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Nuclear Waste Technical Review Board (NWTRB)

Transcript

Summer 2022 Board Meeting

Tuesday
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PUBLIC MEETING - DAY ONE
In-Person and Virtual

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PROCEEDINGS

BAHR: Hello, and welcome to the U.S. Nuclear Waste Technical Review Board's Summer Meeting.

I'm Jean Bahr, Chair of the Board, and this meeting will focus on the U.S. Department of Energy's research and development activities related to geological disposal of spent nuclear fuel and high-level radioactive waste in clay-bearing host rocks, and also the research and development on clay-based engineered barriers.

As we transition from the COVID-19 pandemic, we're holding this meeting in a hybrid format with the combination of both in-person and virtual attendance by Board members and presenters. And while masks are not required, we do have a supply of them available, and you're welcome to take one if you'd like to wear a mask if you're here in the meeting room.

I am going to introduce the Board members and then briefly describe the Board and outline what we do. And then I'll tell you why we're holding this meeting and try to summarize the meeting's agenda. I'll ask that as I introduce some of those Board members who are present here raise their hands so that they can be identified. And we also have two Board members who are participating in the meeting remotely, and I'll ask that they unmute their device to come online and say hello when I introduce them.

First of all I'm Jean Bahr, the Board Chair. And all the Board members serve part time, and we all hold other positions. In my case, I'm Professor Emirate of Hydrogeology at the University of Wisconsin, Madison.

Our first two Board members are going to be joining us remotely. First is Steven Becker. Steve is Professor and Chair of Community and Environmental Health in the College of Health Sciences at Old Dominion University in Virginia. And I assume that Steve is online, raising his hand or saying, "Hi."

Then we have Mr. Allen Croff. Allen's a Nuclear Engineer Adjunct Professor in the Department of Civil and Environmental Engineering at Vanderbilt University.

Present in the room is Dr. Tissa Illangasekare. Tissa is the AMAX-endowed Distinguished

Chair of Civil and Environmental Engineering and the Director of the Center for the Experimental Study of Subsurface Environmental Processes at Colorado School of Mines.

Next is Dr. Lee Peddicord. And Lee is Professor of Nuclear Engineering at Texas A&M University.

Dr. Paul Turinsky has been experiencing some plane delays, but we expect him to show up a little bit later this afternoon. He's the Board's Deputy Chair and is a Professor Emeritus of Nuclear Engineering at North Carolina State University.

So I've introduced 5 Board members, plus myself, not the full complement of 11. Our other Board positions are currently vacant, but we hope that will change in the not-too-distant future.

As I usually do at Board meetings, I want to make clear that the views expressed by the Board members during the meeting are their own and not necessarily Board positions. Our official positions can be found in our reports and letters which are available on the Board's website.

So now, onto a description of the Board and what we do. As many of you know, the Board is an independent federal agency in the Executive Branch; it's not part of the Department of Energy or any other federal department or agency. The Board was created in the 1987 amendments to the Nuclear Waste Policy Act to perform objective, on-going evaluation of the technical and scientific validity of DOE activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste.

The Board members are appointed by the President from a list of nominees submitted by the National Academy of Sciences. We're mandated by statute to report Board findings, conclusions, and recommendations both to Congress and the Secretary of Energy.

The Board provides objective technical and scientific information on a wide range of issues related to the management and disposal of spent nuclear fuel and high-level radioactive waste that we hope will be useful to policymakers in Congress and the Administration.

All of this information can be found on the Board's website: www.nwtrb.gov and that ... and also includes Board correspondence, reports, testimony, meeting materials, archived webcasts of our recent meetings.

If you'd like to know more about the Board, there's a two-page document summarizing the Board's mission and presenting a list of the Board members, and that can be found on the Board's website. And we have some hard copies of that on the document table outside the meeting today, along with some of our recent reports.

The meeting agenda and presentations have been posted on the Board's website and those are available for downloading. We'll have a public comment period at the end of each day's meeting. And those attending the meeting in person and wanting to provide oral comments are encouraged to sign the public comment register at the check-in desk near the entrance to the meeting room. Oral comments will be taken in the order in which they're signed in. When making a comment during the public comment period, please use the microphone that's available in front of the seating area. And please state your name and affiliation so that you'll be identified correctly in the meeting transcript.

I want to remind DOE staff and National Laboratory participants in the room that they should also use the microphone and identify themselves if they're called upon in the meeting to respond to a Board question.

All public comments can also be submitted during the meeting via the outlying meeting viewing platform. There should be a "Comment for the Record" form that you can access. If you're viewing the presentation in the full-screen mode, you can access the Comment for the Record section by pressing the escape key.

I'd like to note that this time for comments is intended for comments to be included as part of our official record, not a question-and-answer period or a question that might require a response. If you do have a question for any of the presenters and we're not able to get to questions during the meeting time, I'd encourage you to contact the presenters directly yourself.

