thinking about this idea of performance monitoring probably in the 1990s. If you are using sensors, it's a really fine line because you want to get this information, but inevitably some sensors are not very reliable. You're going to get bad readings, and you're going to get good readings. My caution would be that, before you even start, you need to know how you are going to explain results that are outliers. For example, we end up spending tons of time and money explaining results from pneumatic piezometer sensors. The fact that we did not state upfront to the regulators that we may get some strange measurements means that there are problems as soon as you get strange measurements.

Craig Benson. Having a data quality process is important so that you have a high degree of confidence that what you're measuring is actually telling you what you think it is. That informs the design or the maintenance or the decisionmaking that you need to do.

Tom Nicholson. If I can't tie it to risk then it's a waste of money.

Roger Seitz. But you may gain information on Pb-210 or moisture. We're looking at moisture, but before you start reporting it officially you need to explain that you're going to see strange things. It is much easier to say it before you start than to state that when you start seeing the strange results. Then people don't believe you and you lose credibility.

Craig Benson. That is what I like about this room. We have different parties here. You need to agree on what you're going to do as a partnership as opposed to trying to satisfy some party. I have spent an enormous amount of time in the last 18 months trying to understand the data that we get and what they mean relative to what was expected. We should be really careful about it.

Roger Seitz. Pneumatic piezometers are interesting instruments and so are advanced potentiometers. You can get all kinds of information from them, and in a compliance environment it can be very difficult to deal with.

Craig Benson. I think your point about the bio-barrier is how to actually get to a stable-state design. There are examples in nature that tell us how we should go about engineering bio-barriers that we can build into new facilities. We ought to be trying to harvest that information proactively so that we can create resilient designs that everybody has a high degree of confidence in. We need to realize they are never going to be perfect, we still need to monitor and check them. I know in my own work I've talked to people who are working on performance assessments, people in LFRG, and people at the sites, and the problems I'm working on are one-off problems that people are struggling with. I'm thinking of trying to do this a little more holistically. How do we look at the family of issues to get to a stable-state design?

Mark Fuhrmann. From the point of view of the analogs, something that came up in that engineered barrier performance conference in 2010 (NUREG/CP-0195) was from the NRC perspective about developing a catalog of natural analogs. That hasn't really gone anywhere, and we are still talking about it. I'm more stuck at the current situation at some of these sites and the issue of having a good understanding of what processes are really driving radon fluxes. I have a better handle on radon, I don't have much of a handle on water. Some of the Pb-210 work will help resolve this. We've assumed diffusion in a homogeneous medium as the model for transport in these things. That is how the covers were built, and that's how they were designed with a substantial margin, so they're okay. Do we need to have a better handle on transport processes, as these things do change? The patchiness in radon flux bothers me. We see such big differences in flux over areas that are less than 1 meter or so. I don't know how that patchiness will evolve, and I'm not even sure we understand very well what's driving it, except in a general sense. Do we have tiny fast pathways that are advective? I don't know, maybe in some spots. Do we have much lateral transport? Some of these have a fair amount of sand and layering within the barriers. Does measuring it here mean anything about what's actually going on directly down below? Or is the radon coming from 50 feet or 100 feet over? We don't know that. I don't know how important that is. Maybe just the whole general flux is the key, and all these details are not so important. They suggest to me that they're telling us something about how the cover is changing, but I'm not sure what that means. I am curious to see others' opinions about that.

Tom Nicholson. The question is, do you understand what could be the mechanism that is operating under what position, and how did they change with time and your spatial distribution? A system that may have been very diffusion dominated at first becomes less and less so if you get changes in the barrier that Mark is talking about. Is it really important for this net flux that either radon is going up or a contaminant is going down into the ground water system? When does it become important?

Mark Fuhrmann. It becomes important if it's an indicator of how things are changing. If it's just an indicator of the way it was built, then maybe you don't need that information. That question would be different at different sites. I don't know how granular you need to get about mechanisms to have a good handle on how things are changing. That is what I'm struggling with.

