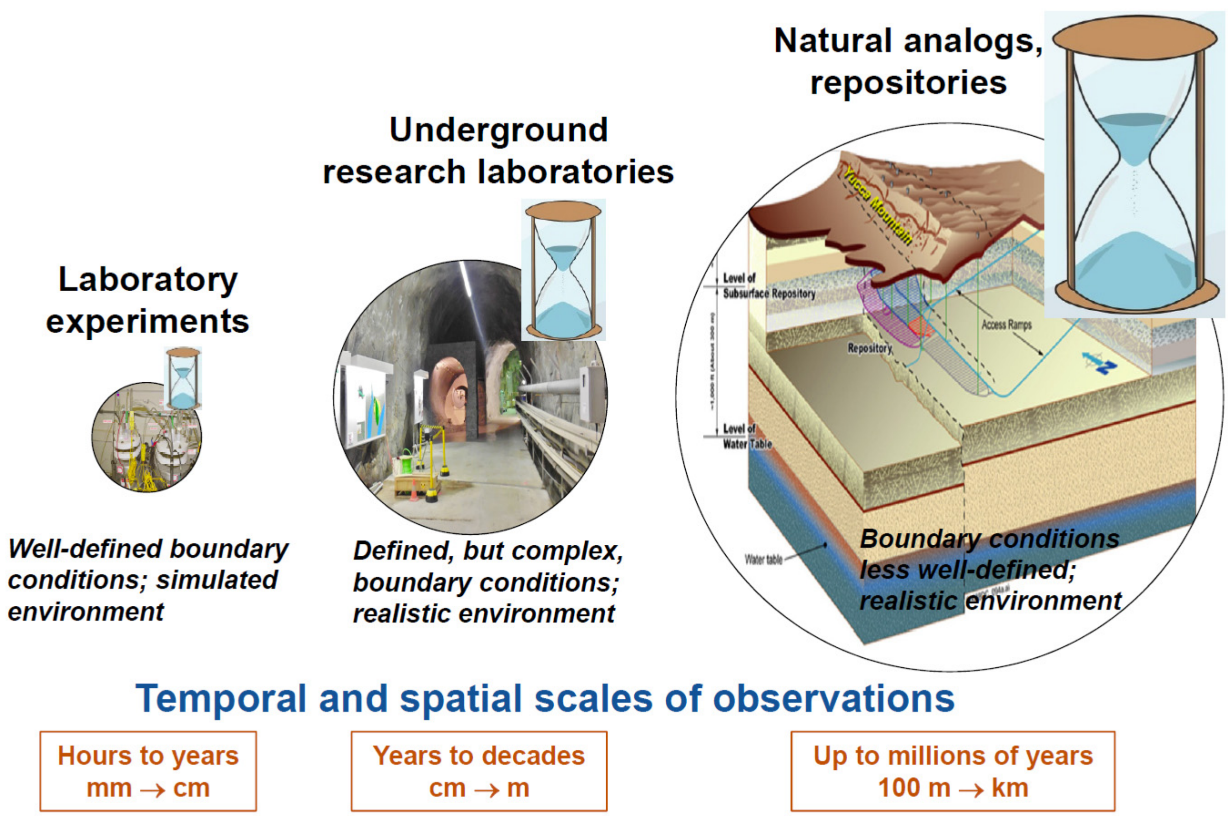
U.S. Nuclear Waste Technical Review Board

A Report to the U.S. Congress
and the Secretary of Energy

Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program



January 2020

U.S. Nuclear Waste Technical Review Board

FILLING THE GAPS: THE CRITICAL ROLE OF UNDERGROUND RESEARCH LABORATORIES IN THE U.S. DEPARTMENT OF ENERGY GEOLOGIC DISPOSAL RESEARCH AND DEVELOPMENT PROGRAM

Report to the United States Congress and the Secretary of Energy

January 2020

U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

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UNITED STATES
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January 2020

The Honorable Nancy Pelosi
Speaker
United States House of Representatives
Washington, DC 20515

The Honorable Chuck Grassley
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Dan Brouillette
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Pelosi, Senator Grassley, and Secretary Brouillette:

Congress created the U.S. Nuclear Waste Technical Review Board in the 1987 Nuclear Waste Policy Amendments Act (NWPAA) (Public Law 100-203) to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy to implement the Nuclear Waste Policy Act. In accordance with this mandate, the Board has undertaken a review of the U.S. Department of Energy (DOE) research and development (R&D) activities related to underground research laboratories (URLs). The Board's review is presented in this report to Congress and the Secretary of Energy titled *Filling the Gaps: The Critical Role of Underground Research Laboratories in the U.S. Department of Energy Geologic Disposal Research and Development Program*.

A number of countries have operated URLs in different types of potential host rocks to support developing deep geologic repositories for the disposal of spent nuclear fuel and high-level radioactive waste. These laboratories enable R&D activities to be conducted under subsurface conditions and at scales relevant to specific repository environments. Since 2012, DOE has collaborated in research conducted in URLs located in Europe and Asia. According to DOE, these international collaborations have been beneficial to its spent nuclear fuel and high-level radioactive waste disposal R&D program, particularly since 2010, when work on the Yucca Mountain repository program stopped and DOE began generic research on alternative host rocks (crystalline, clay, and salt) and in repository environments that are different from the environment at Yucca Mountain.

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Based on the information and findings developed in the report, the Board makes the following four recommendations:

1. *DOE should expand its collaborative international URL activities to enhance its capacity for R&D of geologic repositories. To obtain maximum benefit from its international programs, DOE should consider (i) making use of R&D in URLs to address the technical needs for the design, licensing, construction, and operation of geologic repositories in different host rocks that consider the types of waste in the U.S. inventory; (ii) pursuing international URL R&D partnerships, including those involving non-nuclear waste applications (e.g., carbon sequestration) that require underground knowledge and operations, in which DOE could participate in the design, construction, and operational phases of the collaborations; and (iii) compiling best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication from the experiences of URL programs in other countries.*

2. *DOE should make systematic use of URL R&D results to regularly update generic repository safety cases that can be easily understood by and demonstrated to the public, including safety cases relevant to direct disposal of dual-purpose canisters in different host rocks.*

3. *DOE should pursue one or more domestic URLs to advance the development and demonstration of disposal concepts and provide a platform for training the next generation of U.S. scientists, engineers, and skilled technical workers. DOE should evaluate whether underground sites in the U.S. with existing infrastructure could be used as generic URLs and whether use of existing facilities could be broadened (e.g., for more underground experiments or as training facilities) without impacting their primary missions. If DOE expands its domestic URL program in this way, then it should consider (i) broadening its URL R&D program from one focused on the technical issues relevant to post-closure repository performance to one that includes developing and demonstrating the construction and operational concepts for disposal; (ii) supporting larger, more formal training opportunities in underground disposal research in disciplines needed for the waste disposition mission; and (iii) making domestic URLs broadly accessible to researchers from the U.S. and other countries, including those outside the DOE geologic disposal R&D program.*

4. *DOE should continue advancing its thermal-hydrological-mechanical-chemical-based research and model development and pursue more URL- and laboratory-based studies, particularly at elevated temperatures. In doing so, DOE should consider (i) designing and conducting technical activities in URLs to test hypotheses and assumptions, while at the same time remaining open to unexpected processes or behaviors; (ii) employing an iterative process involving laboratory experiments focused on fundamental processes, modeling, and field experiments and observations; (iii) including geomechanical constraints and thermal effects in fracture flow and transport models; and (iv) focusing on bedded salts and using the heater tests at the Waste Isolation Pilot Plant to improve the constitutive models of salt behavior.*

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The Board trusts that Congress and the Secretary will find the information in this report useful and looks forward to continuing its ongoing technical and scientific review of DOE activities related to nuclear waste management and disposal.

Sincerely,

Jean M. Bahr

Jean M. Bahr
Chair

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ABBREVIATIONS AND ACRONYMS

ALC	high-level waste disposal cell experiment, Bure URL, France
Andra	National Radioactive Waste Management Agency, France
BATS	Brine Availability Test in Salt experiment, WIPP, New Mexico, USA
BRIE	Bentonite Rock Interaction Experiment, Äspö Hard Rock Laboratory, Sweden
CFM	Colloid Formation and Migration project, Grimsel Test Site, Switzerland
CHM	chemical-hydrological-mechanical
CI	Cement clay Interaction experiment, Mont Terri URL, Switzerland
DECOVALEX	DEvelopment of COupled Models and their VALidation Against Experiments
DOE	Department of Energy, USA
DOE-NE	DOE Office of Nuclear Energy
EBS	Engineered Barrier System experiment, Honorobe URL, Japan
FE	Full-scale Emplacement experiment, Mont Terri URL, Switzerland
FEBEX	Full-scale Engineered Barrier Experiment, Grimsel Test Site, Switzerland
FORGE	Fate Of Repository GasEs project
FS	Fault Slip experiment, Mont Terri URL, Switzerland
GDSA	Geologic Disposal Safety Assessment
GREET	Groundwater REcovery Experiment in a Tunnel, Mizunami URL, Japan
HADES	High Activity Disposal Experimental Site, Mol URL, Belgium
HE-E	in situ heater test experiment, Mont Terri URL, Switzerland
HG-A	gas path through host rock and along seals experiment, Mont Terri URL, Switzerland
HLW	high-level radioactive waste
HotBENT	full-scale high-temperature heater test, Grimsel Test Site, Switzerland
LANL	Los Alamos National Laboratory, USA
LASGIT	LArge Scale Gas Injection Test, Äspö Hard Rock Laboratory, Sweden
LBNL	Lawrence Berkeley National Laboratory, USA
LTDE	Long-Term Diffusion sorption Experiment, Äspö Hard Rock Laboratory, Sweden
MaCoTe	Material Corrosion Test, Grimsel Test Site, Switzerland
Nagra	National Cooperative for the Disposal of Radioactive Waste, Switzerland
PFLOTRAN	an open-source multi-physics simulator
R&D	research and development
RWM	Radioactive Waste Management, United Kingdom
SKB	Swedish Nuclear Fuel and Waste Management, Sweden
SNF	spent nuclear fuel
SNL	Sandia National Laboratories, USA
TED	heater experiment two, Bure URL, France
THC	thermal-hydrological-chemical
THM	thermal-hydrological-mechanical
THMC	thermal-hydrological-mechanical-chemical
TSDE	Thermal Simulation for Drift Emplacement experiment, Asse II Mine, Germany
U.K.	United Kingdom
URL	underground research laboratory
WIPP	Waste Isolation Pilot Plant, New Mexico, USA

ACKNOWLEDGMENTS

The Board thanks the participants from the U.S. Department of Energy (DOE) and its contractors from the national laboratories for presenting the DOE Collaboration and Underground Research Program and for sharing their expert knowledge of the program and DOE's research and development activities. The Board also thanks the invited speakers from the U.S. and other countries for sharing their extensive expertise and experience and providing thoughtful insights and ideas during the workshop discussions. The figure on the front cover is based on a graphic first developed in 2012 by Ingo Blechschmidt of the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra).

EXECUTIVE SUMMARY

A number of countries have operated underground research laboratories (URLs) in different types of potential host rocks to support developing deep geologic repositories for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). URLs enable research and development (R&D) activities to be conducted under subsurface conditions and at scales relevant to specific repository environments. Since 2012, the U.S. Department of Energy (DOE) has collaborated in research conducted in several URLs located in Europe and Asia. According to DOE, these international collaborations have been beneficial to its SNF and HLW disposal research program, particularly when work on the Yucca Mountain, Nevada, repository program stopped in 2010 and DOE began generic research on alternative host rocks (crystalline, clay, and salt) and repository environments very different from that at Yucca Mountain. Recognizing the governing processes and research challenges relevant to the safety case[1] for repositories in alternative host rocks are very different from that for a Yucca Mountain repository, DOE reprioritized its geologic disposal R&D activities. According to DOE, its international URL collaborations provided DOE-funded researchers access to data and to decades of experience gained in various disposal environments in a cost-effective manner and enabled their timely participation in URL-related studies.

The U.S. Nuclear Waste Technical Review Board (Board)[2] held a *Workshop on Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations* in Burlingame, California, on April 24 and 25, 2019, preceded by a fact-finding meeting with DOE in Las Vegas, Nevada, on February 26, 2019. The objectives were to review the technical and scientific validity of DOE R&D activities related to URLs, and to elicit information on international URL R&D programs useful to the Board's review and to DOE's implementation of the R&D activities.

During the workshop, four speakers from other countries—three from those with operating URLs (France, Sweden, and Switzerland) and one from a country without a URL (United Kingdom)—described the integration and contribution of URL science to their respective country's radioactive waste management program. DOE-funded principal investigators from the national laboratories gave technical presentations on DOE's URL-related R&D activities, focusing on near-field perturbation, engineered barrier integrity, hydrologic flow and radionuclide transport, and geologic disposal safety assessment.

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[1] A safety case is a collection of logic and evidence that demonstrates that a nuclear waste repository meets the performance requirements defined by the appropriate regulatory authorities. A safety case includes key results from the safety assessment, which is a quantitative analysis of the overall system performance where the performance measure is radiological impact or some other global measure of the impact on safety, both during repository operations and after repository closure. It also includes quantitative and qualitative supporting evidence and reasoning on (i) the robustness and reliability of the repository, (ii) its design and the rationale for the design choices made, and (iii) the quality and uncertainties of the safety assessment and underlying assumptions. For additional discussion, see International Atomic Energy Agency (2011, 2012).

[2] The U.S. Nuclear Waste Technical Review Board was created by Congress in the 1987 Nuclear Waste Policy Amendments Act (Public Law 100-203) and charged with evaluating the technical and scientific validity of activities undertaken by the Secretary of Energy to manage and dispose of HLW and SNF. The Board reports its findings, conclusions, and recommendations to Congress and the Secretary of Energy.

Based on the information presented and discussed at the workshop and at the fact-finding meeting and from reports published by DOE and others, as well as the Board's evaluation of the information, a number of specific findings and recommendations are provided in this report. From the specific findings, the Board presents the following four principal findings on DOE's URL-related R&D activities.

- DOE participation in URL-related international research greatly benefits the U.S. geologic disposal R&D program by furthering its understanding of generic and site-specific disposal issues relevant to alternative repository host rocks and environments. DOE-funded R&D activities also are benefiting the URL-related research of other countries, especially in the area of complex analytical and numerical model/software development.
- The more developed repository programs in other countries have focused on creating and strengthening their safety cases and making them transparent to the public. Repository programs in other countries use URLs to explain the technical bases underlying their safety cases, periodically reassess knowledge gaps and define new activities to strengthen the technical bases, and demonstrate the technology that will allow implementation of the proposed safety concept.
- Countries with more developed geologic disposal programs have found domestic URLs essential to their repository programs. DOE needs domestic URLs to advance geologic disposal efforts over the next decades and further its ability to train the next generation of scientists, engineers, and skilled technical workers.
- DOE's international URL collaborations have advanced its generic disposal R&D program, including development of modeling capabilities recognized internationally as state-of-the-art, but further work on its coupled thermal-hydrological-mechanical-chemical models and URL- and laboratory-based research can strengthen its program.

Based on these principal findings, the Board makes the following recommendations:

- DOE should expand its collaborative international URL activities to enhance its capacity for R&D of geologic repositories. To obtain maximum benefit from its international programs, DOE should consider (i) making use of R&D in URLs to address the technical needs for the design, licensing, construction, and operation of geologic repositories in different host rocks that consider the types of waste in the U.S. inventory; (ii) pursuing international URL R&D partnerships, including those involving non-nuclear waste applications (e.g., carbon sequestration) that require underground knowledge and operations, in which DOE could participate in the design, construction, and operational phases of the collaborations; and (iii) compiling best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication from the experiences of URL programs in other countries.
- DOE should make systematic use of URL R&D results to regularly update generic repository safety cases that can be easily understood by and demonstrated to the public, including safety cases relevant to direct disposal of dual-purpose canisters in different host rocks.

- DOE should pursue one or more domestic URLs to advance the development and demonstration of disposal concepts and provide a platform for training the next generation of U.S. scientists, engineers, and skilled technical workers. DOE should evaluate whether underground sites in the U.S. with existing infrastructure could be used as generic URLs and whether use of existing facilities could be broadened (e.g., for more underground experiments or as training facilities) without impacting their primary missions. If DOE expands its domestic URL program in this way, then it should consider (i) broadening its URL R&D program from one focused on the technical issues relevant to post-closure repository performance to one that includes developing and demonstrating the construction and operational concepts for disposal; (ii) supporting larger, more formal training opportunities in underground disposal research in disciplines needed for the waste disposition mission; and (iii) making domestic URLs broadly accessible to researchers from the U.S. and other countries, including those outside the DOE geologic disposal R&D program.
- DOE should continue advancing its thermal-hydrological-mechanical-chemical-based research and model development and pursue more URL- and laboratory-based studies, particularly at elevated temperatures. In doing so, DOE should consider (i) designing and conducting technical activities in URLs to test hypotheses and assumptions, while at the same time remaining open to unexpected processes or behaviors; (ii) employing an iterative process involving laboratory experiments focused on fundamental processes, modeling, and field experiments and observations; (iii) including geomechanical constraints and thermal effects in fracture flow and transport models; and (iv) focusing on bedded salts and using the heater tests at the Waste Isolation Pilot Plant to improve the constitutive models of salt behavior.

1 INTRODUCTION

A number of countries, including Belgium, Canada, Finland, France, Germany, Japan, Korea, Sweden, Switzerland, and the United States, have operated underground research laboratories (URLs) in different types of potential host rocks to support the development of deep geologic repositories for the disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF). URLs enable research and technology development activities to be conducted under subsurface conditions and at scales relevant to specific repository environments. Since 2012, the U.S. Department of Energy (DOE) has engaged in active collaborations with the geologic disposal programs of several countries, including participation in research conducted in several URLs in Europe and Asia. DOE's international collaborations now constitute an important component of its geologic disposal research (Birkholzer et al. 2018). According to DOE, these collaborations have been beneficial to its disposal research program in multiple ways. They have provided access to data and to decades of experience gained in various disposal environments in a cost-effective manner, enabled DOE-funded researchers to gain research experience and take advantage of established URLs in a short period of time, and provided opportunities for peer reviews of DOE data and analyses by experts from other countries (Gunter 2019).

The U.S. Nuclear Waste Technical Review Board (Board)[3] held a *Workshop on Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations* in Burlingame, California, on April 24 and 25, 2019. The Board organized the workshop to review the technical and scientific validity of DOE research and development (R&D) activities related to URLs. The Board also elicited information on international URL R&D programs useful to the Board in its review and to DOE in its implementation of these activities. In the Board's view, international URL R&D activities provide unique opportunities to learn about recent advances in the scientific understanding of the long-term performance, as well as in the technology and operation, of geologic repositories for HLW and SNF. These advances and lessons learned can contribute to the U.S. geologic disposal R&D program.

This report presents a summary of the workshop and the Board's observations, findings, and recommendations regarding DOE's URL-related R&D activities based on the presentations and discussions at the workshop and at a Board fact-finding meeting with DOE in Las Vegas, Nevada, on February 26, 2019, as well as from reports published by DOE and others (see References section).[4]

1.1 Board Workshop Agenda

Underground Research Laboratories

The workshop began with an overview presentation by Michael Apted of INTERA, a geosciences and engineering consulting firm, on the purposes and types of URLs throughout the

[3] The U.S. Nuclear Waste Technical Review Board was created by Congress in the 1987 Nuclear Waste Policy Amendments Act (Public Law 100-203) and charged with evaluating the technical and scientific validity of activities undertaken by the Secretary of Energy to manage and dispose of HLW and SNF. The Board reports its findings, conclusions, and recommendations to Congress and the Secretary of Energy.

[4] A glossary of technical terms used in this report is provided after the References section.

world, the R&D activities that are conducted in those facilities, and the evolving role of URLs in the geologic disposal programs across the globe (Apted 2019). This was followed by presentations on the URL R&D programs of four countries: Switzerland, Sweden, France, and the United Kingdom (U.K.).