A reminder of how to submit comments will be displayed during the break and comments we receive online during the meeting will be read by Staff Member Bret Leslie after the attendees' public comments, and those will be in the order that they're received.

Time for each public comment may be limited depending on the number of comments we receive, but the entirety of submitted comments will be included as part of the meeting record. Comments and any other written materials may also be submitted later by mail or email to the points of contact that are noted in the press release for this meeting and that's posted on our website. These will also become part of the meeting record and would be posted on the Board's website, along with the transcript of the meeting and the presentations you'll see today.

This workshop is being webcast live and is being recorded, so you'll see some cameras around the room. Depending on where you're sitting, you might be part of the webcast in the recording. The archived recording will be available on the Board's website by

September 21, 2022, and the transcript will be available by November 14, 2022.

So why did we organize this particular meeting? Well this meeting is part of the Board's continuing review of DOE activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste. Over the past several years, DOE has been conducting research and development efforts on non-site-specific disposal of radioactive waste. According to DOE, the objectives of these activities is to develop a sound technical basis for multiple geological disposal options in the United States and to provide necessary data and analyses to support decisions regarding its disposal research program. The multiple disposal options being investigated include: clay-based, which are also called argillaceous host rocks, as well as clay-based engineered barriers, and those are the topics of this meeting.

We're going to focus on laboratory and field-scale studies that are being used to support development of numerical models that represent the complex processes in a clay-based host rock and engineered barrier.

Our review will focus on DOE's understanding of the processes that impact barrier capability of clay-based host rocks and engineered barriers, and representation of these processes in DOE's numerical model is used to support the development of reference cases for repository performance analysis.

Today's meeting will start with opening statements by Bill Boyle from the DOE Office of Nuclear Energy, and then we'll hear from National Laboratory researchers who are conducting the work for DOE.

Chris Camphouse will give an overview of research and development activities related to clay-based repository and clay-based engineered barriers, including the objectives, research priorities and recent accomplishments.

Then we'll hear about the details of the numerical models developed to assess long-term integrity of clay-based host rock.

After a 15-minute break, starting at 2:30, Eastern Time, Ed Matteo will give an overview of the function and design aspects of the engineered barrier system in a clay-based host rock.

This will be followed by a presentation on experimental studies that focus on coupled processes that impact the barrier capability of bentonite, which is used in the engineered barrier system at high temperatures. Carlos Jove-Colon will present the first part of that, followed by Florie Caporuscio.

Then as I mentioned earlier, we'll have a public comment period and we will adjourn Day 1 of the meeting about 5 p.m., Eastern Time.

We'll resume our meeting tomorrow at noon, Eastern Time, starting with a presentation by Maria Victoria Villar from the Center for Energy, Environmental and Technological Research in Spain. She'll describe some of the laboratory and modeling studies that focus on understanding coupled processes in clay-based barriers.

Then Chris Neuzil will present some of the technical challenges in characterizing clay formations and identify some key technical gaps that need to be addressed to better understand clay behavior at the repository scale.

After a 20-minute break, starting at 2:05 p.m. tomorrow, LianGe Zheng will provide details regarding laboratory experiments, field tests and numerical modeling that focus on understanding coupled processes in bentonite buffers at high temperatures.

The last presentation of the meeting by Tara LaForce will describe how models related to clay-based ... clay-bearing host rocks and engineered barriers are integrated into the geologic disposal safety assessment framework that's going to be used for performance assessment.

A lot of effort went into planning this meeting and arranging the presentations. As noted in our press release, we're planning on having a ... we were planning on having a speaker from Switzerland. He was unable to join us because of the activities related to site selection of a repository in Switzerland.

So I want to thank our speakers for making presentations at the meeting today and especially those who participated in a Board fact-finding meeting that was held at Sandia National Laboratories on July 19th of this year. The fact-finding meeting presentations will also be available on the Board website.

Thanks to Board Members Tissa Illangasekare, who is my co-lead of ... on the Board for this meeting, and to the Board Staff, particularly Chandrika Manepally, Bobby Pabalan and Jo Jo Lee for putting the meeting together.

I'd like to acknowledge Sam Brinton, the Deputy Assistant Secretary for Spent Fuel and Waste Disposition, who is joining us for part of the meeting today in ... as part of their busy schedule.

So now, if you'll please mute your cell phones, let's begin with what I'm sure will be an interesting and productive meeting, and it's my pleasure to turn the podium over to William Boyle who'll get the meeting started.