Tom Nicholson. Is that mechanism causing significant flux of contaminant to the atmosphere or the ground water and under what conditions does it become significant? Knowing this you include it in your modeling. Models can really help you in that regard, and through the natural analogs, where does it make a difference and where does it not make a difference.

Craig Benson. You have to assume that your models captured the mechanisms.

Tom Nicholson. When we were looking at Yucca Mountain, we looked at Rainier Mesa as a prototype of what Yucca Mountain might become by considering the recharge, the snow melt, and other things. There was value in looking at areas very close by with similar mechanisms. It was very valuable.

Mark Fuhrmann. We've been looking at analogs, but we can't really look at them in situ for radon transport because they don't have a source term that's anything like what we're worried about at the sites. We could look at them from the point of view of water transport. For gas diffusion, you could do tracer studies. Would that be a benefit?

Craig Benson. I think you can look at those analogs and find similar processes that you could use to validate some of the models and answer some of the questions. You could test those hypotheses if you use tracer experiments or look at other gases that might be migrating in that system, and you could validate some of the assumptions.

Doug Mandeville. If I had to review a cover design today, what would I be looking for? If it was for a Title II site, the regulations do allow for a vegetative or rock cover. My process for reviewing that would depend on whether I should focus more on the radon emanation or the ground water percolation. Knowing that site-specific part would be important. Also, no licensee and no members of the public are at this workshop. They may have vastly different viewpoints on this than we do. The licensee is going to want to spend the minimum amount possible to design and build a cover that meets the regulations. Their concerns are vastly different than what DOE/LM's concerns will be.

Tom Nicholson. When you do a review, what information are you looking for?

Doug Mandeville. We have a reasonable assurance standard that it will last for 200 to 1,000 years.

Bill Von Till. We haven't had an application like this for a long time. Interestingly enough, we had the potential site in Virginia. Virginia Uranium wanted to have a conventional mill and mine; a pretty large one at that. The company almost came up with an application to us, but politics overcame that. In the process, it pretty much thought through the entire design. This is in a very wet climate, where Virginia Uranium is trying to overcome the type of rain events there. This is in Chatham Virginia, so it is central Virginia near the North Carolina border. Virginia Uranium went through a total design for a new conventional mill. There's also a mill site that has been licensed out in Colorado on the western slope, Pinion Ridge. As far as this kind of review for the actual cover and reclamation plan, I don't think we've dealt with an ET type of cover design in our regulatory reviews. Monticello was more of an EPA site. I've been to Monticello, and it looks to me like that's a great design. I don't know what the cost differences are between that site and a conventional site, if the licensee were to have to pay that money. The other thing I might offer is one of the things we and DOE/LM management are looking to do. The regulations say to build this cover so there's minimum maintenance. I don't know whether that's a good system, it probably is not because I think you're going to have look at the performance indicators and monitor other things over time to really assure the safety of the public. However, the regulations, as they stand now, call for designing for minimal maintenance. How do you design such an impoundment with that standard in mind, with minimal maintenance? What do you have to do, plant the saltbush brushes and the type of vegetation so they can take over in 5 years and then be very stable and then walk away from it? What's necessary to design and build a site that's going to last without a lot of maintenance?

Craig Benson. That's the crux of the question. How do you get to stable-state performance?

Tom Nicholson. What do you have to do to maintain the site from the standpoint of changes such as severe erosion, rainfall, and drought? You have to think in terms of how the site may undergo change.

Bill Von Till. You really do, and for 1,000 years. Just in 20 years, we've seen a lot of problems at some of these sites, like L-Bar and other sites where DOE had to come in and spend a lot of money. Look at Bluewater and the slumping problem. In just a 20- or 30-year period, you've seen a lot of maintenance necessary for the sites that were built with what was supposedly the Cadillac design. Now maybe the ET cover is the Cadillac design. Would an ET cover work in Virginia?

Jody Waugh. What does the design look like at White Mesa?