Irina Gaus of the National Cooperative for the Disposal of Radioactive Waste (Nagra), the implementer of the radioactive waste geologic disposal program in Switzerland, described the Swiss concepts for waste management and HLW repository (Gaus 2019). Dr. Gaus discussed the integration and contributions of URL science to the Swiss radioactive waste management program. Switzerland currently has two operating URLs—the Grimsel Test Site in crystalline rocks (granite/granodiorite) in central Switzerland and the Mont Terri URL in sedimentary rocks (Opalinus Clay) in northwestern Switzerland.

Patrik Vidstrand of the Swedish Nuclear Fuel and Waste Management Company (SKB) followed with an overview presentation on the Swedish waste management system and the safety case[5] that supports SKB's license application for a repository in Östhammar, Sweden (Vidstrand 2019). Dr. Vidstrand also described several R&D activities at the Äspö Hard Rock Laboratory located outside of Oskarshamn.

Daniel Delort of Andra, the French national radioactive waste management agency, provided brief histories of Cigéo, a French project for geologic disposal of HLW in clay sedimentary rocks at a site in northeastern France, and of Andra's nearby URL at Bure (Delort 2019). Mr. Delort also discussed the role of the Bure URL in the completion of the Cigéo license application and described examples of experiments Andra performed there.

Simon Norris of the Radioactive Waste Management (RWM), the implementer of the U.K.'s geologic disposal program, gave an overview presentation on the U.K.'s radioactive waste management program and discussed the role of URL-based R&D in the U.K.'s geologic disposal program (Norris 2019). The U.K., which is in the early stages of a repository siting process, does not have an operating URL, but like the U.S., is participating in URL-related research in other countries.

The four presentations on international URL R&D programs were followed by a facilitated panel discussion regarding international URL programs.

DOE International Collaborations and URL-Related R&D Activities

Following the international panel discussion, William Boyle [DOE Office of Nuclear Energy (DOE-NE)] provided a brief overview of the DOE-NE Office of Spent Fuel and Waste Science and Technology, the DOE R&D priorities on disposal of SNF and HLW, and the DOE activities

[5] A safety case is a collection of logic and evidence that demonstrates that a nuclear waste repository meets the performance requirements defined by the appropriate regulatory authorities. A safety case includes key results from the safety assessment, which is a quantitative analysis of the overall system performance where the performance measure is radiological impact or some other global measure of the impact on safety, both during repository operations and after repository closure. It also includes quantitative and qualitative supporting evidence and reasoning on (i) the robustness and reliability of the repository, (ii) its design and the rationale for the design choices made, and (iii) the quality and uncertainties of the safety assessment and underlying assumptions. For additional discussion, see International Atomic Energy Agency (2011, 2012).

related to international URLs (Boyle 2019). Then, Jens Birkholzer [Lawrence Berkeley National Laboratory (LBNL)] discussed in more detail the rationale for DOE's engagement in international collaborations, particularly in URL R&D activities, how these activities are integrated with DOE's disposal R&D program, how they were selected and prioritized, and their benefits to the DOE program (Birkholzer 2019a).

Dr. Birkholzer explained that when work on the Yucca Mountain, Nevada, repository program stopped in 2010, DOE reoriented its SNF and HLW disposal program and started to look at alternative disposal concepts and designs. Since 2012, DOE has engaged in active collaborations with the disposal programs of many other countries, including in URL-related research. Disposal programs use the characteristics of the repository host rock (i.e., the natural barrier) in combination with engineered barriers to ensure the long-term safety from the disposed wastes.[6]

DOE initiated these collaborations to benefit from the deep knowledge base other countries have developed over decades with respect to disposal in a variety of rock types, including crystalline (e.g., granite), clay (e.g., argillite), and salt host rocks. The repository concepts in these host rocks are dramatically different from that at Yucca Mountain. The Yucca Mountain repository concept involved disposal in fractured volcanic tuff, in a hydrologically unsaturated zone (i.e., above the water table), in chemically oxidizing conditions, and open (unbackfilled) emplacement tunnels. In contrast, the repository concepts in other countries include disposal in low permeability host rocks, in a hydrologically saturated zone (i.e., below the water table), in chemically reducing conditions, and backfilled emplacement tunnels. In addition, the repository concepts in crystalline host rock, for example the KBS-3 disposal concept that is used in Sweden and Finland, and clay host rock are premised on the use of bentonite for the buffer immediately surrounding the waste package and for the backfill in the repository tunnels as part of the engineered barrier system (Box 1-1).

According to Dr. Birkholzer, DOE reprioritized its disposal R&D activities because the processes relevant to the safety of repositories in crystalline, clay, or salt host rocks are different from those for a Yucca Mountain repository and, thus, the research challenges are different. Dr. Birkholzer indicated the DOE disposal R&D activities currently are focused on four key research topics: (i) near-field perturbation, (ii) engineered barrier integrity, (iii) flow and radionuclide transport, and (iv) integrated repository system behavior. The high-level research questions on these four topics that DOE is addressing are listed in Table 1-1.

The DOE URL-related R&D activities directed at the key research topics and questions are illustrated in Figure 1-2. The R&D activities encompass the engineered barrier system and three alternative host rock types—crystalline, clay, and salt. There is more work in crystalline and clay host rocks than in salt, which, according to Dr. Birkholzer, is because not many countries are looking at salt as a potential host rock and also because the U.S. has the Waste Isolation Pilot

[6] The engineered barrier system represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill, and seals. The near-field includes the engineered barrier system and those parts of the host rock in contact with or near the engineered barrier system, whose properties have been affected by the presence of the repository. The far-field represents the geosphere (and biosphere) beyond the near-field (Nuclear Energy Agency 2003).

Box 1-1. Bentonite and its use as an engineered barrier material

Bentonite is a soft, plastic, light-colored rock composed primarily of clay minerals of the smectite group, particularly montmorillonite, which typically forms from chemical alteration of glassy volcanic ash or tuff under marine or hydrothermal conditions (Clay Minerals Society 2019). Typical accessory minerals in bentonite are quartz, feldspars, gypsum, calcite, pyrite, iron oxides/hydroxides, and other clay minerals. Bentonite swells significantly when exposed to water (up to 12 times, depending on bentonite composition) and has many industrial uses.

In some repository concepts, such as the KBS-3 concept for the geological disposal of spent nuclear fuel in crystalline rock in Sweden and Finland, bentonite is used for the buffer that surrounds and protects the individual waste packages and for the tunnel seal that seals off the disposal galleries from the shafts leading to the surface (Sellin and Leupin 2013). The bentonite buffer is integral to the multi-barrier system for isolation of the radioactive waste and is required to perform a number of safety functions. Its low hydraulic permeability in a saturated state ensures that diffusion will be the dominant transport mechanism in the barrier, which will reduce radionuclide migration from the emplaced waste. Bentonite also strongly sorbs many elements, which will retard radionuclide transport, and its swelling pressure ensures self-sealing that will close gaps between the installed barrier and the excavation-damaged zone around the emplacement tunnels. Bentonite can be installed in the form of manufactured pellets or large "blocks", or as loose granular material. Bentonite blocks can be manufactured by uniaxial compression of bentonite granules inside a rigid mold (Figure 1-1), whereas bentonite pellets can be manufactured by roller compaction of bentonite granules using a briquette pressing machine (SKB 2010).

A scientific understanding of the coupled processes (see Box 1-2) and boundary conditions acting on the engineered barriers in a repository is needed to determine how the barriers will perform with time. Examples of areas that need to be evaluated are the temperature evolution in the repository during the early stage due to the waste decay heat, saturation of the installed bentonite, build-up of swelling pressure on the containers and the surrounding rock, and degradation of the smectite component in the bentonite. The form in which the bentonite is used—blocks, pellets, or granular—will affect how the bentonite responds to changes in temperature and hydration. Illitization, the transformation of smectite to illite, could compromise some beneficial features of bentonite, such as sorption and swelling capacity. Because it is believed the rate of illitization could greatly increase at temperatures higher than 100 °C, reducing bentonite's barrier capability, the bentonite buffer temperature in the KBS-3 concept is limited to less than 100 °C. Also, in repositories in fractured host rock, the buffer will become saturated with water as groundwater flows through the fractures. If the water flow rate through the fractures is high enough, the water may erode the bentonite.

Figure 1-1. Photo of a mold SKB used for making ring-shaped bentonite blocks (SKB 2010).

Table 1-1. DOE disposal R&D program priority topics (Birkholzer 2019a)	
Key Topics	**High-Level Research Questions**
Near-Field Perturbation	• How important are thermal, mechanical, and other perturbations? • How effective is healing and sealing of damage zone in the long-term? • How reliable are existing predictive models for the strongly coupled thermal-hydrological-mechanical behavior of clays and salts?
Engineered Barrier Integrity	• What is the long-term stability and retention capability of buffer materials? • Can bentonite be eroded by contact with water from flowing fractures? • How relevant are interactions between engineered and natural barriers? • Is gas pressure increase and gas migration a concern for barrier integrity?
Flow and Radionuclide Transport	• What is the effect of high temperature on the diffusion and sorption characteristics of clays? • What is the potential for enhanced transport with colloids? • Can transport in diffusion dominated (clays, bentonites) and advection dominated systems (fractured granites) be predicted with confidence?
Integrated Repository System Behavior	• Can the early-time behavior of an entire repository system, including all engineered and natural barriers and their interaction, be demonstrated? • Can this integrated behavior be reliably predicted? • Is the planned construction/emplacement method feasible? • Which monitoring methods are suitable for performance confirmation?

Plant (WIPP) in Carlsbad, New Mexico, where it can conduct research and in situ tests underground in a salt formation.

The rest of the two-day workshop included technical presentations on DOE's URL-related R&D activities, focusing on near-field perturbation, engineered barrier integrity, hydrologic flow and radionuclide transport, and geologic disposal safety assessment.

Jonny Rutqvist (LBNL) discussed DOE's near-field natural barrier perturbation R&D activities, specifically the advanced numerical modeling tools DOE developed to simulate coupled thermal-hydrological-mechanical (THM) processes (see Box 1-2), e.g., in bentonite buffers and argillite host rocks (Rutqvist 2019a). Dr. Rutqvist also discussed several examples of model testing and validation using data from in situ heater tests at the Mont Terri and Bure URLs. Three presentations on DOE's engineered barrier integrity R&D activities followed.

Liange Zheng (LBNL) described DOE studies that are being conducted to understand coupled thermal-hydrological-mechanical-chemical (THMC) perturbations in the engineered barrier system, particularly the evolution of bentonite buffer properties when exposed to high temperatures (Zheng 2019). These studies include THMC modeling of the in situ Full-scale Engineered Barrier Experiment (FEBEX) and the HotBENT project. FEBEX is a full-scale heater test that was dismantled after running for 18 years at the Grimsel Test Site. HotBENT is a field test integrated with laboratory experiments and modeling that is planned for the Grimsel Test Site to study bentonite buffer behavior at temperatures up to 200 °C.

Carlos Jové-Colón [Sandia National Laboratories (SNL)] gave a presentation describing DOE studies to evaluate the effect of temperature on bentonite clay properties, including structure, composition, and swelling properties, and on bentonite clay interactions, such as uranium

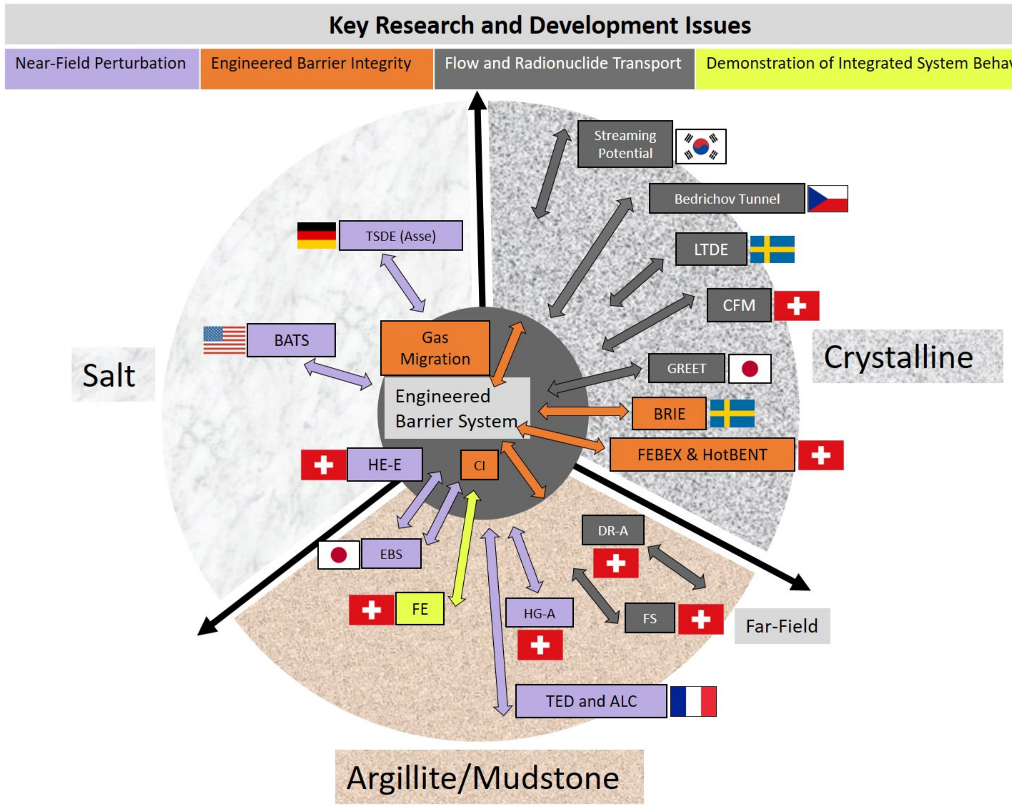


Figure 1-2. Schematic showing the DOE URL-based R&D activities addressing priority R&D topics by rock type and repository position (modified from Birkholzer 2019a).

The center of the circle is meant to represent the engineered barrier system. The outer ring is divided into the different repository host rock types. Abbreviations for the experiments, starting from the top and proceeding clockwise, are as follows: LTDE—Long-Term Diffusion sorption Experiment; CFM—Colloid Formation and Migration project; GREET—Groundwater REcovery Experiment in a Tunnel; BRIE—Bentonite Rock Interaction Experiment; FEBEX—Full-scale Engineered Barrier Experiment; HotBENT—full-scale high-temperature heater test; DR-A—disturbances, diffusion and retention experiment; FS—Fault Slip experiment; HG-A—gas path through host rock and along seals experiment; TED—heater experiment two; ALC—high-level waste disposal cell experiment; CI—Cement clay Interaction experiment; FE—Full-scale Emplacement experiment; EBS—Engineered Barrier System experiment; HE-E—in situ heater test experiment; BATS—Brine Availability Test in Salt experiment; and TSDE—Thermal Simulation for Drift Emplacement experiment.

sorption and interactions with cement (Jové-Colón 2019). The studies Dr. Jové-Colón described used bentonite samples taken from the FEBEX experiment. He also discussed laboratory experiments that studied the interaction of bentonite with steel.

Dr. Rutqvist gave a second presentation on a DOE study to understand the basic mechanisms of gas transport in low permeability materials such as bentonite and claystone (Rutqvist 2019b). That study, part of the DECOVALEX-2019 project, involves modeling of gas flow data from laboratory experiments conducted by the British Geological Survey.

Two presentations discussed DOE R&D activities on hydrologic flow and radionuclide transport. Hari Viswanathan (Los Alamos National Laboratory (LANL)] described modeling studies of flow and transport in fractured granite using data from two URL experiments—the Bentonite Rock Interaction Experiment (BRIE) and the Long-Term Diffusion Experiment (LTDE), both at the Äspö Hard Rock Laboratory (Viswanathan 2019). Then, Hakim Boukhalfa (LANL) gave a

Box 1-2. Coupled thermal-hydrological-mechanical-chemical processes and microbial effects

The emplacement of SNF and HLW in a geologic repository causes large perturbations of the subsurface geologic, hydrogeologic, and environmental systems. The perturbation of the host rock with pore fluids is two-fold. First, the emplaced waste is a substantial and sizeable heat source that is active for a long period of time. This heat source induces hydrologic changes (e.g., buoyant fluid flow) and rock expansion. The degree and extent of these changes depend directly on the magnitude of the temperature rise and on the integrated heat input into the system (Tsang 1987). Second, excavation of emplacement tunnels and shafts for sizeable waste packages results in large cavities that significantly change the original stress distribution in the rock mass. The stress redistribution causes mechanical deformation of the rock that results in the opening or closing of existing rock fractures, which is important for crystalline host rocks. Opening or closing of fractures strongly affects fluid flow and solute transport in the rock mass that, in turn, are important to repository performance (Tsang 1987).

Coupled processes induced by these drastic changes in the subsurface system affect the near-field and involve mainly four effects (Tsang 1987): thermal (T), hydrological (H), mechanical (M), and chemical (C) (see also Figure 3-1). Coupling of processes means that each process affects the initiation and progress of the others. Therefore, under coupled conditions, the behavior of the repository cannot be predicted by considering each process independently (Manteufel et al. 1992). How the effects of coupled processes are manifested depends on the properties of the host rock (e.g., plastic deformation of clay versus discrete fracture in crystalline rocks).

Computer codes are used extensively to perform coupled analyses for design and performance assessment of geologic repositories. Several codes can model coupled processes involving two or three processes; however, they frequently have many limitations. Most codes are for modeling porous media as continua; significant uncertainties can arise with the introduction of fractures (Manteufel et al. 1992) or with the use of granular engineered barrier materials. Similarly, significant uncertainties arise in geochemistry, as it has predominately been studied at low temperatures (< 100 °C). Most of these codes are only partially verified against analytical solutions or experimental data. Reliable numerical prediction of coupled behavior will require computer codes that have been tested against observations. Hence, the development of appropriate mathematical models must be combined with controlled experimental or field studies.

Microbes may be present naturally in the repository host rock or introduced during construction and operation of the repository. Microbiological, or microbial, effects have not been evaluated as part of coupled processes in a repository system (Humphreys et al. 2010), but are treated as specific effects or processes (e.g., microbially influenced corrosion of metallic components of the engineered barrier system and biogenic gas generation). The importance of microbial effects on repository performance likely will be a strong function of the inventory of organic material in the engineered barrier system and host rocks (Humphreys et al. 2010). For repositories sited in organic-rich clay host rocks or that include organic-containing waste forms, such as the bituminous waste to be disposed of in the French repository, microbial processes will be more important. However, microbial processes may need to be considered also in low-organic content host rocks because micro-organisms can also grow and derive energy from the chemical energy in rocks and engineered materials.

presentation describing the Colloid Formation and Migration (CFM) Project, which conducts radionuclide migration experiments in a fracture shear zone at the Grimsel Test Site, and the modeling of the data using simulation tools developed by LANL (Boukhalfa 2019). The project objective is to investigate colloid formation, bentonite erosion, colloid migration, and colloid-associated radionuclide transport.[7]

A presentation by Kristopher Kuhlman (SNL) and Philip Stauffer (LANL) described DOE research activities related to salt repositories, particularly the Brine Availability Test in Salt (BATS), which is a heater test being conducted in the subsurface at WIPP (Kuhlman and Stauffer 2019). They also discussed the process-level modeling of THMC processes in salt, including comparisons with data from the heater test at the Asse salt mine in Germany and from the BATS shakedown test.

The final workshop presentation was by Emily Stein (SNL), who described DOE's Geologic Disposal Safety Assessment (GDSA), which is a portfolio of projects related to developing and demonstrating the next generation of software toolkits for probabilistic post-closure performance assessment (Stein 2019). Dr. Stein also discussed how GDSA benefits from international URL collaborations.

A poster session with 22 papers that were mostly URL-related was held at the end of the first day of the workshop. A final plenary session was held at the end of the second day to identify key issues and lessons learned from URL R&D programs. The workshop agenda is included in Appendix A. The presentations, the transcript of the proceedings, and an archived webcast of the workshop are available on the Board's website at http://www.nwtrb.gov/meetings/past-meetings. The February fact-finding meeting agenda and presentations are posted with the workshop materials.