BOYLE: Thank you, Dr. Bahr. So I just want to provide some opening remarks for these next two days. In the preparations leading up to today and tomorrow, there was a request from Board staff that could we be more consistent or ... in our use of terminology, which, just a casual glance at the titles of the talks shows we're anything but. We use clay-based, argillite, argillaceous. Carlos and Florie are probably the smartest. They have avoided naming any material; they just talk about high temperatures. So we didn't originate this issue, if you will, it goes back a long ways in geology, and I'll show you, by example, the word "clay." What does clay mean? Well one meaning of clay is it's a type ... a family of minerals, just like pyroxenes are or amphiboles or feldspars. Kaolinite and illite are two clays in the family of minerals called clays. So it's in part based upon ... to be a clay by that definition, it has to have a specific composition and structure.

There is a second definition of clay that actually has nothing whatsoever to do with composition and structure, and it's one that earth scientists and earth engineers use all the time. When the ... in plain English meaning, everybody knows what sand and gravel is. But scientists and engineers are much more specific about it, you know, they ... it ranges from boulders and cobbles with big pieces. Sand, silt, and the finest materials are called clay. No matter what their composition is, as long as it passes that last sieve, it's a clay, even if it's actually calcite or silica, right, it doesn't matter, it's a clay.

There's a third definition of clay. At least a third. And that's like the boom clay, it's a formation name. No matter what's in it, it's probably got clay in it, it's probably got silica and calcite and other things in it as well.

And so geologists and earth engineers have been doing this for a long time, it's usually clear from the context what people are talking about. And if it's not clear in any of the presentations, please do ask, we'll try and make it clear.

So I think that's pretty much the opening remarks, it's ... we'll try to be as clear as we can. If there's any confusion what we're talking about, just ask. Any questions of me?

BAHR: Are there any questions for Bill from the virtual participants? Any questions from Board members? Okay.

Well thanks, Bill, for a concise, opening statement.

And I think we'll just ... I'll sit here to announce the next speaker who's going to be Chris Camphouse. And Chris is going to provide us with an overview of the DOE Research and Development Efforts Related to clay-based repositories and clay-based engineered barriers, so ...

CAMPHOUSE: Okay. Thanks, Jean.

I went one too far. I'm Chris Camphouse. I'm happy to be here today in person to talk about the DOE program that Bill just talked about for clay-based repository and clay-based engineered barriers. I want to give a bit of a little preamble to say that this presentation's main focus and goal is to kind of whet your appetite for the more in-depth technical presentations that'll be coming later, just to give you a broad umbrella of how the different work packages fit together and what's under each one.

Here's the outline that we will ... of the different areas that we'll talk about today. So the argillite and engineered barrier system R&D control accounts; the different packages of work in this program are under-funded efforts called control accounts. I'll talk about those a little bit. Each one has a very significant international piece, so we'll spend a little time talking about international collaborations. And then we'll get into the meat of our multi-lab disposal R&D activities for argillite and engineered barrier system R&D crosscuts. Our activities are described in a five-year plan, so I'll discuss that, and then any conclusions at the end.

Okay. So to muddy the waters up a little more, no pun intended, from what Bill said, why do we care? You know, why are we looking at argillite at all? If this is the first time you've seen this, there are a lot of countries looking at argillite host rock for a geologic disposal repository. Why are they interested in argillite? Argillite has some very nice physical properties, it can be low ... have a low permeability so that materials that are solubilized have a hard time getting through that host rock. If it does get through, it takes a really long time to get anywhere.

Same with the diffusion coefficient, has a similar impact there. If any solubilized radionuclides do get into the rock, it tends to stick there. There's a high retention capacity and it's self-sealing. So if a repository is being activated and there's drifts and rooms that are being opened up and that the surrounding host rock is damaged, over time, argillite can self-heal. So you'll ... material that you put in this type of rock will tend to stay there, things that dissolve tend to not get anywhere, so argillite in those ... those characterizations, and that has some nice characteristics, so that's why a lot of countries and the U.S. are looking at it.

So to summarize there, these properties comprise an attractive natural barrier for geologic disposal.

So here's the way the control accounts under argillite host rock and engineered barriers are assembled. There's one big piece of work for argillite, there's another big piece of work for engineered barriers, and supporting both of those are international collaborations.

If we look on the left on this slide, the argillite and EBS R&D work packages are looking at fundamental science. One primary reason, and we'll see more about this later in my presentation, as well as presentations that come later, why we leverage international collaborations is because there are some very nice underground research labs in other countries that the DOE can use to further their program.

So we take these three things together, they feed the process model in parameter developments that are ultimately fed into the geologic disposal safety assessment.

So here are the way the disposal research control accounts are lined up. There are four, they're, well, kind of engineered barrier systems. Three of the host rock, and then an engineered barrier system work package that supports the three host rocks areas. And then international collaborations control account that we'll talk about as well, because we need to, because we have international work that supports each of those R&D work packages.