Craig Benson. I was just thinking about that one. From an owner's point of view, Energy Fuels has a uranium mill where we've been working on an enclosure. We had a group of folks who have designed a water balance cover, an ET cover, for that site. We're actually evaluating it at that site right now. We've built a large test section. We've got a vegetation monitoring program. I've been working on the hydrology part. They are very interested in that design because it's very sustainable. I think you can build it and it will have minimal maintenance. It will continue to function better and better over time because it fits in with the natural system. That was what was really attractive to the owner.

Bill Von Till. That is Energy Fuels Resources at White Mesa. It is regulated by the Agreement State of Utah. It has lined impoundments. It is semi-operational now, really in standby mode now. Are they thinking of actually submitting that kind of design to Utah?

Craig Benson. Yes. It is already submitted, and it has essentially interim approval, provided our test section gives the data that prove out that it actually works. Mainly it's uranium mill tailings, but today Energy Fuels Resources runs a vanadium circuit there too, so there are some other metals. There is a compacted layer, not necessarily a low-permeability clay barrier, but there is a well-compacted layer at the base that is meant to control radon. It is about 2 meters thick, I think.

Jody Waugh. How does the design compare to Monticello?

Craig Benson. It's actually very similar to Monticello. I'd say it is almost identical, except it doesn't have a geomembrane at the bottom and perhaps it is a little thinner.

Hans Arlt. If you put in a geomembrane at these sites, would that solve all the problems or not? I'm not suggesting it because I know it costs money. I just want to find out if you put one in would that solve the radon release and infiltration for at least 200 years? Let's just assume they last for 200 years and you have good quality control. If you don't have quality control then you can forget it, but if you have quality control let's assume it lasts for 200 years. I'm just curious whether anyone would have a problem with that?

Craig Benson. I'm always anxious to answer questions asking whether we are going to solve all the problems. We are building composite barriers for hydrologic control and for gas emissions. They work really well and they do last. We completed a study a few years back (Tian et al., 2016) with the latest science, not only ours. They last about 1,900–2,000 years for polyethylene of the type of materials we are creating now, that is, if it is embedded in the cover.

Tom Nicholson. The value of your membrane, I would think, is to stabilize the situation. You will have silt moving down through the riprap that will cause a fairly uniform layer. The geomembrane won't let it go any further, so this is causing a stable situation temporarily. You'd have to model it and think about plant succession and other things that will cause that geomembrane to fail and degrade eventually.

Jody Waugh. We went through this exercise with Monticello. We did a series of lysimeter studies to show that an ET cover would probably work there. It was a Superfund site, and so we're dealing with EPA. The EPA staff members said that they really liked this but they wanted us to put a geomembrane in there anyway. So we ended up with an ET cover, a radon barrier, but also the geomembrane. That's what allowed us to create this huge lysimeter. We decided that if we're going to have a geomembrane, let's see whether we can capture water coming through the ET cover. EPA just decided that although it liked what we were doing, we needed to add the geomembrane.

Tom Nicholson. Did that add any value or just make people feel better?

Craig Benson. We don't really know. Even at Monticello, we could probably point to 0.2- or 0.3-millimeter-per-year percolation over 18 years. That 0.3 millimeter is really coming out on the membrane. Although at the bottom of the ET cover it is 0.3 millimeter, the membrane takes it from 0.3 millimeter to about zero, so there is reduction. Whether that reduces risk at all is hard to say. Monticello is a lined facility with a composite double liner with leachate collection. It does give you benefits by keeping things moist, it'll keep roots away, and ants will not go through while it's there.

Roger Seitz. What is the cost difference?

Craig Benson. The cost difference is about 75 cents per square foot. Maybe in the DOE/EM world it is a dollar a square foot. You have to validate that it's functioning.

Roger Seitz. That's one thing that I've been trying to push. Since we've invested in these liners with the need for performance monitoring, that liner is your performance monitor and you're collecting leachate, especially for sites with a double or composite liner.

Nick Orlando. I have a couple of clarifying questions. First, you were sampling locations at four sites that were fairly biased. You focused on areas where it appeared that there was some change—slumping or where there were trees or deep-rooted plants. You saw no cases where there was an indication that the radon flux was different from the as-built in areas that weren't impacted, is that correct?