[7] Colloid is defined as a state of subdivision of matter in which the particle size varies from that of true 'molecular' solutions to that of a coarse suspension (International Atomic Energy Agency 2003). The diameters of the particles range between 1 and 1000 nm. The particles are dispersed in a liquid phase and do not quickly settle out.

2 Role of Underground Research Laboratories in Enhancing International Knowledge and Experience

Of the more than 20 countries with geologic disposal programs, eight currently have operating URLs. These facilities host a variety of R&D activities, ranging from basic research into subsurface processes that affect long-term repository performance, to full-scale tests of sealing methodologies, and to operational testing. These activities are carried out by a combination of domestic researchers and researchers from other countries. A total of fifteen countries currently have operating URLs, had URLs in the past, or have plans for future URLs (Delay et al. 2014; Apted 2019). Information on 27 active, past, and future URLs is summarized in Table 2-1.

URLs range in depth below the land surface from 100 to 1,300 m (330 to 4,300 ft), although many are ~500-m (~1,600 ft) deep, the same depth as many planned geologic repositories. In Table 2-1, the URLs are categorized as either generic (for general study) or site-specific (in or close to the planned repository rock mass). URLs either use pre-existing tunnels and mines or are purposely built (purpose built in Table 2-1). The specific distinctions and advantages of generic and site-specific URLs are covered below. We first address the utility of an underground research facility.

2.1 Why an Underground Laboratory?

Three of the four speakers from other countries at the workshop came from countries where robust URLs are a key part of their repository program (France, Sweden, and Switzerland). All three countries have had at least two separate URLs during the evolution of their programs. In each of these countries, international research and collaboration within their URLs are a vital part of their overall effort. The fourth speaker, from the U.K., represented a country that currently has not defined either a repository site or rock type—similar to the U.S. Thus, much like the U.S., the U.K. is engaging in a number of collaborative R&D activities in other countries' URLs.

URLs are useful for a variety of purposes because they take advantage of the conditions at depth surrounded by natural rock, none of which can be exactly replicated in a standard surface laboratory. The workshop participants highlighted three main unique opportunities afforded by URLs that are not possible in surface facilities:

- **Opportunity to engage in long-term studies that directly probe the coupled processes acting in the subsurface at the same temperature and pressure conditions expected in a repository within a large zone of natural, undisturbed rock.**

  Conducting research in URLs leads to a more complete scientific understanding of coupled processes and improved capability for developing predictive performance models. URLs enable detailed characterization of the undisturbed rock and the hydrogeologic, mechanical, geochemical, and microbial environment at depth, as well as

Table 2-1. List of some generic and site-specific URLs (modified from Delay et al. 2014)*				
URL	**Dates of operation**	**Country**	**Host rock, depth**	**Comments**
Generic URLs				
HADES	1984-	Belgium	Boom Clay, 230 m	Purpose built
Whiteshell	1984-2003	Canada	Granite, 240-420 m	Purpose built, shaft sealed
Beishan Experimental Tunnel (1)	2015-2016	China	Granite, ~50 m	Purpose built to test Beishan URL construction methods
Beishan (1)	~2020	China	Granite, 560 m	Purpose built
Bedřichov Tunnel (2)	2003-2015	Czech Republic	Granite, 150 m	Pre-existing tunnel
Bukov (2)	2017-	Czech Republic	Metamorphic (amphibolite), 550 m	Pre-existing uranium mine, new tunnel excavated
Amelie	1986-1992	France	Bedded salt	Pre-existing tunnels
Fanay-Augères Mine	1980-1990	France	Granite	Pre-existing tunnels in uranium mine
Tournemire Research Tunnel	1990-	France	Shale, 250 m	Pre-existing tunnels
Asse Mine	1965-1997	Germany	Salt anticline, 490-950 m	Existing mining levels 490-800m, cavern at 950m
Mizunami	2004-	Japan	Granite, 1000 m shaft	Purpose built
Horonobe	2005-	Japan	Sedimentary rock, 500 m shaft	Purpose built
Korean Underground Research Tunnel	2006-	Korea, Republic of	Granite, 90 m	Purpose built
Stripa Iron Mine	1976-1992	Sweden	Granite, 360-410 m	Pre-existing tunnels
Äspö Hard Rock Lab.	1995-	Sweden	Granite, 240-460 m	Purpose built
Grimsel Test Site	1984-	Switzerland	Granite, 450 m	Purpose built, parallel to existing tunnels
Mont Terri	1995-	Switzerland	Opalinus Clay, 400 m	Purpose built, parallel to existing tunnels
Climax stock, Nevada	1978-1983	USA	Granite, 420 m	Pre-existing tunnels
G-tunnel, Nevada	1979-1990	USA	Tuff, 300 m	Pre-existing tunnels
Site-Specific URLs				
ONKALO, Olkiluoto	2003-	Finland	Granite, 500 m	Purpose built
Meuse/Haute-Marne (Bure)	2000-	France	Shale (indurated clay), 450-500 m	Purpose built
Gorleben	1985-1990 2010	Germany	Salt dome, >900 m	Purpose built, moratorium cancelled 2010
Morsleben repository	1998 -	Germany	Salt dome, >525 m	R&D on decommissioning
Nizhnekansky, Krasnoyarsk (3)	~2025	Russia	Metamorphic (gneiss), 450-550 m	Purpose built
Waste Isolation Pilot Plant (WIPP)	1982-1999	USA	Bedded salt, 655 m	Operating repository since 1999; DOE URL R&D testing resumed in 2017 (4)
Busted Butte, Yucca Mountain, Nevada (5)	1998-2001	USA	Non-welded tuff, 70 m	Purpose built to access rock layers under the repository
Exploratory Studies Facility, Yucca Mountain, Nevada.	1996-2010	USA	Welded tuff, 300 m	Purpose built, activities stopped in 2010
*Other references: (1) Wang et al. 2018. (2) Smutek 2018. (3) Murlis 2018. (4) Johnson et al. 2019. (5) Wang and Bodvarsson 2003.				

characterization of the in situ behavior of engineered barrier system components. Experiments can be conducted to measure the impact and interactions of waste heat and disposal system components on the subsurface geologic environment at scales that are relevant to repository conditions. For example, while only single fractures can be studied in standard laboratory tests, an entire fracture system can be probed in URLs. Many studies have shown that experiments using small isolated pieces of rock cannot reproduce the behavior of larger undisturbed pieces of the same rock or in a field setting. In addition to enabling experiments at the same spatial scale as in a repository, the larger spatial scales require that URLs run experiments much longer (i.e., years to possibly decades) than surface laboratory experiments.

- **Opportunity to test a variety of technical and operational activities.**

  In URLs, the impacts of construction and excavation on the host rock over small and large spatial and temporal scales can be directly observed. Characterization methods can be tested that could be used routinely during operations to make detailed decisions about rock suitability as each disposal space is built out. URLs also permit the development and testing of specialized rock excavation and waste package emplacement machinery, and full-scale demonstrations can be carried out on the emplacement and performance of wastes, engineered barrier systems, and seals. Furthermore, laboratory experiments can be designed based on current knowledge of important variables, but field studies allow for surprises that teach planners about unexpected processes or behaviors.

- **Opportunity for training and confidence building in a subsurface environment similar to the repository.**

  URLs provide unique training and underground working or experimentation experience for scientists, engineers, and technicians relevant to subsurface processes that could impact the integrity of the complete repository system (geologic/hydrologic environment and engineered barriers). Also, URLs allow realistic in situ testing, demonstration of aspects of the safety case and operations to stakeholders and the public, and development and testing of long-term monitoring options and technologies.

2.2 Site-Specific versus Generic Underground Research Laboratories

URLs can be characterized as site-specific or generic (Table 2-1). A generic URL is typically located in a rock type under consideration for a repository, but is specifically not developed at the locality where the planned repository, if known, will be built. Generic URLs offer a geological environment for conducting experiments, but not necessarily one exactly like that of the final repository. Site-specific URLs are constructed close to or in the footprint of an existing repository or the potential future disposal facility. Site-specific URLs allow direct subsurface characterization of the repository rock mass, including possible microbial activity, and the projected in situ THMC processes and the interaction of these processes with the planned engineered barrier system.

Workshop participants noted a number of uses and advantages of generic URLs for their repository programs. Very few locations around the world are available to scientists and engineers to study the intact subsurface. Thus, many investigators may never have been underground. Generic URLs provide valuable opportunities for testing and validating coupled subsurface process models, as well as for understanding the interactions between engineered barriers and the local geologic and hydrologic setting relevant to potential repositories of similar rock type. Generic URLs also afford a great training opportunity for a wide range of underground operations, including excavation methods, simulated waste handling machinery, and sealing systems. In addition, as one participant noted (NWTRB 2019a, pg. 151), having a URL at a site that would not make an acceptable repository, e.g., a location with extensive fractures and faults, allows better opportunities to study processes, such as fracture flow and fault movement, than might be possible at an ideal site chosen for a repository because the geologic processes would be more visible and rapid.

Another advantage of generic URLs is that it might be easier to find willing host communities for generic URL sites if assurance is given that those will never be used as repository sites. In addition to the technical training opportunities, generic URLs provide unique opportunities for outreach to and confidence building with the public, most of whom have only vague notions of what the subsurface looks like.

It should be recognized, however, that in some sense all URLs are actually "site-specific". There is no "generic" argillite, granite, salt, or crystalline rock. Some granites are largely unfractured and have low permeabilities, while others are more highly fractured and, therefore, are more permeable. Some clay-rich rocks are relatively homogeneous, others are quite textured, with very directional properties (e.g., the Opalinus Clay), and the amounts and types of clay minerals and degree of induration can vary significantly. Finally, even within the same formation, significant variation often is observed over centimeters to meters to kilometers.

Workshop participants generally agreed that, eventually, most programs will need a dedicated, site-specific URL as a final repository site is selected and characterized. For example, Switzerland already has two generic URLs, one in granite and one in Opalinus Clay, the two potential host rocks that have been considered for a Swiss repository. Irina Gaus of Nagra reported at the workshop that Nagra is now beginning surface investigations and drilling programs at three potential repository sites in northern Switzerland (all in Opalinus Clay) to assist in the final site selection (Gaus 2019). Once one (or more) site is selected for further investigation, Nagra plans to construct a new URL and a pilot facility at the site. The pilot facility will be monitored during the construction and operational phases of the repository to determine the evolution over time of safety relevant conditions and processes, including barrier effectiveness, for early recognition of unexpected developments, and to support the post-closure safety assessment. As planned by Nagra, the pilot facility is distinct from a URL; validated full-scale models should come from prior experiments in a URL where much more intensive and intrusive instrumentation is possible. The Swiss also continue to support their generic URLs and are funding the URL operations, with substantial additional support from collaborators from other countries. The German program also is considering multiple types of potential host rocks. The German site selection process requires underground characterization of at least two sites, meaning at least two URLs will be developed (German Federal Ministry of Justice and Consumer Protection 2017).

Finland opted to create a site-specific URL in the rock mass close to the planned repository. However, Finland benefitted from many of the process and operational studies in Sweden's Äspö generic URL, since Finland also selected fractured granite as the host rock for its repository. France operated a generic URL in bedded salt at Amelie and one in granite at the Fanay-Augères Mine until its repository program shifted the focus to clay. The Bure URL, which was developed in clay, is considered to be a site-specific URL as it is only 5 to 10 km (3 to 6 mi) from the proposed French repository site.

2.3 Lessons Learned from the International Experience

Overall, the workshop demonstrated that there are appreciable advantages to performing R&D in URLs. While rock types and disposal concepts vary from country to country, there is a strong consensus that URLs have proven invaluable in moving national programs forward by both completing strategically planned research and by making unexpected discoveries along the way. In fact, all of the international programs that are now well on a path to licensing indicated that they would not be where they are today without a URL. Irina Gaus of Nagra indicated that the Swiss consider URLs a necessary tool for strengthening the safety case in support of the license application and, as such, are an essential part of their program.

Many countries participate in research at multiple URLs (Birkholzer 2019a, pg. 10), including URLs in rock types different from those they are targeting, and noted many benefits from these subsurface investigations: (i) sharing science, (ii) testing models on unusual and/or well developed datasets, (iii) providing datasets for testing or development of conceptual and numerical models; (iv) learning from other scientists; (v) training the next generation of researchers; and (vi) learning to scale up from laboratory to field scale.

The following are the key lessons from international experience in URLs identified at the workshop:

- **Flexibility**—Irina Gaus of Nagra emphasized that, considering the long timeline (decades) of waste disposal programs, their work at URLs had highlighted the importance of not making decisions too early (NWTRB 2019a, pg. 61). Decisions that are made too early could lock a program into an inappropriate choice that reduces flexibility. It is essential to maintain flexibility during the repository siting and implementation process to accommodate unanticipated outcomes. Starting in 1980, for example, Switzerland designated the crystalline basement of northern Switzerland a top priority and a regional characterization program was initiated (Vomvoris et al. 2013) and, in 1984, built the Grimsel URL. However, the program later pivoted to clay/argillite rock and began to operate the Mont Terri URL in 1995. Dr. Gaus also argued for iteratively developing and refining a succession of safety cases, as new facts are learned.
- **Scientific surprises and unexpected challenges**—All repository programs to date have experienced surprises and unanticipated challenges and URLs have been part of this experience. Two unexpected scientific findings made in URLs were the potential importance of gas generation and of microbial activity. Patrik Vidstrand of SKB reported that Sweden's program now has a significant research focus on the impact of microbial activity within the repository stemming from some early serendipitous studies by a curious young researcher. Irina Gaus of Nagra commented that it was generally thought

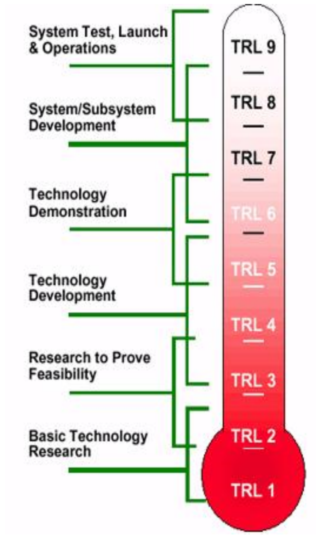
there would be a period of some hundred years after emplacement of the waste into bentonite during which oxygen would be available. However, when Nagra conducted its one-to-one scale URL experiment (i.e., the FE, Full-scale Emplacement, experiment), they found that, surprisingly, oxygen consumption began immediately and it was too late for them to install devices to monitor oxygen concentration (NWTRB 2019a, pg. 170; Giroud et al. 2018). Daniel Delort of Andra noted that work in the Bure URL has allowed them to technically explore construction feasibility for large galleries, a problem they had not considered at the outset. Dr. Vidstrand also noted that experience in a number of hard rock URLs and deep drill holes indicated that, locally, horizontal stresses may be too high to maintain cylindrical boreholes, that fracturing may be more extensive at depth than previously thought, and that the thermal effects on fractures remain a challenging scientific problem.

- **Strengthening the safety case**—The goal of radioactive waste disposal programs is to address the question: Is the repository safe in the long term? Experiments are not possible over the tens of thousands to million years timescale of actual geologic processes. The use of natural analogs in the geologic environment may provide some insights. However, long-term experiments (on the scale of decades) at appropriate spatial scales in the subsurface as conducted in URLs are the best hope of bridging from laboratory timescales to geological analogs while providing experimental constraints. One lesson learned from URL-based research is that such experiments should begin early in the program and include monitoring of all conceivable parameters because what parameters might be important may not be known at the outset.

- **System and operations optimization**—Another lesson emphasized by the results of work at URLs is that if the disposal system is optimized for one characteristic, it might reduce options for understanding the overall system; thus, care is needed. Simon Norris of the U.K. noted that when deciding how quickly the emplacement drifts should be backfilled, there is a tradeoff between quickly backfilling the drifts to ensure mechanical stability and leaving them unfilled to better enable monitoring. Backfilling might preclude longer-term monitoring, for example, to determine how long it takes to saturate the backfill and restore reducing conditions.

- **Demonstrating technical and operational competence**—In his talk, Patrik Vidstrand of SKB noted that without the benefit of R&D activities at their Äspö URL, the Technology Readiness Level of the Swedish repository program would have been only at approximately Level 4 (technology validated in the laboratory, Figure 2-1), but because of ongoing technical testing at the URL, they stated they are at Level 7 (system prototype demonstration in operational environment). This result highlights the value of these facilities in advancing the state-of-the-art in repository technology operations.

- **Public confidence building**—At the workshop, the three speakers from other countries with URLs emphasized the importance of making the URLs open and accessible to the general public in addition to researchers. All felt their respective country's underground facilities are critical in building public confidence as well as for technology development and demonstration. The underground is, by definition, not visible to us and must be experienced in order to build confidence on the part of everyone. Opportunities for the public to visit the underground facilities help them envision the safety case and observe



The term "Technology Readiness Level" was originally created by NASA in 1974 and was formally defined in 1989.

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).
TRL 8 – system complete and qualified
TRL 7 – system prototype demonstration in operational environment
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 4 – technology validated in laboratory
TRL 3 – experimental proof of concept
TRL 2 – technology concept formulated
TRL 1 – basic principles observed

The TRL scale is also used extensively in Swedish and European research programs, often requiring the TRL level to be achieved in the projects

Figure 2-1. Repeated testing at the Äspö URL enabled Sweden's waste disposal program to advance from technology readiness level (TRL) 4 to 7 (Vidstrand 2019).

the safe, efficient, and state-of-the-art methods of remote waste handling. Sweden's Äspö URL has a spiral ramp that can accommodate tour buses, and the URL is, currently, one of the top 20 tourist attractions in Sweden.

2.4 Steps Toward a Successful Repository Program

The workshop presentations and discussions made evident that URL research has been vital to the progress of repository programs of countries that now have a clear path to a repository. These successful programs offer lessons on steps that can be taken to achieve a successful repository program, including the following:

- Acknowledge a need for one or more dedicated URLs separate from the repository. The URLs should be open to use by researchers from around the world and to tours for the general public.
- Recognize that repository programs are multi-generational in nature, and R&D to support these programs should be planned accordingly and should take full advantage of the evolution of knowledge over time.
- Incorporate a step-wise, iterative approach and remain flexible by learning and adapting over time.
- Prioritize research and technological efforts based on their relation and contribution to the safety case: "Is the repository safe in the long term?"
- Expect surprises and unanticipated challenges, as not all aspects can be defined at the outset. While engineering may be able to address some of these challenges, others may require a change in approach or design.

In addition, every national program that is on a path to a repository (France: near-term submission of license application; Finland: repository under construction; Sweden: license application under review; Switzerland: currently narrowing down site selection to one of three sites) has several additional characteristics (e.g., Ewing 2013). All programs are (i) run by single-purpose organizations that have the ability to make long-term plans and decisions that are not subject to annual budget swings, and (ii) have one or more URLs that are open, not only to researchers from around the world, but also to the general public.

2.5 Observations and Recommendations Relevant to DOE's International Collaboration Program

The U.S is taking advantage of available URLs to advance the understanding of generic and site-specific disposal issues that have applications in more than one repository host rock type. Furthermore, the U.S. contributions to the R&D in URLs in other countries are widely viewed as beneficial and productive, especially in the areas of complex analytical and numerical model/software development and computing power.

2.5a Finding: Given that the U.S. has no single target rock type and no URL (other than WIPP, which is an operating transuranic waste repository in salt), and that URLs are by their nature expensive to develop and operate, it makes sense scientifically and financially to collaborate with URLs in other countries to gain across-the-board expertise.

Recommendation: DOE should expand its international URL R&D activities.

Patrik Vidstrand of SKB particularly noted the value of adding new people and ideas to the intellectual community of HLW disposal experts. In Sweden, the disposal science community is small and many researchers studied together at the same universities and share similar perspectives. International collaboration benefits the entire community through information and knowledge sharing. The Clay Club, Crystalline Club, and Salt Club[8] of the Nuclear Energy Agency are good examples and the U.S. is a participating member of these working groups. The European Commission-funded[9] geologic disposal-related projects Modern2020,[10] Microbiology in Nuclear Waste Disposal (MIND),[11] and Modern Spent Fuel Dissolution and Chemistry in Failed Container Conditions (DisCo)[12] were other avenues for collaboration.

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[8] The Clay Club, Crystalline Club, and Salt Club are international working groups established by the Nuclear Energy Agency (Paris, France) to promote the exchange of information and share state-of-the-art approaches/methods to improve the understanding of clay-rich rocks, crystalline rocks, and salt rocks, respectively, as potential host rock formations for radioactive waste repositories. See https://www.oecd-nea.org/rwm/clayclub/, https://www.oecd-nea.org/rwm/crystallineclub/, and https://www.oecd-nea.org/rwm/saltclub/.

[9] The European Commission is an institution of the European Union responsible for proposing legislation, implementing decisions, upholding the European Union treaties and managing the day-to-day business of the European Union.

[10] Modern2020 was an international research project funded by the European Commission that ran from June 2015 to June 2019. The project focused on the research, development, and demonstration of monitoring strategies and technologies for HLW repositories (Meyermans et al. 2019).

[11] The MIND program was an international multidisciplinary project funded by the European Commission from 2014 to 2018. It addressed key technical issues involving microbial processes relevant to the safe implementation of planned geological disposal projects in the European Union. See https://www.mind15.eu/about/.

[12] The DisCo project is a collaborative project funded by the European Commission from June 2017 through June 2021. The project objectives are to (i) enhance the understanding of spent fuel matrix dissolution under conditions

2.5b Finding: International collaboration is healthy and productive for all participants.

Recommendation: DOE should support the participation of its staff and national laboratory-based scientists in European Commission projects and other international programs.

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representative of failed containers in reducing repository environments and (ii) assess whether novel types of fuel (mixed oxide, doped) behave like conventional ones. See https://www.disco-h2020.eu/.

3 Research into Complex Coupled Processes

The DOE disposal R&D program seeks to provide sound technical bases for multiple, alternative disposal options and to develop the science and engineering tools needed to support the implementation of a specific disposal concept when permitted to do so (Boyle 2019; Birkholzer 2019a). As noted in Table 1-1, the DOE disposal R&D program's high priority areas are:

- Near-field perturbation
- Engineered barrier integrity
- Flow and radionuclide transport
- Integrated repository system behavior

However, research in each of the identified priority areas is not independent because the processes that occur in a geologic repository at a fundamental level are complex and their interactions are not well understood. These basic processes are broadly categorized into thermal (T), hydrological (H), mechanical (M), chemical (C), and biological (B). They control the behavior of the system and, thus, affect the effectiveness of engineered and natural barriers to isolate the waste and mitigate the migration of radionuclides. Understanding these processes, including their interactions and couplings, is essential for reliably assessing repository performance and evaluating the safety case (Figure 3-1; Box 1-2). Figure 3-1 as an example depicts directly coupled processes, primarily in the host rock, expected for a repository in fractured crystalline rock. Similar figures illustrating the interaction of THMC processes in crystalline, clay, and salt rock formations and in bentonite buffer can be found in a report by Manepally et al. (2011).

The coupled processes that occur in different repositories are dependent on the properties of both host rock and engineered barriers. For example, fluid flow rates through the host rock will depend on its matrix and fracture properties, whereas the mechanical properties of the host rock or engineered barrier will determine whether it will deform in a brittle or plastic fashion from an applied load. The coupled processes within a bentonite engineered barrier will be substantially different than those depicted in Figure 3-1 and may include other processes, such as osmotic (thermal osmosis and chemical osmosis) and biological processes, which may have a significant effect on radionuclide transport through the bentonite (Tsang 1987).

Currently, DOE's R&D activities are mainly on coupled THMC processes, with little effort on microbial (biological) processes. A number of these coupled processes are discussed below based on information DOE presented at the workshop. DOE is using a combination of laboratory experiments, modeling, and URL-based studies to gain insights into THMC processes and their complex interactions that could impact the performance of repositories sited in crystalline, clay, and salt host rocks. Included in DOE investigations are those on direct geologic disposal of large SNF canisters (Box 3-1), which could lead to higher temperatures in the engineered barrier and host rock than previously considered in repository performance assessments.

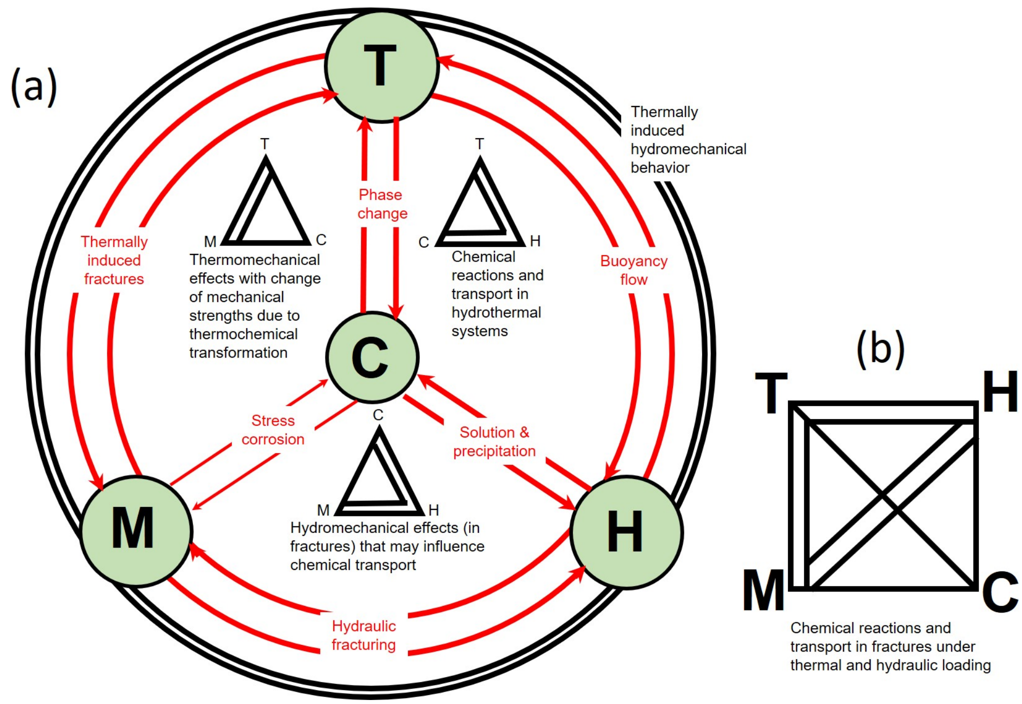

Figure 3-1. The eleven directly coupled THMC processes associated with a nuclear waste repository in fractured rock as conceptualized in current models (Tsang 1987).

The diagram primarily reflects the processes that could occur in the host rock (i.e., natural barrier) rather than in the engineered barrier. The two-way couplings (e.g., TH) shown in (a), 6 in total, are in red arrows and example processes are in red text. Strong couplings are thick arrows and weak couplings (i.e., CM) are thin arrows. The four three-way couplings (i.e., THM, THC, TMC, and CHM) shown in (a), the one four-way coupling shown in (b), and example processes are in black lines, with strong couplings in double lines and weak couplings in single lines (Manteufel et al. 1992). Currently, none of these models incorporate biological (B) processes.

The focus of this report section is to evaluate the DOE process-level research and identify knowledge gaps and future research and experimental design and modeling strategies. Approaches are explored to better incorporate coupled processes into numerical models and design URL-based experimental investigations through international collaborations. General observations on information provided by DOE and other workshop participants in specific topical areas are summarized, and recommendations based on these observations are presented.

In evaluating DOE's R&D activities, the Board considers that a robust disposal R&D program requires an iterative process involving laboratory experiments, modeling, and field observations, schematically shown in Figure 3-3. Field experiments should include URL and natural analog studies. Also, important questions that need to be addressed are how the knowledge gained from tests at small length scales can be extrapolated or upscaled to larger (e.g., repository) spatial scales, and how tests conducted at relatively short timescales can be used to make predictions for much longer time horizons (e.g., repository performance period).

Box 3-1. Direct geologic disposal of large spent nuclear fuel canisters

Most of the U.S. inventory of spent nuclear fuel in dry storage has been loaded into dual-purpose (storage and transport) canisters (see, for example, Figure 3-2). These are generally larger and can accommodate more fuel assemblies (currently, depending on canister design, up to 37 pressurized water reactor or 89 boiling water reactor fuel assemblies) than containers other countries intend to use to dispose of spent nuclear fuel in their repositories. For example, Sweden's waste canister holds four pressurized water reactor assemblies. Direct disposal of dual-purpose canisters, instead of repackaging the spent fuel for disposal, is attractive because it could be more cost-effective, reduce the complexity of the waste management system, reduce waste volume, and result in less cumulative worker dose during interim storage and handling before eventual disposal in a geologic repository.

A fundamental question facing the U.S. radioactive waste management program is whether disposal of these large canisters directly in a repository would be technically feasible. One of the key aspects that must be considered in answering this question is thermal management, i.e., how best to handle the heat produced by radioactive decay that will continue to be generated by the spent nuclear fuel after it is disposed of in a repository. For example, a common repository design criterion is a 100 °C temperature limit on the bentonite buffer around the waste package in order to avoid degradation in its performance as an engineered barrier (Birkholzer et al. 2018). This limit means the spent fuel must be allowed to cool long enough prior to emplacement underground so the bentonite buffer, once emplaced around the canister, would not exceed 100 °C. The required cooling time could be several hundred years, even for the coolest spent nuclear fuel in storage (Hardin et al. 2015, pg. 48), although this would include the time it was stored above ground and the time after it was emplaced in the repository but prior to emplacement of the bentonite.

DOE continues to investigate the technical feasibility aspects of direct disposal of dual-purpose canisters, including the feasibility of a repository design with a bentonite barrier where bentonite temperatures could reach 200 °C. As part of its research on bentonite barrier performance at high temperatures, DOE is planning to participate in the underground research laboratory-based HotBENT research program. HotBENT is a proposed high-temperature test intended to investigate if clay-based barrier materials such as bentonite can tolerate temperatures higher than 100 °C without being degraded to the extent that they cannot perform their intended barrier safety functions. The test will be conducted at the Grimsel Test Site in Switzerland.

Figure 3-2. Holtec Hi-Star 100 dry storage systems each containing a dual-purpose canister (see inset photo). (Source: Holtec International)

Figure 3-3. Process of iterative learning from laboratory experiments, modeling, and field observations (which include both URL and natural analog studies).

Overcoming the technical challenges is difficult, but doing so also provides exciting opportunities to advance science through experimental and modeling investigations conducted in many URLs around the world. International collaborations allow coordination of this research to capitalize on the work being conducted in different host rock environments and diverse spatial and temporal scales. Appropriately, DOE is leveraging its URL-based international collaborations to develop its science and engineering tools and advance its SNF and HLW disposal R&D program.

3.1 Modeling

Model Development and Validation

Modeling is a critical and central activity related to evaluations of repository safety. Models serve several essential functions. In the context of URLs, these functions include providing insights to governing processes, helping in the design of experiments and in data interpretation, making predictions of post-closure repository performance, and conducting parameter sensitivity and uncertainty analysis. Modeling and model issues related to URLs were included in the workshop presentations. The process-based models, all involving coupled processes, are at various stages of development, testing, and validation. The spatial and temporal scales of modeling were mostly limited to the URL field-test scales and relatively short time horizons.

3.1a Finding: The Board finds that comparison of models developed internationally and by DOE is a particularly relevant and useful activity. These efforts to involve multiple models *developed internationally are commendable because they help build understanding among developers and confidence in model performance. The DOE THMC models are recognized internationally as state-of-the-art.*

Recommendation: DOE should continue advancing its THMC model development. In addition to model comparisons to determine whether the models provide a reasonable fit to observations, the investigators also should attempt to determine what processes are essential and vital under different URL settings.

3.1b Finding: The Board recognizes that modeling coupled processes is challenging. The current DOE practice of modeling coupled processes is reasonable. This involves the use of constitutive models of individual processes (e.g., capillary pressure vs. porewater saturation used in modeling the unsaturated flow process), and the coupling is done by solving the governing equations sequentially, in parallel, or iteratively (e.g., the dependence of flow on formation stress). Incorporating chemical and microbiological processes into the THMC simulators through well-conceptualized constitutive models is expected to be hard. Long duration and slow chemical changes may be the most difficult to predict because long-term experimental data do not exist.

Recommendation: More basic research is needed on fundamental processes that will lead to improved and accurate constitutive models suitable for simulating coupled processes efficiently for long timescales under repository conditions. In addition, there is a need for innovative experiments to validate these models. Model development and testing should be an iterative process, as illustrated in Figure 3-3.

The DOE research, as presented at the workshop, primarily focused on laboratory and URL-based experiments and demonstrations. As there are many key knowledge gaps, opportunities exist to test hypotheses, including multiple alternative hypotheses, using experimental data. The models that evolve can be used as tools in designing and conducting additional experiments and demonstrations. Testing multiple alternative hypotheses is part of the iterative approach recommended above. Furthermore, all model development and design involve many assumptions. These assumptions determine the model's ability to capture the behavior of field systems accurately. It is essential to state and recognize these assumptions so that the model predictions and uncertainties can be better assessed. DOE’s approach in handling some of the process complexities often is to develop very sophisticated models. Once tested and validated, such models can become useful tools, including in the development, when required, of simpler surrogate models.

3.1c Finding: In some of the topical areas, there seems to be an overemphasis on trying to make the model predictions agree with the observations by calibration of the model parameters. This approach can lead, in some cases, to a mere fitting exercise rather than to evaluation of whether the underlying processes are correctly conceptualized and represented.

Recommendation: Research should focus on hypothesis testing, including comparing multiple alternative models for a phenomenon to observations from experiments, while simultaneously developing more complex coupled models that incorporate the latest findings from models for separate phenomena.

The effects of microbial processes generally are discounted in modeling repository performance. However, during the panel discussion, Patrik Vidstrand of SKB reported about their R&D experience related to the impact of microbial activity. This research was initiated because of the personal interest of a graduate student and was undertaken simply out of curiosity; now, the project is one of their more important research foci because of the potentially important effect of microbial processes on copper canister corrosion. Presenters from other countries made clear microbial processes have become a big focus issue in URL research. Irina Gaus of Nagra emphasized the point of "surprises to anticipate" — such as the microbial experiments. For example, Nagra's Material Corrosion Test (MaCoTe)[13] was designed to obtain reliable corrosion rates needed to support canister lifetime predictions, but now the influence of the hydrochemical and microbial environment is being explored (Gaus 2019, pg. 57). Several researchers agreed that such experiences suggest that R&D must be undertaken with an open mind rather than as a way to confirm assumptions that are made in the research, modeling, and development activities. Furthermore, these discoveries were specifically enabled by use of a URL and might not have been investigated without such a laboratory.

3.1d Finding: Given that surprises are expected in the underground, such as the discovery that microbial activity is important, it makes sound scientific sense to approach the repository development program, including developing and implementing URL R&D activities, with an open mind.

Recommendation: DOE technical activities in URLs should be designed and conducted to test assumptions and remain open to unanticipated processes or behaviors rather than focusing on confirming assumptions and conceptualizations or models.

Spatial Upscaling and Time Extrapolation

All URL process-based models are relevant to the spatial scale of the URL tests, typically in the range of centimeters to meters. Some of the parameters that characterize the processes are derived from laboratory-scale experiments with length scales in the range of millimeters to centimeters. In contrast, the relevant spatial scales in repositories extend to hundreds of meters to kilometers. Figure 3-4 shows the spatial and temporal scales that are involved.

Upscaling the knowledge and parameters generated from experiments at smaller (laboratory and URL) spatial scales to field scales is going to remain a major challenge. One of Nagra's drivers for defining its URL R&D priorities is developing and verifying procedures for upscaling laboratory-scale information to field-scale (Gaus 2019). As Figure 3-4 highlights, laboratory experiments are conducted under well-defined boundary conditions. In URL-based experiments, some of the boundary conditions are controlled and others remain under complex conditions expected in the field. Natural analogs and geologic repositories both have large length scales and boundary conditions defined by the natural state of the system. A basic question that needs to be

[13] MaCoTe consists of heated and non-heated experiments on the corrosion of candidate canister materials embedded in bentonite. The test, which is being conducted in situ at the Grimsel Test Site, aims to (i) determine the long-term anaerobic corrosion rate of carbon steel, stainless steel, and copper in compacted bentonite under repository-relevant environmental conditions, and (ii) provide experimental evidence of the inhibiting effect of the bentonite buffer on microbial activity and microbially-influenced corrosion. See http://www.grimsel.com/gts-phase-vi/macote-the-material-corrosion-test/macote-introduction.

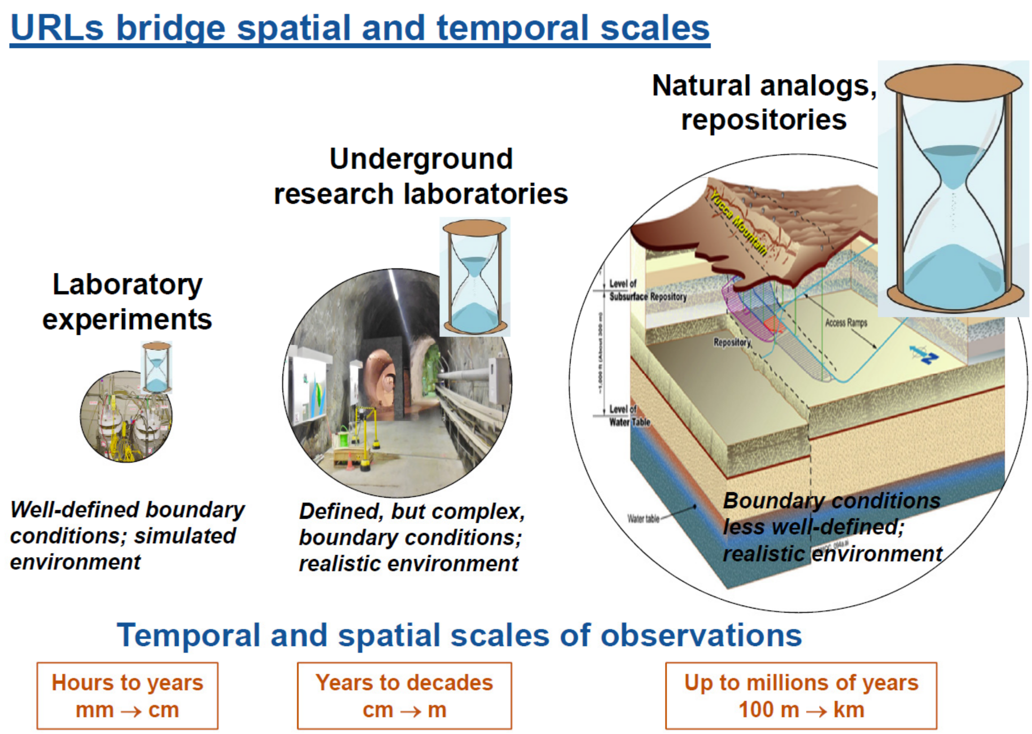

Figure 3-4. Spatial upscaling and temporal extrapolation (modified from Gaus 2019).

answered is how the knowledge gained through process understanding, parameterization, and modeling at laboratory and URL scales can be extended to the much larger spatial scales of natural analogs and repositories.

The question of spatial upscaling has been successfully addressed in some problems of subsurface flow and transport (e.g., homogenization, effective parameters). The Board believes that in the case of nuclear waste repositories where coupled THMC processes govern the behavior of the system, more extensive research on upscaling is needed. URLs are one way to test models of upscaling while natural analogs are another way. Laboratory- and URL-based research should continue, but in long-term strategic planning, R&D activities should include the use of natural analogs.

URL experiments and natural analog studies are also useful to “upscale” time, i.e., extrapolate from relatively short durations of laboratory experiments to much longer time horizons. As shown in Figure 3-4, the timescales of experiments in small test systems are in the range of hours to years. URL-scale experiments can be designed to run for much longer durations and natural analogs can sometimes provide constraints on the longest timescales. The Board recognizes that temporal extrapolation is at the same time more complicated than, but also closely coupled to, spatial upscaling. To test models for a geologic repository, very long-term experiments are required to learn about temporal effects into long time horizons. URLs enable such long-term experiments to be conducted. These experiments need to be simple in design, but strategic in collecting data optimally (large amounts of data have to be collected continuously) to increase the likelihood of success. Geological analogs also can be used to extrapolate over time. However, while analogs are not as well controlled or characterized as URL experiments, they embody the time dimension that could enable researchers to address "what happens after a time interval that is unobtainable in the laboratory?"