Craig Benson. Well, we didn't really have a true control, I guess. We did bias our sampling.

Nick Orlando. So the areas where you did your biased sampling, you saw some increases in the radon flux over the as-built?

Mark Fuhrmann. At one site I know the average of the as-built and the average of our sampling were very similar. I think maybe they were each biased in different ways, but you know it's very hard to determine for something done 20 years ago.

Nick Orlando. My point is that the burrowing animals, burrowing insects, and deep-rooted plants seem to be the problem for disrupting the cover. The shallow-rooted plants maybe not so much, with the dust coming in. Is that mostly a 60-percent true statement?

Morgan Williams. Just speaking to the morphology of the plants, even the shallow-rooted plants like the grasses have root structures that penetrate through the radon barrier. Those factors seem to control hydrologic properties more so than coarsely rooted vegetation because they're more evenly distributed, and fine roots are everywhere. [Editor's note: at Bluewater, the plant-impacted location was pit 5, where the bottom flux was 1.85 Bq/m^2-s with an average top flux of 0.63 (n=6), and the nearby, unvegetated "control" was pit 4 with a bottom flux of 11.99 Bq/m^2-s with an average top flux of 0.018 (n=8). Both bottom fluxes were substantial. Thus, the unvegetated location (with an attenuation factor of 670) provided much greater retention of radon than did the vegetation impacted location (with an attenuation factor of 2.9).]

Nick Orlando. For the most part, the current suite of sites in the DOE portfolio is rock armored. I can think of two or three that are grass—Shirley Basin South and Fall City.

Jody Waugh. The top slope of Durango is vegetated.

Nick Orlando. Right now, the long-term surveillance plan that DOE uses to manage the sites includes provisions for repair and maintenance and emergency procedures. There is a little table in the back of the plan that says a category 5 or a priority 5 (I won't call it an emergency, but a priority 5 "thing") is the observation of any vegetation. If the majority of the sites are rock armored and the issue is burrowing plants, burrowing insects, and deep-rooted plants, DOE is supposed to be addressing those. If there's a regulatory mechanism in place that appears to address the main causes of potential disruption, like plants or animals, what is going to be the regulatory outcome? You are going to do all this great science. Mark will have his lead analog figured out. What do we do if the majority of the issue is something that can pretty much be resolved just by close inspection of the site and spraying plants? It is not the best thing to do, but the risk of pulling up an acacia tree is probably pretty low. So keep that in mind, that from a regulatory perspective some of these problems may already be taken care of. Focus on what the regulatory outcome of all of this will be. What is the regulator going to do to DOE or the State or whomever is the long-term custodian based upon what your science shows?

Craig Benson. That is the synthesis part, what are the impacts in terms of regulation or design?

Nick Orlando. There may already be a regulatory mechanism that is addressing some portion of the problem.

Jody Waugh. I think that's right. When we focus on the radon part, there is a regulatory mechanism. If we remove the plants, the barrier stays moist. We have lower radon diffusion and flux by removing the plants. However, this is the tradeoff I was trying to illustrate yesterday.

At some of the sites, perhaps water percolation would be a greater risk than an increase in radon flux, such as at Bluewater. By removing the plants and maintaining the rock cover, we're essentially harvesting water because we're reducing evaporation. Where will that water go? My lysimeter studies are suggesting that we will get an increase in percolation flux. There's the tradeoff with the plants. If we were just focused on radon flux using the mechanisms in place to get rid of the plants, we are going to have a wetter cover, especially with rock on it. How about those sites where we have a ground water problem and we're concerned about the tailings as a continuing source for ground water contamination? At those sites where ground water may be the greater risk, maybe we should be managing the water balance, and plants help us do that. That's the tradeoff; we have to look at this on a site-by-site basis.

Craig Benson. I think the impact from a regulatory perspective informs decisionmaking. I take an action, I have a series of consequences in the field. Do we go in and remove all the plants or do we think about what's the priority here? Maybe radon flux will go up but maybe it's low enough that is doesn't make a difference. I've been worrying more about the ground water.

Hans Arlt. I work in performance assessment and the answer is almost always site specific.