The Swiss researchers at Nagra have given careful thought to spatial and temporal scaling in their R&D strategies and how it fits into their safety case methodology (Gaus 2019). Figure 3-5 illustrates the methodology that integrates experiments, synthesis, and system analysis in the context of both spatial and temporal scaling (or extrapolation). Fundamental to the systems approach is that, in addition to studying a specific process, phenomenon, or mechanism within each system, the interaction of each sub-system with other sub-systems also is studied to predict the behavior of the whole system.

As mentioned in Section 2.2, the Swiss plan to construct a new URL for underground investigations and a pilot facility at the repository site. They envision the pilot facility would have full-scale dimensions and properties representative of the barrier systems and waste emplaced at the repository. The pilot facility would be monitored to provide information on safety-relevant conditions and processes and barrier effectiveness, for early recognition of unexpected developments, and to support the safety assessment for repository closure (Gaus 2019). The pilot facility would be distinct from a URL, where much more intensive and intrusive instrumentation is possible. As Irina Gaus of Nagra stated, "URL activities do not provide direct input for the safety case, [but] the outcomes are part of the continuous integration of the knowledge base provided by lab experiments, natural analogs and upscaling in time and space" (Gaus 2019, p. 35). The Board believes that DOE should capitalize on international collaborations to incorporate into its R&D activities the types of thinking presented by Nagra related to issues of scaling.

3.1e Finding: The methodology of Nagra researchers for integrating experiments, synthesis, and system analysis in the context of both spatial upscaling and time extrapolation has potential value in developing a vision for DOE's URL- and natural analog-based research.

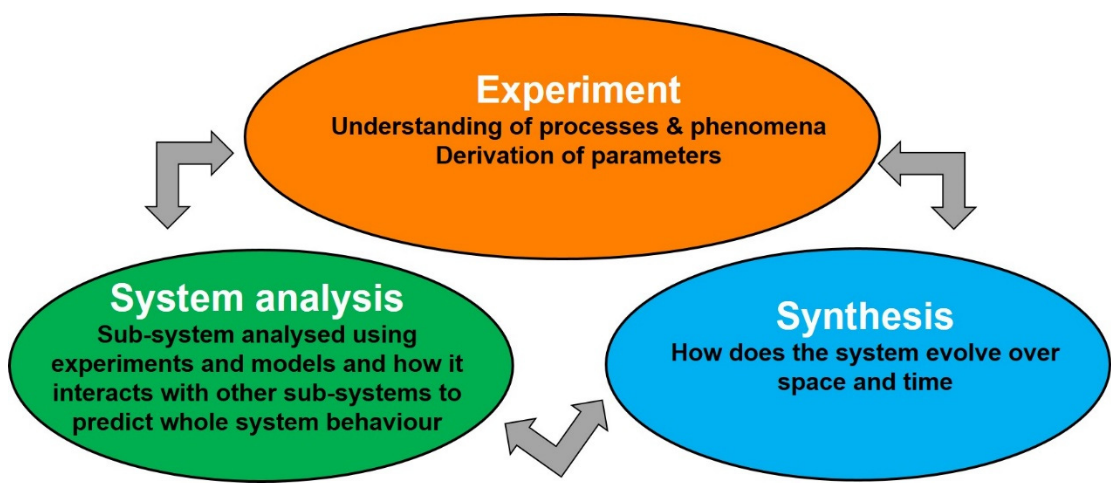

Figure 3-5. Integration of URL results as a part of safety case methodology (modified from Gaus 2019).

Recommendation: DOE should adopt the methodology of integrating the URL results and synthesis within a systems analysis framework for safety case evaluation (Figure 3-5). Such a framework allows for the integration of process understanding, experimental data, and models by factoring in spatial upscaling and time extrapolation to repository systems.

3.2 Near-field Perturbation and Engineered Barrier Integrity

Bentonite Behavior

Bentonite is used as an engineered barrier for repositories sited in crystalline and clay host rocks (Sellin and Leupin 2013; Box 1-1). The bentonite provides multiple safety functions that vary with the type of host rock and the waste emplacement configuration (e.g., vertical or horizontal waste packages). For example, in the Swedish KBS-3 disposal concept, the bentonite buffer limits advective transport, suppresses microbial activity, protects the waste packages from minor rock movements, and prevents the waste packages from contacting the host rock (SKB 2011). Understanding how the bentonite evolves in response to perturbations in the near-field environment, e.g., due to the heat pulse provided by the emplaced waste, is key to demonstrating that the specified safety functions are met and establishing bentonite's effectiveness as an engineered barrier (Box 3-1).

There have been substantial decades-long international efforts in URLs to understand the coupled THMC processes in bentonite and clay host rocks at temperatures less than 100 °C (Gaus 2019; Delort 2019; Figure 3-6). In existing repository designs, potential adverse geochemical changes in bentonite (e.g., illitization, which is the transformation of a smectite mineral, such as montmorillonite, to illite) are minimized by keeping the temperature of the bentonite below 100 °C (SKB 2011). URL-based geochemical experiments have focused on waste package corrosion (Gaus 2019, pgs. 16 and 57), changes near or at interfaces between bentonite and cement or metal (e.g., Jové-Colón 2019), and on gas generation and migration (Gaus 2019; Vidstrand 2019).

The coupled THMC processes that could affect the ability of the bentonite engineered barrier to perform its safety function could also affect similar clay host rocks and will evolve temporally and spatially (Figures 3-6 and 3-7). How the coupled processes evolve in space and time will be driven by the amount and spacing of the emplaced heat-generating waste. Initially after emplacement, the bentonite buffer will be partially saturated and will undergo transient desaturation (dessication) and shrinkage caused by heat emitted by the waste (Figure 3-7). As water infiltrates from the host rock (e.g., through crystalline rock fractures or argillaceous rock matrix), the bentonite will rewet and saturate, causing it to swell. Bentonite swelling will seal the spaces or gaps initially present, for example, between the disposal container and the surrounding bentonite and between the bentonite and the host rock. If the bentonite is unable to expand freely, a swelling pressure develops, which would exert mechanical load on the disposal container and the host rock. Bentonite's capacity to swell varies with its chemical composition and will decrease if the montmorillonite component transforms into illite, which could weaken its barrier function. At the same time that these chemomechanical processes are ongoing, other processes, such as oxidation of trace pyrite in the bentonite, may occur. Such reactions, occurring abiotically or catalyzed by micro-organisms, consume oxygen and generate sulfuric acid that can then dissolve local mineral grains, perhaps affecting transport properties.

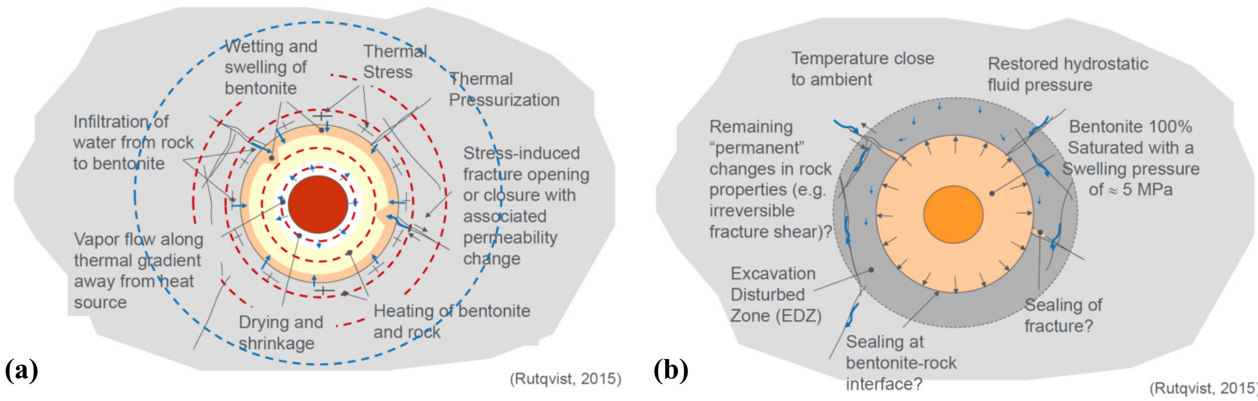

Figure 3-6. (a) Short term (0 to 10,000 years) thermally driven coupled THM processes and (b) long term (10,000 to 100,000 years) impact of coupled THM processes (Rutqvist 2015, 2019a).

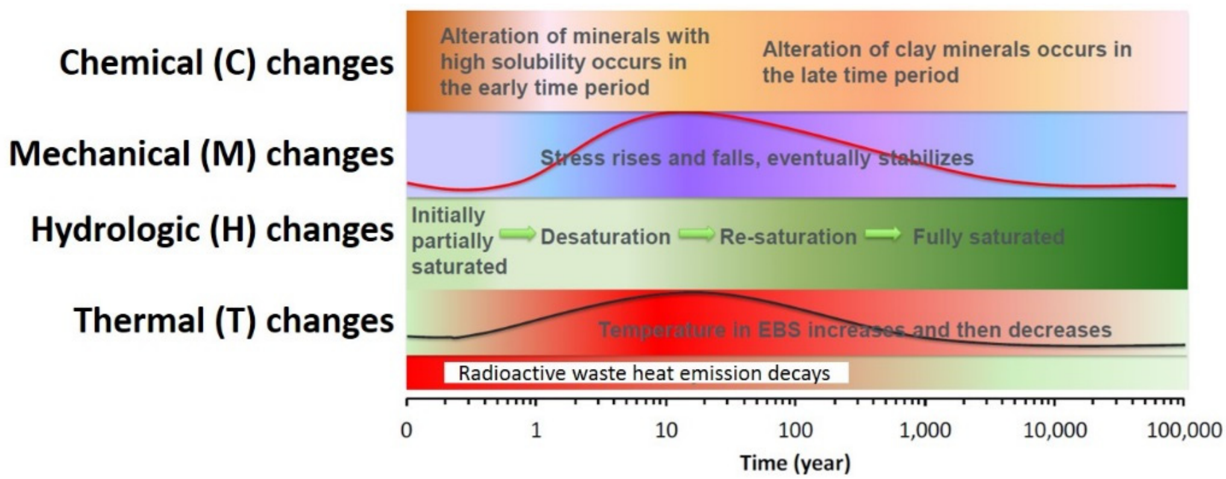

Figure 3-7. Temporal evolution of thermal, hydrologic, mechanical, and chemical changes in a bentonite engineered barrier system (modified from Zheng 2019).

Until 2018, DOE had not focused on coupled THMC processes at temperatures greater than 100 °C (Birkholzer et al. 2018). DOE recognizes that at temperatures of 150 to 200 °C, key knowledge gaps need to be narrowed (Zheng 2019). These gaps include understanding of

- How the hydrologic/hydraulic and mechanical behavior of bentonite changes when it evolves from partial saturation to full saturation at temperatures up to 200 °C;
- Mineralogical alterations of bentonite in the short-term and long-term (e.g., illitization and loss of swelling capacity, pyrite oxidation, etc.); and
- Whether the models (including processes, constitutive relationships, and parameters) developed for 100 °C are suitable for high temperature conditions.

The DOE R&D activities are directed toward reducing uncertainties, improving the understanding of coupled THMC processes, and modeling for engineered barrier system evaluation (Rutqvist 2019a,b; Zheng 2019; and Jové-Colón 2019). The DOE model development efforts are guided by a number of questions pertaining to the key processes that have to be included, the reliability of constitutive relationships and parameters [i.e., constitutive models (Box 3-2)] to describe THM processes, the availability of reliable chemical process models, and the types of laboratory (e.g., multi-scale) and large-scale in situ experiments that are needed (Zheng 2019). According to DOE, chemical models and parameters should be able to describe the evolution of porewater geochemistry, mineralogical changes, retardation capacity, and interactions between canister, bentonite buffer, and host rock.

The accuracy of DOE's THMC simulations depends on the constitutive models that characterize the various processes and how these models are used to develop simulation models that couple these processes. There are remaining challenges both in the development of constitutive models and in developing appropriate couplings of multiple processes in simulation models. The constitutive model challenges related to bentonite include developing thermo-elasto-plastic

Box 3-2. Constitutive models of bentonite behavior

What are constitutive models and why are they needed?

Constitutive models are defined as a set of mathematical relationships for a material that describe, for example, components of stress and components of strain (Carter 2006). They are an essential component of any numerical model of a physical problem and are commonly applied in geotechnical engineering practice (e.g., predicting building foundation response, such as settling in soil, which is a volume of particles including void space, from vertical loading of the building foundation above). A constitutive model allows extrapolation from laboratory or field-testing measurements (e.g., measured soil behavior) to system response (e.g., a model prediction of the anticipated ground response from a construction activity). Understanding how soils or rocks could behave, especially swelling-prone clay-rich materials such as bentonite (Box 1-1), is critical to determining whether an engineered structure such as a building or tunnel will be stable or fail.

What are some constitutive models?

A simple geotechnical model for soil, with only two variables, is the elastic constitutive model that is based on Hooke's law for springs, which in this case describes the relationship between components of stress and components of strain (Carter 2006). This constitutive model is used to define how much settlement occurs as the load increases. A characteristic feature of elasticity is that it predicts behavior that is reversible, for example, deformation of soil under a load will return to an undeformed state when the load is removed. Another geotechnical soil model is the plastic constitutive model, which is used to determine the load at which collapse occurs. In this case the material does not deform until its strength is exceeded by the applied load, at which point the material fails (i.e., deforms) and this deformation is permanent. Other more complicated constitutive models include elasto-plastic constitutive models that incorporate features of the elastic and plastic constitutive models. Elasto-plastic constitutive models have been used to model underground research laboratory heater tests [e.g., Barcelona Basic Model (Rutqvist et al. 2014)]. Finally, thermo-elasto-plastic constitutive models have been developed to account for thermal volume changes and tested against FEBEX heater test results (Dupray et al. 2013).

constitutive models that address processes (e.g., plastic thermal expansion and contraction that could lead to permanent changes in thermal and hydraulic properties) that have not been as important at lower temperatures. Another challenge related to constitutive models is developing the parameters for these models from careful laboratory experiments for each of the types of bentonite used in URL experiments or in repositories as model parameters are sensitive to the initial conditions and structure of the emplaced bentonite. Challenges remain for specific process couplings that could be more important at higher temperatures, such as those expected in the HotBENT experiment (McCartney 2019). For example, the effect of temperature on the soil-water retention curve or hydraulic conductivity is one coupling that deserves additional scrutiny.

The Board recognizes that thermo-elasto-plasticity is an important topic that should be considered in THM modeling of unsaturated bentonite, especially when considering higher temperatures (e.g., as planned for the HotBENT project). It is important to recognize that even though knowledge exists on some of the relevant processes, investigators should be aware that other active mechanisms also may be important. Several important aspects of the behavior of bentonite under thermal stresses are not incorporated into DOE's current models. Examples include the coupled effects of heat on bentonite dehydration/hydration and expansion/contraction on effective permeability. The bentonite buffer surrounding the heat source can be susceptible to desiccation shrinkage and cracking as the water in the buffer evaporates during heating. The desiccation cracks may create preferential pathways for water and radionuclide transport. If these other mechanisms are not included in the model, the predictions will be in error. DOE investigators also noted that further research is needed to better represent the correct underlying physics, such as dual structure behavior, in models that could be efficiently applied at a repository tunnel scale (Rutqvist 2019a).

DOE THMC simulations (Zheng 2019), and some laboratory measurements (Jové-Colón 2019), show mineral reactions occur in regions of lowest saturation and highest temperature at or close to an environment with little or no liquid water but where steam is present. These observations suggest that important changes to the engineered barrier system may occur at elevated temperatures under unsaturated conditions (Bish 2019), e.g., in a steam environment. For example, literature data show that steam causes drastic reductions in smectite's ability to osmotically swell (e.g., Couture 1985). Also, it is not clear why DOE models include advective transport (NWTRB 2019a, pg. 314) of some solutes (e.g., magnesium and chloride) at a relative humidity less than 40% when there is no free-flowing liquid water. Thus, more research is needed on the thermal-hydrological-chemical behavior of bentonite under unsaturated conditions at elevated temperatures, including whether other processes such as chemical osmosis, rather than water advection, could be responsible for chemical species transport.

3.2a Finding: Important changes to the bentonite engineered barriers may occur at elevated temperatures (150 to 200 °C) that could exist during the early phases of repository closure, which have yet to be assessed in URL experiments.

Recommendation: More URL and laboratory-based research should be pursued on the thermal-hydrological-chemical behavior of bentonite at elevated temperatures.

3.2b Finding: Constitutive models are a prerequisite for accurately modeling the coupled processes that could occur in bentonite at temperatures between 150 to 200 °C and assessing *whether it can perform the safety functions ascribed to it. Whether existing constitutive models used to simulate THM processes up to 100 °C are adequate for higher temperatures is a key uncertainty. Developing new constitutive models that reflect different processes than previously considered, such as THC and THMC processes, will require new carefully controlled experiments to develop the needed parameters that reflect the specific processes. Multi-scale laboratory experiments, such as cylindrical bentonite column experiments, which can serve as an analog for the HotBENT field experiment, will yield early results that could indicate whether new processes occur and whether new constitutive models need to be developed to accurately model the longer-term HotBENT field test.*

Recommendation: In the near-term, DOE should increase its focus on laboratory experiments that reflect the elevated temperatures expected in the bentonite after emplacement of dual-purpose SNF canisters in a repository to assess whether additional coupled processes occur and whether new constitutive models need to be developed to accurately model the longer-term HotBENT URL test.

Gas Transport through Clay

Gas generation in a repository can occur due to various thermal, chemical, radiolytic, and microbial processes (Norris 2015). For example, canister corrosion and water radiolysis can produce hydrogen gas, and radioactive decay of the waste can produce noble gases. Depending on the rate of gas production and the diffusion rate of gas molecules in the pores of the barrier material (bentonite buffer or host rock), a pressurized gas phase could accumulate at the canister–barrier interface until the gas pressure exceeds some critical entry pressure specific to the barrier material. Gas generation and transport potentially could affect the performance of the engineered barrier (e.g., by causing fractures), perturb any groundwater flux, and affect the host rock mass-transport properties (Rodwell et al. 1999). Gas generation also may promote environments for bacterial growth. Thus, the potential importance of gas generation and subsequent transport needs to be considered at an appropriate level in repository safety cases (Norris 2015).

Gas generation and transport through clay-based engineered barriers and low permeability host rocks were not important research topics for DOE during the Yucca Mountain program because clay-based engineered barriers were not planned to be used and the host rock had high gas permeability. However, those topics have been the focus of several European projects during the last 15 years (Nuclear Energy Agency 2015; Norris 2015), including the Fate Of Repository GasEs (FORGE) project and the Large Scale Gas Injection Test (LASGIT).[14] Although substantial insights have been gained on gas transport processes from the LASGIT experiment and the FORGE project (Norris et al. 2013; Shaw 2015), DOE indicated the basic gas transport mechanisms in bentonite and low permeability host rocks are still not understood in enough detail and, therefore, detailed predictive capabilities are limited (Rutqvist 2019b).

[14] FORGE is an international project specifically designed to address the key research issues associated with the generation and movement of gases in geologic repositories (Norris et al. 2013). LASGIT is a full-scale gas injection experiment operated by SKB at the Äspö URL designed to answer specific questions regarding gas movement through bentonite (Cuss et al. 2011).

As part of its international R&D collaborations, DOE has been developing expertise and modeling capabilities relevant to gas transport through clay through its participation in the DECOVALEX-2019 project (Rutqvist 2019b). In this project, LBNL investigators have been working with international modeling teams to understand the processes governing the advective movement of gas in low permeability materials such as bentonite and claystone. Figure 3-8 shows the different scenarios of gas transport as conceptualized in DOE models.

The Board is encouraged that DOE is developing capabilities to simulate gas transport. The Board notes that gas transport mechanisms have not been modeled at a repository-relevant spatial scale. However, such modeling could be part of a potential DECOVALEX-2023 task that would model the LASGIT results (Rutqvist 2019b). In addition, information DOE provided at the workshop on the planned HotBENT experiment (Rutqvist 2019b; Zheng 2019) indicates there is no plan to collect data that would allow an assessment of the importance of gas transport at conditions pertinent to disposal of the large, hot, SNF-containing dual-purpose canisters used in the U.S.

3.2c Finding: Experimental and modeling studies are needed at spatial scales and under stress/displacement boundary conditions relevant to those expected in the engineered barrier system of a repository that disposes of large dual-purpose canisters.

Recommendation: DOE should assess the importance of gas generation and gas transport to the safety case for a repository under the conditions expected in a U.S. HLW and SNF repository that may include direct disposal of SNF in large dual-purpose canisters (i.e., temperatures well above 100 °C).

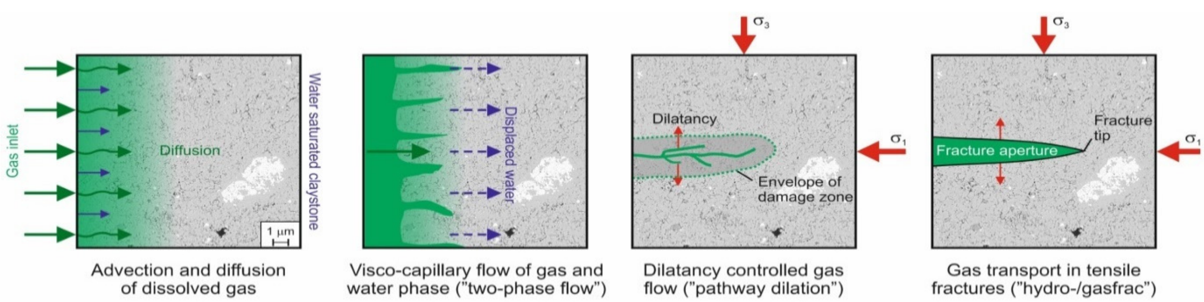

Figure 3-8. Conceptualization of gas transport mechanisms in clay (Rutqvist 2019b).

Coupled Processes in Salt

Salt formations were among the first to be considered as host rocks for geologic repositories (National Academy of Sciences 1957) because they have natural properties favorable to long-term disposal of nuclear waste—low water content, very low connected porosity and permeability, tectonic stability, and high elasticity. The very existence of salt formations indicates the absence of flowing groundwater for a very long time. Additionally, the high salt thermal conductivity would allow fast conduction and dissipation of heat from the waste canister and the presence of chloride reduces the potential for nuclear criticality. However, there are complexities in geologic disposal in salt associated with metal corrosion, salt dissolution if fresh water enters, modeling of brine chemistry, and creep of salt requiring drift maintenance during the operational phase.

There is typically no significant groundwater flow in relatively pure salt, but it is not an anhydrous medium (i.e., water is present, but typically <5% by weight). There are three sources of water in salt: hydrous minerals, intragranular brine (fluid inclusions), and intergranular brine (interconnected pores). The only fluid that moves under hydraulic gradients is the intergranular brine. The water types in the salt respond differently to heat. Hydrous minerals, when subjected to heat, will dehydrate to form vapor that condenses to brine. Thermal gradients move the intragranular brine.

DOE is conducting heater tests, referred to as the Brine Availability Test in Salt (BATS), at WIPP (Kuhlman and Stauffer 2019). In this test, the brine distribution, inflow, and chemistry in heated salt are being measured using geophysical methods and direct sampling. DOE also is applying process-level models to simulate repository processes, gain confidence in long-term predictions, explore and reduce uncertainties in the design of field tests, and for incorporation into its integrated performance assessment.

As in other disposal environments, the performance of both the engineered and natural barriers is controlled by coupled THMC processes. Issues that need to be investigated relate to which variables are important to measure, which constitutive models are needed, and which coupled processes are to be considered in the models (see also Section 4). Improved modeling in salt is useful in the iterative design of heater tests, interpreting data from field tests, and assessing repository safety.

The constitutive models needed to simulate the mechanical behavior of salts are complex because they need to simulate the elastic, creep, damage, and healing behavior of salt, particularly during the pre-closure period. The resulting equations have many parameters. The temperature dependent creep in these models needs to be validated. The current models do not include moisture impact on creep. Thermally and mechanically induced compaction are important at the current test scales. However, the models need to address the length of time needed for complete compaction and sealing of the backfill. Careful experiments with controlled temperature, moisture, and loading are needed to validate models.

3.2d Finding: The science needed to fully understand THMC processes in salt is in early development. The field tests that have been initiated will help fill the knowledge gaps. The preliminary models that have been developed are useful in designing the field tests. The THM constitutive model that is currently used was developed based on a large number of laboratory experiments in domal salt in Germany. The application of these models for bedded salt, which is layered and typically interspersed with non-salt materials like anhydrite, shale, and dolomite, will introduce uncertainties into predictions.

Recommendation: The WIPP heater tests should be used to improve the understanding of the coupled THM processes and improve the constitutive models by focusing on bedded salts.

3.3 Flow and Radionuclide Transport

Flow and Transport in Fractured Rock

Crystalline rocks are considered good candidates for repository host rocks because of their very low matrix permeability (or permeability excluding flow through fractures) and, at many sites, their poorly interconnected fractures. However, in areas where the fractures are interconnected, the fractures could become the primary pathways for transport of radionuclides that are in solution or attached to colloids. To fully characterize mass transport through fractured formations, data on fracture properties (orientation, spacing, aperture distribution, roughness, and surface area) and matrix diffusion coefficient are needed. In a presentation at the workshop, DOE described three approaches that are being used in URL-related work to model flow through fractures (Viswanathan 2019). In the first, the connected discrete fractures are modeled as a network. In the second, the fractured rock is considered a continuum as in conventional porous media models. In a third, a surrogate model in which the fractures are treated as one-dimensional pipes is used to mimic the response of a network model while reducing the computational complexity of the problem. The fracture flow and transport models have evolved to a stage where complex meshing algorithms are used for mechanistic representation. Viswanathan (2019) emphasized how they were comparing and contrasting these models and at the same time exploring new data-driven models. This general approach of comparing multiple models with one another and with data (largely enabled by URLs) is lauded by the Board.

One limitation to DOE's statistical methods for generating and representing connected fracture networks is that the methods ignore the fact that the subset of fractures that are permeable in-situ is defined by local geologic processes. The ubiquitous observation of near hydrostatic pore pressure in many wells at depths from 0.5 to 8 km (1,600 to 26,000 ft) in diverse geologic settings around the world attests to the fact that active geologic processes keep fracture networks open and connected. Downhole logging allows for detailed characterization of the 3-D fracture distributions in these wells and high-resolution temperature logs are used to detect which fractures are hydraulically conductive. Numerous studies have demonstrated that the hydraulically conductive fractures tend to be those fractures most well-oriented for shear slip in the ambient stress field, so called "critically stressed faults" (Barton et al. 1995; Townend and Zoback 2000). The in-situ stress field is straightforward to determine by direct measurements. Resolving an in-situ stress field on a computationally-derived fracture network could provide a powerful physics constraint on possible fracture flow. To date, DOE's hydrologic fracture flow models have not utilized this constraint.

A number of questions can be posed in the context of R&D research in fractured rock systems and DOE's team is consistently exploring these questions or moving toward such exploration with state-of-the-art approaches. The topology required to represent the network in discrete fracture network models is hard to define. The continuum approach, where the details of the fractures are lumped into representative equivalent homogeneous elementary volumes, may not be sufficient to represent flow behavior in large systems, specifically those with low fracture density. DOE researchers described new reduced order models (e.g., graph-based machine learning emulators) that are being explored for efficient simulation of multiscale processes associated with the interaction between the fractures and the matrix. This exploration is an innovative step forward that shows DOE is responding to the rapid growth in understanding of how to develop data-driven models. Of course, the question remains whether these models are sufficient and necessary for uncertainty quantification.

As a result of international collaborations, the Äspö Hard Rock Laboratory located in a granite host rock in Sweden provided data for network characteristics that are needed to validate numerical simulations of flow and transport through fracture networks in crystalline rock at ambient temperatures. The issue of how water flows from surrounding fractures to initially unsaturated bentonite-filled boreholes was investigated using data from the Bentonite Rock Interaction Experiment (BRIE) at Äspö. Data from the Long-term Diffusion Sorption Experiment (LTDE), where enhanced penetration depth of cesium was measured in the crystalline rock matrix, was used to show how the increased penetration relative to standard matrix diffusion models, could be explained using fracture microstructure.

3.3a Finding: Although DOE's modeling work is state-of-the-art, characterization of in-situ large-scale fracture topology for computational models applicable to crystalline rock remains a challenge. The Board recognizes that DOE's international collaborations have enabled it to exercise high-performance computing, multiphysics-based methods for coupled processes, and multi-scale analysis to extend the laboratory findings to field systems. To date, geomechanical controls on which fractures are hydraulically conductive, as well as thermal effects on flow and transport in fractured systems, have not been adequately factored into the current fracture models. Well-tested models for flow in fractured crystalline rock are needed for modeling the long-term performance of crystalline rock repositories.

Recommendation: Different types of fracture network models should be explored and compared to data from URLs, largely as described by the DOE team, and should be expanded to include geomechanical constraints as well as thermal effects in order to improve predictions for performance and uncertainty analysis. Improved multi-scale models that are validated at relevant scales should be used in the design of future experiments.

Colloid-Facilitated Radionuclide Transport

DOE has conducted studies on colloid-facilitated radionuclide transport, including participation in the Colloid Formation and Migration (CFM) Project at the Grimsel Test Site. DOE's colloid research is most relevant to a repository scenario in which radionuclides released from a waste package sorb onto bentonite backfill, which subsequently is eroded and forms colloids that facilitate the transport of radionuclides attached to them. This research has enabled DOE to gain new insights on radionuclide transport in fractures and state-of-the-art knowledge on colloid-facilitated radionuclide transport. According to the DOE investigators, most indications are that only a very small fraction of strongly-attached radionuclides will be amenable to colloid-facilitated transport over repository time and distance scales.

The Board observes that international R&D activities on colloids (e.g., BRIE and CFM projects; Figure 1-2) focus on both colloid formation associated with erosion of a bentonite engineered barrier and colloid-facilitated radionuclide transport. DOE has identified bentonite erosion by groundwater flowing in fractures as a priority R&D topic (Table 1-1), but its international colloid research has focused mainly on colloid transport (Boukhalfa 2019; Viswanathan 2019;

Birkholzer et al. 2018). Also, DOE's generic repository R&D program has not addressed bentonite barrier erosion (Sevougian et al. 2019).

DOE is reviewing and revising its disposal R&D activities, which include international collaboration R&D, and assessing priorities and gaps in its R&D program (Birkholzer 2019a, pg. 22; Sevougian et al. 2019). DOE's ongoing evaluation relies on professional judgment and uses state-of-the-art level knowledge (from 1 = well understood to 5 = fundamental gaps) and importance to safety case (from 1 = Low to 5 = High) as the metrics to determine research priorities (Birkholzer 2019b, pg. 40). DOE preliminarily identified bentonite erosion as a fundamental R&D gap that may have high importance to the safety case, but it has not determined whether it will conduct any R&D on this topic. Also, previous URL bentonite erosion tests (e.g., CFM) were conducted under ambient conditions, and there is a lack of data to indicate whether erosion of bentonite under those conditions will be different from erosion of bentonite exposed to high temperatures (close to 200 °C). Bentonite exposure to high temperatures could occur if dual-purpose (storage and transportation) canisters are directly disposed of and bentonite is emplaced prior to any substantial reduction in canister temperature during storage.

The Board believes the high-level question of whether bentonite can be eroded by water flowing in fractures is an important issue that also needs to be addressed as it could affect not only the bentonite's barrier capability, but the radionuclides released from a crystalline repository, both dissolved and colloidal. An experiment similar to the CFM project currently is being planned to be conducted in a fast-flowing shear zone at the Grimsel Test Site to better understand bentonite erosion processes (Birkholzer et al. 2018). However, the Board notes that DOE is no longer participating in the CFM project.

3.3b Finding: DOE has not focused on the issue of whether a bentonite barrier can be eroded by water flowing through fractures, particularly under high temperature conditions. DOE has not assessed whether changes in infiltrating fluids (both flow rates and chemistry), regardless of the mechanism (e.g., coupled processes), and potential geochemical changes in bentonite from exposure to higher temperatures would affect bentonite erosion. If colloids are generated during erosion, it will be necessary to determine what fraction of strongly-sorbing radionuclides will be capable of colloid-facilitated transport over repository time and distance scales.

Recommendation: DOE should focus its colloid-related R&D activities on colloid generation, particularly from bentonite erosion, in addition to colloid transport. These activities should address whether bentonite erosion could affect repository performance under conditions expected for a generic U.S. repository, for example, one with a bentonite engineered barrier that is subjected to coupled THMC processes at temperatures up to 200 °C.

3.4 Microbial Processes

The Board observes that microbial processes in repository environments traditionally had not been a focus of research either abroad or in the U.S. generic geologic disposal R&D program. This is well exemplified, for example, by the relatively mature development of THMC models that do not incorporate "B", i.e. biota. However, microbial processes recently have become the subject of several European research efforts (e.g. MIND 2015, Taborowski et al. 2019) and this development is largely the result of observations made in URLs.

A combination of issues related to the topics of formation and migration of gas and how it interrelates to microbial activity are now increasingly seen to be contributing to important knowledge gaps. As long as temperatures are below about 120 °C and water and nutrients are present in pores or fractures large enough for entrance and growth of cells, micro-organisms will likely extract energy for growth from the inherent lack of redox equilibrium (e.g., transient oxidizing environment) around newly emplaced canisters, clay buffers, or other engineered barriers. Micro-organisms also can stimulate the formation of precipitates that can clog pores or can generate biogenic gases that accumulate along with abiotically-produced gas (e.g., from general corrosion of steel components), leading to changes in gas pressure that could be important in impermeable media. Growth of organisms can occur through fixation of inorganic carbon out of the fluid or atmosphere, or through utilization of organic matter that may be present in the engineered system or host rock. This growth or utilization of organic matter can in turn release organic molecules to pore fluids that can attach to radionuclides or form organometallic colloids. Understanding the effects of microbial activity, therefore, could be important in terms of knowing the redox state, complexation capability, and pH of porewaters in the near field, the gas chemistry and pressure, and ultimately, the mobility of radionuclides.

3.4 Finding: Internationally, microbial activity has become an important R&D focus, but DOE is pursuing little research in this area. Other countries limit temperatures in bentonite to below 100 °C and some plan to dispose of organic-containing waste (e.g., low-level and intermediate-level waste) in the same repository, but in a separate area, as SNF and HLW. The lower temperature and presence of organic-containing waste both will tend to increase microbial activity. Large, hot, dual-purpose canisters may heat a bentonite engineered barrier closer to 200 °C, and while this will stop microbial growth due to the dry out of the bentonite, cooling of the system may ultimately allow microbial growth and activity that has not yet been explored in lower-temperature URL experiments.

Recommendation: DOE should pursue R&D activities related to microbial activity in URLs, including investigating potential microbial processes in the pending HotBENT experiment.

4 USING INTEGRATED MODELING FOR THE SAFETY CASE AND GAP ANALYSIS

The results of process-level research and models discussed in the previous section are intended to contribute to an improved basis for evaluating and demonstrating an integrated "safety case" for a geologic repository. In DOE's current disposal research program, simulation tools for this type of evaluation are being developed in the Geologic Disposal Safety Assessment (GDSA) Framework (Figure 4-1). As currently implemented, this framework includes PFLOTRAN, an open-source, multi-physics simulator developed and maintained at the national laboratories with DOE funding. PFLOTRAN incorporates models of properties and processes controlling release of radionuclides from the waste, perturbations to and evolution of the engineered barrier system and the near field of the repository, flow and transport from the near field into the farther field of the host rock, and pathways to the biosphere that can ultimately result in human exposure and doses. Additional components of the framework include a database of input parameters for reference disposal concepts in several distinct host rock settings, tools for analyzing uncertainty and sensitivity as a function of variations in parameters, and tools for pre- and post-processing and visualization.

The presentation by Emily Stein (SNL) illustrated how each of the international collaborative projects described in the workshop can feed into the PFLOTRAN sub-system models. In some cases, the subsystem models developed as part of the URL and associated research can be incorporated directly into PFLOTRAN. In other cases, PFLOTRAN can incorporate simplified "reduced-order" or "surrogate" models [such as those described by Viswanathan (2019) for transport in fracture networks] in order to reduce the computational burden associated with uncertainty and sensitivity analyses.

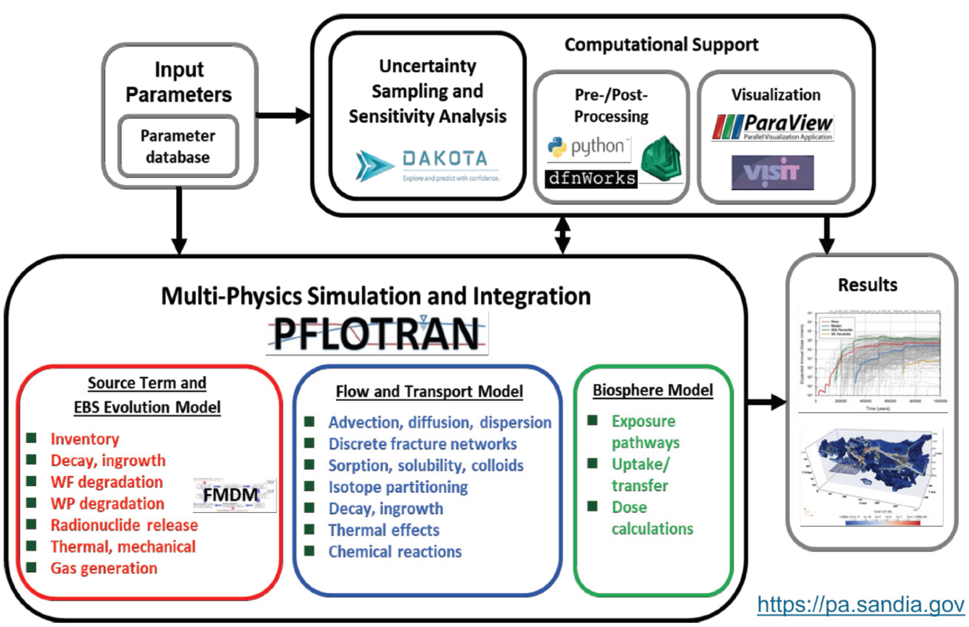

Figure 4-1. Components of DOE's Geologic Disposal Safety Assessment Framework (Stein 2019).

This integrative framework is ultimately designed to serve as a tool for performance assessment as part of a safety case. When used in a performance assessment, multiple runs of this type of model using different sets of input parameters (within the ranges of values that have been determined to be plausible or conservative), and/or with different sets of forcing and boundary conditions, can provide information on the likelihood of and uncertainty in outcomes such as releases, arrival times, and doses. Discussions during the workshop suggested that simulations of repository system performance also could be used to evaluate the sensitivity of outcomes to particular parameters, processes, forcings or boundary conditions. Sensitivity analyses of this type could be a powerful tool to identify and prioritize research gaps and uncertainties that should be addressed in current and future research. These gaps and uncertainties may be associated with (i) critical processes that affect repository safety but are poorly understood, or (ii) input parameters for models that may be poorly constrained or highly variable in space and/or time. Simulations of integrated repository system behavior could be used to ask questions such as whether colloid-facilitated transport or migration of intragranular brine are likely to be significant contributors to releases of radionuclides from the waste form or engineered barrier and, if so, would those have significant impacts on far-field concentrations and doses.