Tom Nicholson. That's right. It is the risk that you're focusing on. Glendon Gee said, why are you dumping all this rock on top of those Hanford tanks where you're just creating a recharge mound? You need to know what causes the risk to increase dramatically. How does something malfunction? For instance, it isn't just vegetation, it's the type of vegetation. Some vegetation grows deeper roots. They could be the pathways of fluids. You have to understand the site and get into the conceptual model and tie it directly to risk; risk in the short term and the long term.

Jody Waugh. My understanding is the regulatory mechanism isn't in place for us to manage these sites as risk-informed performance monitoring like we're talking about. We have a long-term surveillance plan, and for a lot of the sites that plan says spray the vegetation. We follow the plan. That was one of the questions that came out of the 2011 workshop. How might the regulations change if they become more based on risk-informed performance monitoring? If they do change, how does DOE/LM go about monitoring these sites to demonstrate performance?

Nick Orlando. Is DOE considering proposing to let the vegetation grow on one site and see what happens? And change the long-term surveillance plan? Is that the proposal?

Jody Waugh. We did back in the 1990s on the Burrell site. We measured hydraulic conductivity with air-entry permeameters where the deep-rooted plants were growing, we measured the moisture content, we reran RAECOM with those in situ water contents, and we came to the conclusion that the plants growing really didn't matter. We submitted that to the NRC, we proposed to change the long-term surveillance plan and let the plants grow. The NRC agreed, and so there is a model of change. There's a case history.

Craig Benson. At Cheney right now, we've got side-by-side experiments, in which we ran test covers identically for 7 years and now we are letting one of them go.

Jody Waugh. I should mention that at Burrell there are 4 curies of radium in the whole thing, so it is exceptionally low.

Craig Benson. I think this has been really helpful. We're going to prepare a document from this workshop. I don't know about the process but it would be good if people have a series of recommendations in that document. It would be good to get all the different stakeholders to reflect on those as part of our review process.

Tom Nicholson. The NRC put on a workshop in 2010. What has changed in those years? Where is the focus today? I think it would be very helpful if you prepared conference proceedings. The public was not here, and the States were not here, but I'm sure we would be very interested in seeing what comes out, not only the conference proceedings from this workshop but also the white paper that you're talking about.

Craig Benson. I was thinking about what's going on at White Mesa. The last workshop proceedings came out in 2011. It drove White Mesa to a different type of design.

Tom Nicholson. I also was thinking about what Ming Zhu brought up earlier. What we are doing now is moving towards the risk informed. He's saying that Craig and Roger are helping him look at uncertainties and other issues. I think that we didn't discuss that much in 2010. We did talk more about disruptive scenarios. We did talk about some modeling, like using the Siberia code, but, as Mark brought up earlier, are we looking at individual, very localized issues and trying to expand that over the whole site? How do you understand the whole site performance as opposed to individual locations?

Craig Benson. We've done a lot of one-off analysis, and I think we really need to begin to think of it as a system as opposed to pieces. Ming Zhu's group, the Performance Assessment Community of Practice, is really a great vehicle to share a lot of this information. In 2011, it was kind of still nascent and was just really taking off. That group has become very active, so that's a good vehicle for this type of activity.

Ming Zhu. We will make sure to invite you all to our next meeting so that you can hear some discussion, or it would be very good for you to share some of your presentation information with the group.

Craig Benson. Thank you everybody.

Mark Fuhrmann. I'd like to thank Tom Aird especially for helping out with the webinar.

4 REFERENCES

10 CFR 40.28, “General License for Custody and Long-Term Care of Uranium or Thorium Byproduct Materials Disposal Sites.

10 CFR 51.22(c)(6) Criterion for Categorical Exclusion.

40 CFR 192.02, “Standards,” Subpart A, “Standards for the Control of Residual Radioactive Materials from Inactive Uranium Processing Sites.

Arlt, H., R.L. Johnson, D. Mandeville, G. Alexander, M. Meyer, J. Philip, J. Kanney, M. Fuhrmann, and T. Johnson, “Documentation of the Engineered Covers Technical Group (ECTG) Activities by U.S. NRC Staff,” 2011 (ADAMS Accession No. ML112300105).

Benson, C., W. Albright, M. Fuhrmann, W. J. Likos, N. Stefani, K. Tian, W. J. Waugh, and M. M. Williams, Radon Fluxes from an Earthen Barrier Over Uranium Mill Tailings after Two Decades of Service, WM-2017, 2017 Waste Management Conference, March 5-9, 2017, Phoenix, Arizona, USA.

CNWRA, “Analysis of Mill Tailings Cover Performance,” August 2012 (ADAMS Accession No. ML12256A992).

CNWRA, “Evaluation of Approaches to Simulate Engineered Cover Performance and Degradation,” October 2007 (ADAMS Accession No. ML072950120).

CNWRA, “Methods for Monitoring Net Inflow Through Soil Covers of Uranium Mill Tailings Impoundments,” November 2013 (ADAMS Accession No. ML14015A328).

CNWRA, “Modeling of Net Infiltration through Soil Covers at Selected Title II Uranium Mill Tailings Sites,” April 2015 (ADAMS Accession No. ML15121A610).

CNWRA, “Software Validation Test Plan and Report for Channel-Hillslope Integrated Landscape Development (CHILD) Version 2.3.0,” November 2008 (ADAMS Accession No. ML083360379).

CNWRA, “Software Validation Test Plan and Report for EAMS Version 2.09 and SIBERIA Version 8.33,” October 2008 (ADAMS Accession No. ML083020359).

CNWRA, “Software Validation Test Plan and Report for GeoStudio^{TM} VADOSE/W$^{©}$ 2007 Version 7.11,” October 2008 (ADAMS Accession No. ML082980094).

CNWRA, “Uranium Tailings Impoundments—Bottom Liners and Their Performance,” January 2015 (ADAMS Accession No. ML15055A117).

Department of Energy Order 435.1 “Radioactive Waste Management”.

National Research Council, 2005, Mineral Tolerance of Animals: Second Revised Edition, The National Academies Press, Washington, DC, https://doi.org/10.17226/11309.

NRC Regulatory Guide 3.64, “Calculation of Radon Flux Attenuation by Earthen Uranium Mill Tailings Covers,” 1989.

NUREG/CP-0195, “Proceedings of the Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities,” August 3–5, 2010, T.J. Nicholson and H.D. Arlt, August 2011 (ADAMS Accession No. ML11238A056).

NUREG/CR-2765, A Mathematical Model for Radon Diffusion in Earthen Materials, K.K. Nielson and V.C. Rogers, 1982.

NUREG/CR-3533, “Radon Attenuation Handbook for Uranium Mill Tailings Cover Design, Rogers, V.C., K.K. Nielson, D.R. Kalkwarf, 1984.

NUREG/CR-7028, “Engineered Covers for Waste Containment: Changes in Engineering Properties and Implications for Long-Term Performance Assessment,” Volumes 1 and 2, C.H. Benson, W.H. Albright, D.O. Fratta, J.M. Tinjum, E. Kucukkirca, S.H. Lee, J. Scalia, P.D. Schlicht, and X. Wang, December 2011 (ADAMS Accession No. ML12005A110).

NUREG/CR-7200, “Influence of Coupling Erosion and Hydrology on the Long-Term Performance of Engineered Surface Barriers,” C.L. Smith and C.H. Benson, May 2016 (ADAMS Accession No. ML16125A124).

NUREG-1623, “Design of Erosion Protection for Long-Term Stabilization,” 2002 (ADAMS Accession No. ML052720285).

NUREG-1748, “Environmental Review Guidance for Licensing Actions Associated with NMSS Programs,” 2003

Rogers, V.C., K.K. Nielson, Correlations for Predicting Air Permeabilities and ^{222}Rn Diffusion Coefficients of Soils, Health Physics, pp. 225-230, Vol. 61, #2, 1991.

Tian, K., C. Benson, and J. Tinjum, “Antioxidant Depletion and Service Life Prediction for HDPE Geomembranes Exposed to Low-Level Radioactive Waste Leachate,” *J. Geotechnical & Geoenvironmental Eng.*, Vol. 143, # 6, June 2016.