Another question that could be addressed with system-level simulations is the capability of an engineered barrier to prevent the release or substantially reduce the release rate of radionuclides from the waste. As yet another example, simulations focusing on sensitivity analyses of sorption parameters could be used to identify thresholds or ranges of sorption parameters for which retardation exerts a dominant control on radionuclide migration. Answers to such questions could guide prioritization of research efforts to focus on those questions that are most likely to contribute to an improved evaluation of repository safety. In the longer term, a well-developed repository system analysis tool kit also could play a very useful role in screening and comparing potential repository sites and concepts within and across host rock settings.

4.1a Finding: Responses to questions posed during the workshop indicated that the GDSA Framework is not yet sufficiently well developed to contribute to gap and uncertainty analyses for research prioritization or to site screening and comparison.

Recommendation: The Board encourages DOE to accelerate efforts to move the framework toolkit to the point that it could be used for uncertainty analyses to inform research prioritization and for possible future site screening and comparison.

4.1b Finding: The code that is the key component of the current GDSA Framework, PFLOTRAN, is open source and was developed and maintained by DOE-funded national laboratory scientists. This allows it to be available to the international community. The Board heard from several speakers from other countries that DOE's modeling capabilities are one of the benefits they receive from the collaboration.

Recommendation: The Board encourages DOE to expand collaboration in the modeling arena, both within the U.S. national laboratories and academic community as well as internationally. Expanded use of PFLOTRAN would allow it to be tested and validated in a variety of repository environments and for other problems of coupled THMC processes.

4.1c Finding: Uncertainty and research gap analyses driven by projections of long-term repository performance based on simulations of processes that are sufficiently understood to incorporate into numerical or analytical models represents a top-down approach. In addition to a top-down approach, the speakers from other countries also pointed to advantages of a bottom-up approach to identifying research questions for which processes and properties that are not currently recognized as important to a safety case but also not thoroughly understood are, nevertheless, pursued by researchers with relevant expertise. A prominent example is the exploration of microbial activity at the Äspö URL that was driven initially by "curiosity," but which is now recognized may be an important factor to the integrity of engineered barriers.

Recommendation: DOE should employ both top-down and bottom-up approaches to identify and prioritize disposal research. Identification and prioritization efforts should involve broad participation and interdisciplinary and inter-laboratory collaboration among researchers from the full range of relevant disciplines.

5 Critical Role of Underground Research Laboratories in Technology Development and Demonstration, Training, and Public Confidence Building

As described in Chapter 2, all the speakers from other countries noted the benefit of URLs for technology development, demonstrating construction and operational activities, training, and public confidence building. The representatives of the three countries with active URLs and a clear path to a repository (France, Sweden, and Switzerland) all noted that URLs in their respective countries will remain open after their repositories are approved for construction. One might think that as soon as a repository is approved for construction, a URL no longer would be needed. But construction and operation of repositories will occur over a long period of time, multiple decades to a century or more. Some multi-decade URL experiments have been designed to support licensing phases after construction authorization. Monitoring technology will change over that time period (NWTRB 2018) and new questions will arise. The URLs can play a major role over this period (NWTRB 2018). URLs will be important well beyond the construction authorization phase and opening of the repository.

5.1 Developing and Demonstrating Technology and Construction and Operational Capabilities

Public perceptions of safety can drive nuclear waste disposal programs and this applies not only to the disposal safety case, but also to repository construction and operations. These perceptions can be informed by direct observations of the technology demonstrations and experiments conducted in URLs. In 2013 and 2016, some Board members and staff were privileged to visit URLs in Belgium, France, Sweden, and Switzerland. Our observations of the ongoing scientific research at these URLs, as well as operational research (Ewing 2013), strengthened the Board's confidence in these programs and our conviction that DOE needs to do much more in this area.

5.1a Finding: Repository programs in other countries benefit from utilizing URLs in developing and demonstrating technologies for constructing and operating geologic repositories.

Recommendation: The U.S. should develop a URL for both scientific and operational confidence building over multiple decades.

The U. S. currently has approximately 3,000 very large capacity dual-purpose canisters. By 2050, the number could grow to ~10,000. These dual-purpose canisters are significantly larger and produce significantly more decay heat than canisters being used or considered by other countries (Box 3-1).

5.1b Finding: Much of the extensive data that are needed to make an informed decision about whether dual-purpose canisters can be directly disposed of in a repository could be learned from R&D activities in URLs.

Recommendation: DOE should seek to increase its international URL R&D activities relevant to direct disposal of dual-purpose canisters. These R&D activities could include addressing operational and handling aspects, including moving the large and heavy loads underground and placing them either vertically or horizontally in drifts at repository depths.

The Exploratory Studies Facility at Yucca Mountain and the experimental galleries at WIPP both have hosted underground experiments in the past, and new experiments are currently underway at WIPP. The Board recognizes that conducting more experiments at WIPP or using it as a training or outreach facility would have to be managed carefully to avoid interfering with its disposal mission. However, the WIPP site currently has staff that coordinate underground experiments and visits from outside groups, including a visit by the Board in the fall of 2018.

5.1c Finding: The speakers from other countries noted the advantages of using existing infrastructure to develop and operate URLs, conducting multi-decadal experiments, and testing the existing knowledge base (e.g., persistence of oxygen in the near-field). While collaboration in URLs in other countries is yielding invaluable data, insights, and intellectual stimulation, DOE researchers will only have full control over subsurface research in their own domestic URLs.

Recommendation: DOE should evaluate whether underground sites in the U.S. with existing infrastructure could be used as generic URLs, including assessing whether those facilities could provide opportunities for international collaboration; identifying scientific studies to evaluate how hydrogeologic, geochemical, and geotechnical conditions at an existing facility have evolved since the conditions were last monitored; and identifying opportunities to develop expertise and demonstrate technical and operational concepts for disposal.

5.2 Training the Next Generation of Researchers

The safe and successful disposal of SNF and HLW is a multi-generational process that relies on having a continuing stream of quality research and well-trained researchers who have benefited from the knowledge gained by those who preceded them. A common theme in the presentations by the speakers from other countries was the value of URLs for training. Experience in the Swiss repository program (NWTRB 2019b, p. 335) has shown that framing geologic disposal around safety and about solving a grand environmental challenge attracts a wide range of young scientists to their disposal program, even those who are non-supporters of nuclear energy but recognize the need to successfully dispose of the existing waste. This reframing has the potential to attract a much broader range of scientific talent to address this problem. It has been demonstrated that visits by the public to these URLs can be instrumental in stimulating student interest in solving the problems related to nuclear waste.

5.2 Finding: URLs offer unique opportunities to attract a younger generation to careers dealing with SNF and HLW, particularly by allowing junior scientists and engineers, graduate students, and others to gain valuable experience working and conducting research in deep underground environments. Participation in international URLs may be particularly important in attracting and retaining junior talent, especially in countries, like the U.S., that are not pursuing a specific *site for a SNF and HLW repository. DOE's involvement with international URLs helps to advance its geologic disposal R&D program.*

Recommendation: DOE should consider making its URL-related R&D, and generic geologic disposal R&D program, even more widely known to U.S. university students from potentially relevant fields, including by reframing the description of its disposal R&D program around safety and solving a grand environmental challenge. DOE should support larger, more formal training opportunities in underground disposal research through programs that could include undergraduate scholarships, graduate fellowships and post-doctoral appointments in disciplines needed for the waste disposition mission. These training opportunities could include periods of time at one or more of the URLs to enable participants to become better acquainted with the URL activities, and the national and international programs participating in the joint research projects.

5.3 Public Outreach and Other Research Applications

URLs provide rare, first-hand opportunities for stakeholders, policymakers, and the public to observe and learn about various repository-related projects and research. This first-hand engagement can help clarify complex technical issues and processes, provide important information and insights, and facilitate public understanding and confidence. With URLs around the world now hosting large numbers of visitors every year, considerable experience has been gained with respect to public outreach, making complex technical information more comprehensible, and providing first-hand opportunities for people to see and become familiar with disposal-related processes and activities.

5.3a Finding: Experience from programs at URLs in other countries that focus on public outreach, engagement, and risk communication could be valuable when a program to site and build a repository in the U.S. goes forward.

Recommendation: DOE should compile examples of best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication that have emerged from the experiences of the various URLs in other countries with which it has partnered.

5.3b Finding: URLs provide unique opportunities for exploring other scientific and technical applications involving subsurface in-situ processes, in addition to opportunities for public outreach and engagement.

Recommendation: DOE should actively pursue opportunities to broaden the use of existing underground facilities in the U.S. for research related to other applications (e.g., carbon sequestration) that can benefit from the type of full-scale in-situ experiments that can be undertaken in a URL, as well as for public outreach and engagement.

6 NEW FRONTIERS AND MONITORING DURING OPERATION AND POST-CLOSURE

The construction and operation of a geologic repository to dispose of HLW and SNF are many years away for the U.S. Over this time period, there will be increased understanding of expected repository performance and many technological advances gained from continuing laboratory experiments, URLs, natural analogs studies, and modeling. Equally important, several geologic repositories are planned to have been constructed and begun operating from which valuable information will have been gained. The same can be said for a U.S. geologic repository once it begins operating. That is, geologic repositories will also be serving as URLs as a result of continuing characterization of repository performance (i.e., performance confirmation).

6a Finding: Many advances in understanding geologic repository performance, from currently operating and future URLs and from construction and operation of geologic repositories in other countries, will occur prior to the U.S. constructing and operating its repository.

Recommendation: To obtain maximum benefit from these advances, DOE should consider taking the following steps within the context of participation in international programs:

- **Periodically assess and rank the technical needs for completing the safety case, design, licensing, construction, and operation of a geologic repository in different host rocks;**
- **Evaluate where R&D in URLs or in repositories can serve to address the identified needs; and**
- **Create international R&D partnerships in which DOE and its contractors could participate, not only in data interpretation and modeling activities, but also in the design, construction, and operational phases of the collaborations.**

Technological advances in areas other than geologic repositories that are relevant to a repository's safety assessment, design, construction and operation will also be occurring prior to the U.S. constructing and operating its repository. Examples of topics that are advancing at a rapid pace include real-time monitoring, where sensor technology (e.g., what can be measured and associated accuracy, and robustness in harsh environments), signal transmission, and power source longevity are all undergoing revolutionary advances. As mentioned during the workshop, the European Commission has formed a collaboration to further develop real-time monitoring capability for a geologic repository, recently issuing a report on accomplishments (Lagerlöf et al. 2018). Another example undergoing a rapid pace of advancement includes computational simulation, driven by advances in high performance computers, machine learning (e.g., non-parameter-based modeling such as deep learning), and multiscale and multiphysics modeling algorithms. Given DOE's leadership position in scientific computing, this area provides an opportunity for DOE to organize and lead collaborative efforts in geologic repository modeling.

6b Finding: Rapid technology advances are taking place in topics relevant to understanding the performance of geologic repositories, such as in real-time monitoring and computational simulation. Real-time monitoring that is broadly accessible can enhance public trust. Although *post-closure monitoring of a U.S. geologic repository is not required by the regulator, it is possible that in the future the public will both expect and demand such monitoring (NWTRB 2018).*

Recommendation: Within the theme of collaborative efforts, DOE should seek partnerships to advance technologies relevant to evaluating the performance of geologic repositories, specifically in real-time monitoring that can be tested and demonstrated in URLs and in computational simulation.

7 Conclusions, Findings, and Recommendations

Siting, developing, and operating a geologic repository for HLW and SNF is a multi-generational endeavor and URLs are crucial to repository programs. URLs permit the collection of data at temporal and spatial scales that can test and support the safety case and allow the demonstration of technologies that can address engineering challenges and enhance public understanding of and confidence in geologic disposal. URLs also provide training opportunities for scientists, engineers, and skilled technical workers and provide continuity to disposal programs. In short, URLs provide an environment for teaching and learning that cannot be attained with any other approach. Furthermore, experience in URLs in other countries demonstrates that solving the technology challenges associated with construction and emplacement of waste and other engineered barriers (i.e., pre-closure activities) is as important to the overall repository program as addressing the post-closure safety issues.

Since 2012, when DOE began generic research on alternative host rocks (crystalline, clay, and salt) and repository environments very different from that at Yucca Mountain, DOE's collaborative research in URLs located in Europe and Asia has provided DOE-funded researchers access to data and to decades of experience gained in different disposal environments in a cost-effective manner and has advanced DOE's SNF and HLW disposal R&D program. Until 2018, DOE's URL-based R&D activities focused on the disposal concepts of the URL host countries and not on a disposal concept that could apply to most of the U.S. inventory of commercial SNF, i.e., the direct disposal of SNF in large dual-purpose canisters. Internationally, a safety case with prescribed safety functions for each engineered and natural barrier is the technical foundation for each repository program and guides the R&D that is conducted in the laboratory and in URLs. DOE has not yet developed generic safety cases, and associated safety functions and technical bases, for disposal of dual-purpose canisters in crystalline, clay, and salt host rocks.

Based on the information presented and discussed at the workshop and at the fact-finding meeting and from reports published by DOE and others, and the Board's evaluation of the information, a number of specific findings and recommendations are provided in the preceding chapters. From the specific findings, the Board presents the following four principal findings on DOE's URL-related R&D activities.

- DOE participation in URL-related international research greatly benefits the U.S. geologic disposal R&D program by furthering its understanding of generic and site-specific disposal issues relevant to alternative repository host rocks and environments. DOE-funded R&D activities also are benefiting the URL-related research of other countries, especially in the area of complex analytical and numerical model/software development.
- The more developed repository programs in other countries have focused on creating and strengthening their safety cases and making them transparent to the public. Repository programs in other countries use URLs to explain the technical bases underlying their safety cases, periodically reassess knowledge gaps and define new

activities to strengthen the technical bases, and demonstrate the technology that will allow implementation of the proposed safety concept.

- Countries with more developed geologic disposal programs have found domestic URLs essential to their repository programs. DOE needs domestic URLs to advance geologic disposal efforts over the next decades and further its ability to train the next generation of scientists, engineers, and skilled technical workers.
- DOE's international URL collaborations have advanced its generic disposal R&D program, including development of modeling capabilities recognized internationally as state-of-the-art, but further work on its coupled thermal-hydrological-mechanical-chemical models and URL- and laboratory-based research can strengthen its program.

Based on these principal findings, the Board makes the following recommendations:

- DOE should expand its collaborative international URL activities to enhance its capacity for R&D of geologic repositories. To obtain maximum benefit from its international programs, DOE should consider (i) making use of R&D in URLs to address the technical needs for the design, licensing, construction, and operation of geologic repositories in different host rocks that consider the types of waste in the U.S. inventory; (ii) pursuing international URL R&D partnerships, including those involving non-nuclear waste applications (e.g., carbon sequestration) that require underground knowledge and operations, in which DOE could participate in the design, construction, and operational phases of the collaborations; and (iii) compiling best practices, innovative approaches, and notable successes and failures in public outreach, engagement, and risk communication from the experiences of URL programs in other countries.
- DOE should make systematic use of URL R&D results to regularly update generic repository safety cases that can be easily understood by and demonstrated to the public, including safety cases relevant to direct disposal of dual-purpose canisters in different host rocks.
- DOE should pursue one or more domestic URLs to advance the development and demonstration of disposal concepts and provide a platform for training the next generation of U.S. scientists, engineers, and skilled technical workers. DOE should evaluate whether underground sites in the U.S. with existing infrastructure could be used as generic URLs and whether use of existing facilities could be broadened (e.g., for more underground experiments or as training facilities) without impacting their primary missions. If DOE expands its domestic URL program in this way, then it should consider (i) broadening its URL R&D program from one focused on the technical issues relevant to post-closure repository performance to one that includes developing and demonstrating the construction and operational concepts for disposal; (ii) supporting larger, more formal training opportunities in underground disposal research in disciplines needed for the waste disposition mission; and (iii) make domestic URLs broadly accessible to researchers from the U.S. and other countries, including those outside the DOE geologic disposal R&D program.
- DOE should continue advancing its thermal-hydrological-mechanical-chemical-based research and model development and pursue more URL- and laboratory-based

studies, particularly at elevated temperatures. In doing so, DOE should consider (i) designing and conducting technical activities in URLs to test hypotheses and assumptions, while at the same time remaining open to unexpected processes or behaviors; (ii) employing an iterative process involving laboratory experiments focused on fundamental processes, modeling, and field experiments and observations; (iii) including geomechanical constraints and thermal effects in fracture flow and transport models; and (iv) focusing on bedded salts and using the heater tests at the Waste Isolation Pilot Plant to improve the constitutive models of salt behavior.

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GLOSSARY[15]

advection	The movement or transfer of a substance, solute or heat, etc. by the motion of the fluid medium (e.g. air or water) in which it is present.
argillite	A compact rock derived from mudstone (claystone or siltstone) or shale that has hardened (i.e., indurated) via heat or pressure or introduction of a cementing material.
backfill	The material used to refill excavated portions of a repository (drifts, disposal rooms, or boreholes) during and after waste has been emplaced.
bentonite	A soft, plastic, porous, light-colored rock composed of clay minerals formed by chemical alteration of volcanic ash. Compacted bentonite has been proposed for backfill and buffer material in many repositories.
buffer	Any substance placed around a waste package in a repository to serve as an additional barrier to: stabilize the surrounding environment; restrict the access of groundwater to the waste package; and reduce by sorption the rate of eventual radionuclide migration from the waste.
canister	The container into which the waste form is placed for handling, transport, storage, and eventual disposal. For example, molten high-level waste glass would be poured into a specially designed canister where it would cool and solidify. The canister is normally a component of the waste package. However, DOE uses the term canister, instead of waste package, especially in older reports. Also, the Swedish radioactive waste disposal program uses the term canister instead of the term waste package.
clay	Minerals that are essentially hydrated aluminum silicates or occasionally hydrated magnesium silicates, with sodium, calcium, potassium and magnesium cations. Also denotes a natural material with plastic properties which is essentially a composition of fine to very fine clay particles. Clays differ greatly mineralogically and chemically and consequently in their physical properties. Because of their large specific surface areas, most of them have good sorption characteristics.
colloid	A state of subdivision of matter in which the particle size varies from that of true 'molecular' solutions to that of a coarse suspension. The diameters of the particles range between 1 and 1000 nm and the particles are dispersed in a liquid phase and do not sediment out.
constitutive model	Mathematical description of the relationship between two physical quantities, for example, between the stress put on a material and the strain produced in it.

[15] Most of these definitions were taken from the *Radioactive Waste Management Glossary* (International Atomic Energy Agency 2003). The definitions of some terms were altered to make them more applicable to this report, and other terms have been added. The International Atomic Energy Agency is not responsible for those changes. The definitions of geologic terms were derived from the *Glossary of Geology* (American Geological Institute 2011). The definitions of "safety assessment" and "safety case" were derived from the International Atomic Energy Agency (2011, 2012) reports.

crystalline rock	A term for igneous rocks and metamorphic rocks (*e.g.*, granite and gneiss), as opposed to sedimentary rocks.
diffusion	The movement of atoms or molecules of a diffusing species from a region of higher concentration to a region of lower concentration, due to a concentration gradient.
dual-purpose canister	A waste canister designed for storage and transportation.
engineered barrier system	The designed, or engineered, components of a disposal system that contribute to isolation of the waste from the human-accessible environment. Examples of engineered barriers include waste forms, waste packages, and seals with physical and chemical characteristics that significantly isolate the waste or decrease the mobility of radionuclides.
far field	The geosphere beyond the near field. See also near field.
geologic repository	A facility for disposing of radioactive waste located underground (usually several hundred meters or more below the surface) in a geologic formation. It is intended to provide long-term isolation of radionuclides from the human-accessible environment.
geomechanical properties	The strength and deformation parameters of the rock, in addition to the initial *in situ* stresses that exist at a specific depth.
granite	Broadly applied, any holocrystalline quartz-bearing plutonic rock. The main components of granite are feldspar, quartz and, as a minor essential mineral, mica.
high-level radioactive waste	Highly radioactive material resulting from reprocessing spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations.
host rock	A geological formation in which a repository is located.
induration	The hardening of a rock or sediments by the effects of temperature, pressure, cementation, etc.
monitoring	Continuous or periodic measurement of radiological and other parameters or determination of the status of a system.
multiple barriers	The natural and engineered system of barriers used in a disposal system, such as a geologic repository, to isolate radioactive waste and prevent migration of radionuclides from the disposal system to the human-accessible environment.
multiphysics	The coupled processes or systems involving more than one simultaneously occurring physical fields and the studies of and knowledge about these processes and systems. The physics refers to common types of physical processes, e.g., heat transfer (thermal), pore water movement (hydrologic), and stress and strain (mechanical).
natural analog	A situation in nature that allows conclusions relevant for making a judgement upon the safety of an existing or planned nuclear facility.
natural barrier	Attributes of Earth that tend to isolate radionuclides from the human-accessible environment.

near field — The excavated area of a repository near or in contact with the waste packages, including filling or sealing materials, and those parts of the host medium/rock whose characteristics have been or could be altered by the repository or its content. See also far field.

performance assessment — An assessment of the performance of a system or subsystem and its implications for protection and safety at a planned or an authorized facility. This differs from safety assessment in that it can be applied to parts of a facility and does not necessarily require assessment of radiological impacts.

permeability — The property or capacity of a material such as a porous rock, sediment, or soil for transmitting a fluid.

radiolysis — Change in chemical composition of materials induced by ionizing radiation.

radionuclide — A radionuclide, or radioactive nuclide, is an atom that has excess nuclear energy, making it unstable. This excess energy can result in the emission from the nucleus of radiation (gamma radiation) or a particle (alpha particle or beta particle), or the excess energy can be transferred to one of the electrons, causing it to be ejected (conversion electron). During this process, the radionuclide is said to undergo radioactive decay.

redox — Contraction of the name for reduction–oxidation reaction, which is a type of chemical reaction that involves a transfer of electrons between two chemical species and, as a result, changes the oxidation state of the chemical species involved.

safety assessment — A quantitative analysis of the overall system performance where the performance measure is radiological impact or some other global measure of the impact on safety, both during repository operations and after repository closure.

safety case — A collection of logic and evidence that demonstrates that a nuclear waste repository meets the performance requirements defined by the appropriate regulatory authorities. A safety case includes key results from the safety assessment. It also includes quantitative and qualitative supporting evidence and reasoning on (i) the robustness and reliability of the repository, (ii) its design and the rationale for the design choices made, and (iii) the quality and uncertainties of the safety assessment and underlying assumptions.

salt formation — A geological formation resulting from the evaporation of sea water. Salt formations occur as bedded or domal (salt dome) deposits. In a bedded formation the salt is still in a similar shape as it was when deposited. A salt dome results from an uplift within a bedded salt formation.

seal — Engineered barrier placed in passages within and leading to a repository to isolate the waste and to prevent seepage leakage of water into or radionuclide migration from the repository area. Sealing is performed as part of repository closure.

sedimentary rock — A rock resulting from the consolidation of loose sediment that has accumulated in layers consisting of mechanically formed fragments of older rock transported from its source and deposited in water or a chemical rock (such as salt) formed by precipitation from solution.

sorption	The interaction of an atom, molecule or particle with the surface of a solid. A general term including absorption (sorption taking place largely within the pores of a solid) and adsorption (surface sorption with a non-porous solid). The processes involved may also be divided into chemisorption (chemical bonding with the substrate) and physisorption (physical attraction, for example by weak electrostatic forces).
spent nuclear fuel	Nuclear fuel removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material, buildup of poison, or radiation damage.
transuranic waste	Alpha bearing waste containing nuclides with atomic numbers above 92, in quantities and/or concentrations above clearance levels.
URL	Underground research laboratory. A special underground laboratory for conducting in situ tests on waste repository system interactions under the full range of repository environment conditions.
waste canister	(see **canister)**
waste package	The vessel in which the canistered or uncanistered waste form is placed.

APPENDIX A:

SPRING 2019 WORKSHOP AGENDA

AGENDA

Workshop on Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations

Embassy Suites by Hilton San Francisco Airport Waterfront
150 Anza Boulevard, Burlingame, CA 94010

Wednesday, April 24, 2019 (Ambassador Ballroom)

8:00 a.m. **Call to Order and Introductory Statement**
Jean Bahr (Board Chair)

8:15 a.m. **Underground Research Laboratories: Purposes, Types, and Activities**
Michael Apted (INTERA)

QUESTIONS TO BE ADDRESSED:

- What is an underground research laboratory (URL) and what purposes are they serving in national nuclear waste disposal programs?
- Where are the major URLs located, and in what types of potential repository host rocks are these constructed?
- What are the characteristics of these types of host rocks that (1) are advantageous for a mined geologic repository and (2) might be disadvantageous to a mined geologic repository?
- What are some key uncertainties that remain with respect to processes in these host rock environments?
- The Nuclear Energy Agency of the Organization for Economic Co-operation and Development distinguishes between "generic" and "site-specific" URLs. What are the features and advantages of each of these?
- What types of research, development, and demonstration activities are undertaken at URLs (e.g., site characterization, experiments on host rock and engineered barrier behavior, and demonstration of disposal concepts)?
- Can you describe a few key processes and uncertainties for repository safety cases that are being or have been investigated in URLs?
- Can you provide examples of URL observations or experiments that have been successful in discriminating between competing hypotheses or conceptual models for repository performance?

Note: The questions have been provided to the speakers in advance of the meeting to convey the Board's primary interests in the agenda topics and to aid in focusing the presentations.

8:45 a.m. *Questions, discussion*

9:00 a.m. **International Programs, Part 1 – each speaker has 30 minutes**
Irina Gaus (Nagra, Switzerland)
Patrik Vidstrand (SKB, Sweden)

10:00 a.m. **Break**

10:10 a.m. **International Programs, Part 2 – each speaker has 30 minutes**
Daniel Delort (Andra, France)
Simon Norris (Radioactive Waste Management, United Kingdom)

QUESTIONS TO BE ADDRESSED BY EACH INTERNATIONAL SPEAKER:

- Please begin by briefly describing the geologic/hydrologic setting of your country's expected repository and the key components of your safety case.
    - What is the role of your URL research and development (R&D) program in your country's repository program?
- How were the objectives of the URL R&D program initially defined and how have the R&D activities evolved?
    - What key parameters needed for the safety case were defined?
    - Was the R&D prioritization done based on conceptual models and/or features, events, and processes?
    - Describe successes to date, particularly experiments that discriminated between competing hypotheses.
    - What was the most unexpected thing learned from the URL program?
- How are the results of the URL R&D incorporated into repository performance assessments (e.g., as parameter values in performance assessment models, model validation, etc.) and the safety case (e.g., confirmation of predicted system behavior)?
- What are the most important R&D activities related to demonstrating repository operations?
- What R&D activities have proven most helpful for performance confirmation monitoring and waste retrievability/reversibility?
- How effective have URLs proven to engendering stakeholder confidence and public acceptance of a repository?

11:10 a.m. **Facilitated Panel Discussion**
Panelists: *Michael Apted* (INTERA), *Irina Gaus* (Nagra, Switzerland), *Patrik Vidstrand* (SKB, Sweden), *Daniel Delort* (Andra, France), *Simon Norris* (Radioactive Waste Management, United Kingdom)

11:55 a.m. **U.S. Department of Energy's (DOE) Collaborations and Underground Research Program: Overall Program and Approach**
William Boyle (DOE Office of Nuclear Energy)

QUESTIONS TO BE ADDRESSED:

- What are the main objectives and mission of DOE's Disposal R&D Program within the Office of Spent Fuel and Waste Science and Technology?
- What are the main components of the program?
- What are the priority R&D areas and associated questions/challenges?
- How do these priorities relate to key uncertainties associated with each of the generic host rock environments (crystalline, clay/argillite, salt)?

12:15 p.m. *Questions, discussion*

12:30 p.m. **Lunch Break (1 hour)**

1:30 p.m. **DOE's Specific Research and Development Activities Related to International URLs**

Jens Birkholzer (Lawrence Berkeley National Laboratory)

QUESTIONS TO BE ADDRESSED:

- Summarize the DOE portfolio of URL collaboration efforts in the context of the overall disposal research program.
- What are the key processes and uncertainties in the disposal research program that can be addressed in URL collaborative research?
- How are these questions similar to or different from those other countries are attempting to address?
- What policy, logistical, and technical issues were considered by DOE in selecting its URL participation?
- How have the results obtained to date informed and challenged assumptions of DOE modeling (conceptual and numerical)?
- How are these activities integrated into and supporting DOE's generic disposal efforts related to its generic disposal safety assessment and direct disposal of dual-purpose canister efforts?

2:10 p.m. *Questions, discussion*

2:30 p.m. **DOE's Near-Field Natural Barrier Perturbation Activities: Talk 1 Thermo-Hydro-Mechanical (THM) Perturbations in Bentonite/Argillite Repositories: Heater Tests at Mont Terri and Bure**

Jonny Rutqvist (Lawrence Berkeley National Laboratory)

QUESTIONS TO BE ADDRESSED:

- Describe the conceptual model for near-field perturbations in a bentonite/argillite repository.
- What are the key unknowns (knowledge gaps) and uncertainties in the conceptual model?
- What has been learned to date from the heater tests?

- How important is the near-field damage to a host rock (such as clay and salt) due to initial mechanical and thermal perturbation, and how effective is healing and sealing of the damage zone in the long term?
  - Describe the constitutive models used to capture coupled heat transfer and water flow in deformable, unsaturated geomaterials, and their calibration. How reliable are available constitutive models for capturing the thermal volume change of unsaturated bentonites under high temperatures? Are sufficient data available in the literature to calibrate advanced constitutive models, or are additional testing programs needed to understand the behavior of these geomaterials?
- How do the small-scale element tests performed in the laboratory for calibration of constitutive models address uncertainties in the values of key parameters in the constitutive model?
- How can small-scale physical-modeling experiments (i.e., experiments that measure variables during coupled heat transfer and water flow processes in deformable geomaterials) be upscaled to repository-scale predictions?
- How are the repository-scale heater tests integrated into and supporting DOE's generic disposal R&D efforts for:
  - different host rocks and the engineered barrier system
  - the generic disposal safety assessment tool
  - direct disposal of dual-purpose canisters?
- Specific to the FE Heater Test as a demonstration experiment:
  - Can the behavior of an entire repository system, including all engineered and natural barriers and their interactions, be demonstrated, and is the planned construction and emplacement method feasible?
  - How suitable are the monitoring methods employed in the FE test to performance confirmation monitoring?

3:10 p.m. *Questions, discussion*

3:30 p.m. **Break**

3:45 p.m. **DOE's Engineered Barrier Integrity Activities: Talk 1**
Understanding Engineered Barrier System Coupled Processes and Mineral Alterations at High Temperatures: From Full-Scale Engineered Barrier Experiment-Dismantling Project (FEBEX-DP) to High Temperature Bentonite Project (HotBENT)
Liange Zheng (Lawrence Berkeley National Laboratory)

QUESTIONS TO BE ADDRESSED:
- Please explain why an engineered barrier/backfill is important and what aspects of the barrier are essential.
- Explain the conceptual model for engineered barriers, specifically for bentonite, in different host rocks
- What are the key unknowns and uncertainties in the conceptual models and how do they vary with host rock?

- What has been learned to date from the experiments?
    - What is the long-term stability and retention capability of backfills and seals?
    - What is the impact of elevated temperature on bentonite properties (thermo-elasto plastic model parameters, hydraulic properties, thermal properties)?
    - What is the impact of different bentonite compaction/placement strategies and initial conditions (i.e., distributions in initial density, initial gravimetric water content)?
    - Can we achieve temperatures approaching 200 °C, and are current constitutive models representative of this regime?
    - How relevant are interactions between engineered and natural barrier materials, such as metal-bentonite-cement interactions?
- Describe any research focusing on the effects of the change from partially saturated to saturated conditions with time, especially as the temperature decreases. Are the models that will be used to make forecasts for thousands or tens of thousands of years capable of modeling reactions in unsaturated conditions; for example, are reaction kinetics known for systems where the environmental conditions vary from unsaturated to saturated conditions?
- Do any experiments or simulations address the effect of vapor or steam on mineralogy (i.e., for early time periods where conditions are unsaturated)?
- How are these activities integrated into and supporting DOE's generic disposal R&D efforts for:
    - different host rocks and the engineered barrier system
    - the generic disposal safety assessment tool
    - direct disposal of dual-purpose canisters?

4:25 p.m. *Questions, discussion*

4:45 p.m. **Public Comments**

4:59 p.m. **Adjourn Public Meeting**

5:00 p.m. – 6:15 p.m. **Poster Session (Diplomat A & B)**
DOE posters and program posters from international speakers

Thursday, April 25, 2019 (Ambassador Ballroom)

8:00 a.m. **Call to Order and Introductory Statement**
Jean Bahr (Board Chair)

8:15 a.m. **DOE's Engineered Barrier Integrity Activities: Talk 2**
Thermal Implications on Transport in Bentonite: Using Full-Scale Engineered Barrier Experiment-Dismantling Project (FEBEX-DP) Samples for Laboratory Studies and Model Testing
Carlos Jove-Colon (Sandia National Laboratories), with help from *Patricia Fox* (Lawrence Berkeley National Laboratory) and *Florie Caporuscio* (Los Alamos National Laboratory)

QUESTIONS TO BE ADDRESSED:

- Explain the conceptual model for transport in bentonite.
- What are the key uncertainties and unknowns in transport properties and processes?
- What has been learned to date from the URL experiments?
    - What is the effect of high temperature on the swelling, sorption, water retention, hydraulic conductivity, and thermal conductivity characteristics of clays (i.e., considering the heat load from dual-purpose canisters)?
    - What is the role of thermal volume change over a wide range of temperatures in unsaturated bentonite?
    - How relevant are interactions between engineered and natural barrier materials, such as metal-bentonite-cement interactions?
    - How can the diffusive transport processes in nanopore materials, such as compacted clays and bentonites, best be described?
- How are these laboratory studies integrated into and supporting DOE's generic R&D disposal efforts for:
    - different host rocks and the engineered barrier system
    - the generic disposal safety assessment tool
    - direct disposal of dual-purpose canisters?

8:55 a.m. *Questions, discussion*

9:15 a.m. **DOE's Engineered Barrier Integrity Activities: Talk 3**
Gas Migration in Clay-Based Materials — International Collaboration Activities as Part of the DEvelopment of COupled models and their VALidation against EXperiments (DECOVALEX) Project
Jonny Rutqvist (Lawrence Berkeley National Laboratory)

QUESTIONS TO BE ADDRESSED:

- Describe the gas generation process in nuclear waste repositories, including the rate of gas generation, the expected pressure range, and gas composition, and explain the relevance of gas migration to repository performance.

- Comment on the available laboratory experiments on gas migration in various host rocks and engineered barrier materials and how they represent the expected initial saturation conditions and stress state in a repository.
- How are heterogeneities and construction seams in the bentonite pellets or blocks considered in the gas migration processes?
- Under what conditions do unsaturated conditions occur? How important is the role of unsaturated conditions in the bentonite and homogeneity of hydration in the engineered barrier system on gas migration?
- How does the total stress distribution in the engineered barrier system during partial hydration affect gas migration, and is this captured in simulations?
- How does the relationship between dilation and boundary conditions affect gas migration?
- How do deformation effects on the hydraulic properties of bentonite (permeability and water retention curve when the material is unsaturated) relate to gas migration?
- How important is the temperature distribution on the gas intrusion process?
- What is the effect of high temperature on gas formation and behavior?

9:45 a.m. *Questions, discussion*

10:00 a.m. **Break**

10:15 a.m. **DOE's Flow and Radionuclide Transport Activities: Talk 1**
Flow and Transport in Fractured Granite: Modeling Studies Involving the Bentonite Rock Interaction Experiment (BRIE) and the Long Term Diffusion Experiment (LTDE)
Hari Viswanathan (Los Alamos National Laboratory)

QUESTIONS TO BE ADDRESSED:

- What are the key uncertainties associated with predicting radionuclide transport in fractured crystalline rock?
- What has been learned from the experiments to date?
  - Can the active fracture network be identified and characterized adequately to predict near field and farther field transport?
  - How relevant are interactions between flowing fractures and bentonite (e.g., bentonite erosion, homogeneity)?
- For each of the experiments:
  - What questions does the experiment address?
  - How is the experiment designed and how are experimental conditions expected to evolve over time?
  - How does modeling of the experiment contribute to improved understanding of processes and parameter identification/quantification?
  - What has been learned to date from the results of the experiment (if it has been completed)?

10:45 a.m. *Questions, discussion*

11:00 a.m. **DOE's Flow and Radionuclide Transport Activities: Talk 2**
Colloid-Facilitated Transport: Studies Related to Colloid Formation and Migration (CFM) Project at Grimsel Test Site
Hakim Boukhalfa (Los Alamos National Laboratory)

QUESTIONS TO BE ADDRESSED:

- Colloidal transport in both unsaturated and saturated porous media has been extensively studied. However, in the context of media such as rocks and clay, the mechanisms of colloidal transport can be fundamentally different because of the presence of fractures and very small permeabilities. Describe the conceptual model for colloid-facilitated transport in the host rocks under consideration.
- What is the most likely source of colloids and what is the potential for transport of radionuclides by colloids in any of the host rocks under consideration?
- In conventional settings, transport of dissolved solutes is modeled by parameterizing the diffusivity, the permeability, the dispersivity, and the chemical reactions. What parameters are needed to characterize colloid-facilitated transport in host rocks? What are the unknowns and uncertainties for the key parameters controlling colloid-facilitated transport, and how do these uncertainties vary with host rock type?
- Will colloid transport be the same or different in different geomedia? What is the state of models that are used to simulate colloid associated transport in porous media? Can these models be applied with confidence to host rock conditions at URLs? With expected uncertainties in obtaining parameters for models, what is the level of confidence in predictions in URL settings?
- Describe the CFM project—the geometry, measurements, interpretation, rationale, and underlying assumptions. What has been learned to date from the experiment?
- What experimental data are available or what experiments are under way to generate data at URLs with different host rocks that will benefit DOE's R&D efforts to support generic disposal models? Please describe data that will help to address issues related to safety assessment of disposal systems, engineered barriers, and direct disposal of dual-purpose canisters.

11:30 a.m. *Questions, discussion*

11:45 a.m. **Lunch Break (1 hour)**

12:45p.m. **DOE's Salt Research and Waste Isolation Pilot Plant (WIPP) Activities: Understanding Heat-Driven Brine Migration in Salt: From Collaborations with the German Salt Program to the Planned WIPP Heater Test**
Kristopher Kuhlman (Sandia National Laboratories) and *Philip Stauffer* (Los Alamos National Laboratory)

QUESTIONS TO BE ADDRESSED:

- What is the significance of heat-driven brine migration to overall performance of a salt repository?
- What is the conceptual model for heat-driven brine migration in salt?
- What are the key unknowns and uncertainties in the conceptual model?
- What has been learned from the experiments to date?
    - How relevant are thermally-driven brine migration processes? Can they be predicted with confidence?
    - How important is the near-field damage to salt due to initial mechanical and thermal perturbation, and how effective is healing and sealing of the damage zone in the long term?
    - How reliable are existing constitutive models for the deformation of elastoplastic and plastic geomaterials as affected by temperature and water-content changes?

1:40 p.m. *Questions, discussion*

2:05 p.m. **Geologic Disposal Safety Assessment (GDSA): How GDSA Benefits from International Collaborations**
Emily Stein (Sandia National Laboratories)

QUESTIONS TO BE ADDRESSED:

- In which general ways does GDSA benefit from international collaboration (e.g., use of international datasets, development of post-closure PA models, confidence enhancement)?
- How have the individual international activities presented before supported GDSA developments and safety assessments?

2:45 p.m. *Questions, discussion*

3:00 p.m. **Break**

3:15 p.m. **Closing Facilitated Panel Discussion**
Panelists: *Michael Apted* (INTERA), *Irina Gaus* (Nagra, Switzerland), *Patrik Vidstrand* (SKB, Sweden), *Daniel Delort* (Andra, France), *Simon Norris* (Radioactive Waste Management, United Kingdom), *William Boyle* (DOE Office of Nuclear Energy), *Peter Swift* (Sandia National Laboratories)

4:45 p.m. **Public Comments**

5:00 p.m. **Adjourn Public Meeting**

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