APPENDIX A WORKSHOP ATTENDEES

Name	E-Mail Address
David Esh	david.esh@nrc.gov
Lloyd Desotell	lloyd.desotell@nrc.gov
Lifeng Guo	lifeng.guo@nrc.gov
Randall Fedors	randall.fedors@nrc.gov
Cynthia Barr	cynthia.barr@nrc.gov
Greg Chapman	gregory.chapman@nrc.gov
George Alexander	george.alexander@nrc.gov
Mike Salay	michael.salay@nrc.gov
Dominick Orlando	dominick.orlando@nrc.gov
John Saxton	john.saxton@nrc.gov
James Webb	james.webb@nrc.gov
Doug Mandeville	douglas.mandeville@nrc.gov
Robert Evans	robert.evans@nrc.gov
Thomas Nicholson	thomas.nicholson@nrc.gov
Bill Von Till	bill.vontill@nrc.gov
Ron Linton	ron.linton@nrc.gov
Joseph Kanney	joseph.kanney@nrc.gov
Meredith Carr	meredith.carr@nrc.gov
Jacob Philip	jacob.philip@nrc.gov
Zahira Cruz	zahira.cruz@nrc.gov
Varughese Kurian	varughese.kurian@nrc.gov
Elise Striz	elise.striz@nrc.gov
Thomas Lancaster	thomas.lancaster@nrc.gov
Mark Fuhrmann	mark.fuhrmann@nrc.gov
Hans Arlt	hans.arlt@nrc.gov
Mike Cheok	michael.cheok@nrc.gov
Mark Thaggard	mark.thaggard@nrc.gov
Andrea Kock	andrea.kock@nrc.gov
Thomas Aird	thomas.aird@nrc.gov
Justin Marble	justin.marble@em.doe.gov
Skip Chamberlain	grover.chamberlain@em.doe.gov
Sherri Ross	sherri.ross@em.doe.gov

Name	**E-Mail Address**
Juan Morales	juan.morales@em.doe.gov
Silvia Garcia	silvia.garcia@em.doe.gov
Ximena Lugo	ximena.lugo@*em.doe.gov*
Ming Zhu	ming.zhu@*em.doe.gov*
Kurt Gerdes	kurt.gerdes@*em.doe.gov*
Jaffet Ferrer-Torres	jaffet.ferrer-torres@hq.doe.gov
Craig Benson	chb4x@virginia.edu
Jody Waugh	jody.waugh@lm.doe.gov
Morgan Williams	morgan.williams@berkeley.edu
William Likos	likos@wisc.edu

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11. ABSTRACT (200 words or less)

The “Radon Barriers Project” is a research program to study the effects of changes in the properties of in-service engineered earthen covers over uranium mill tailings as these covers age. Field studies were conducted at four mill tailing disposal sites: Falls City in Texas, Bluewater in New Mexico, Shirley Basin South in Wyoming, and Lakeview in Oregon. Small areas on these sites were excavated, radon fluxes were measured, numerous observations were made, and samples were taken for a variety of parameters, such as saturated hydraulic conductivity, root counts, moisture, density, lead-210 concentrations, soil texture, structure, chemistry, and nematode counts.

On July 25–26, 2018, a one-and-a-half-day workshop took place at NRC Headquarters to discuss findings from the project with regard to the current state of the barriers and comparison to their as-built condition and natural analog sites, prediction of long-term evolution, monitoring approaches, and long-term implications. Presentations included detailed background and project findings that included: radon fluxes, diffusion coefficients and transport times, ecology, hydraulic conductivity changes and depth profiles, soil structure, impacts of plants and insects, soil architecture, soil biology, and Pb-210 profiles.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Uranium mill tailings, disposal of uranium mill tailings, UMTRCA covers, radon barriers, radon fluxes, radon diffusion coefficients, radon transport times, ecology, hydraulic conductivity, soil structure, impacts of plants and insects, soil architecture, soil biology, Pb-210.

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