If you look more in-depth at those control accounts, there is argillite on the left, engineered barrier on the right. And you see for each ... for example, look at argillite. For argillite disposal R&D that Los Alamos leads, there's also an international piece. You look at the piece that Lawrence Berkeley leads, there's also an international piece. As you go down this list, for each one of the labs' work packages, there's an international piece that complements it. And the same with engineered barriers.

So the point from this slide is to emphasize that for the work the DOE is doing on argillite, international collaborations are very important. There's a very cohesive team of multi-laboratory contributors to these work packages. And the funding for the international piece isn't just a little tiny piece, it's on the same order of what's in the lab R&D packages for each specific activity. Because international collaborations are so important, let's talk about international collaborations for a minute. Why would we ... I've sort of already answered some of this ... but why would we want to look at international collaborations as we develop our argillite and engineered barrier research activities? There's a lot of global activity where they are looking at similar

R&D as what we are doing in the DOE program. So this helps us stay abreast of science advances and gain access to international datasets and experiments. And that last piece is really important.

I think, as I said, there are multiple underground research labs that we get to participate in. We get to look at their data, use it to validate models, use it to validate parameters. So we get to bring the international work experience and lessons learned into our program, into the DOE program, and push it forward.

There are a lot of similar needs in international programs as there are in the U.S. So we get to understand the research needs arising from critical (and sometimes surprising) issues related to "real" host rock sites.

Other benefits. A real nice benefit of this is that it helps build the next generation of workers. They get to go and see. A lot of times disposal research is sort of academic until you're walking in an underground research lab, and you see that host rock around you, or you see a big mock-up of an engineered barrier, and it becomes very real and then that gives a lot of motivation for why students would want to get involved in this. And we're seeing some good progress there. I'll talk more about that a little bit later.

And prioritization; it helps us prioritize which international activities we want to be involved in, which ones are looking at key aspects similar to what the DOE is, how we can leverage those activities and progress.

So as I mentioned, the disposal research activities are scoped out in a five-year plan; international collaboration is no different. The plan is broken up into near-term activities and far-term activities. Near-term means one to two years; far-term means further out than that, out to five years.

What are the near-term thrust areas that we want to look at for international? Continued participation with international R&D in underground research labs, that's very important. We're pursuing a more active role in conducting the experimental work in those labs and leading it. And we'll see more about that when we talk about some of the specific international things that we're involved in.

And contribute to building confidence for the geologic disposal system analysis and look at the international experience and lessons learned for pushing forward different processes like gas transport, diffusion, sealing elements, in situ corrosion.

What are the longer-term thrust topics? We want to utilize international activities, as I mentioned a minute ago, for workforce development in disposal science. Like I said, if you go into a ... an actual physical drift and see that host rock or an engineered barrier mock-up, that's very motivating, and it will help with eventually the best site for site selection and characterization.

So DECOVALEX. DECOVALEX is really one of the, the gemstones of the international program that supports argillite and engineered barrier systems and the disposal research control account even more generally.

So what happens in DECOVALEX? It model comparison against experiments. So teams from different nations that participate in this compare their models, compare their process. [It] models parameterizations and their numerical codes, data from different underground research labs are provided, and then these teams can use that data to see how ... how well their models captures the data from a real URL, underground research lab. There's a broad range of challenges that everyone works on and coordinates results and presents their findings. There's in-depth and regular discussion among national agencies and research teams.

So you see here ... it may be hard to see, but for example, for one underground research lab in Mont Terri in Switzerland, you see the countries involved on the bottom there: Germany, China, the U.S., Switzerland, France, Japan, South Korea and the U.S.A. So they're very multinational activities that are very, very good.

And there's an excellent publication record. Ph.D. students are trained as part of DECOVALEX and a successful long-term platform of information and knowledge exchange.

So going into a little bit more detail on

DECOVALEX for THM. What does THM mean? It's thermal-hydrological-mechanical. So, heat, water flow through the host rock, and then geomechanics, essentially, and how those processes are coupled.

So the last phase of DECOVALEX ended in 2019. What were the big activities and what were the results from there? Upscaling methods for THM processes were upscaled at ... using clay host rock at the Bure URL in France. And we ... they started with small-scale borehole heater tests, then expanded to a micro-tunnel heater test and then to an entire waste repository that was based on the French design. Andra led the five modeling teams from five different countries. The U.S. DOE was part of that team. The comparison between these modeling teams provide a confidence that upscaling methods for THM repository predictions are tractable and robust.

So from 2019 when we finished up that ... those DECOVALEX activities, then DECOVALEX was extended to 2023, with a goal of essentially taking what was at the end of 2019 and moving it forward with a full-scale experiment. So the experiments that are part of

DECOVALEX 2023 are THM modeling of the full-scale and placement experiment in Opalinus Clay at Mont Terri, and as well as a full-scale engineered barrier system experiment at Horonobe in Hokkaido, Northern Japan.

So moving away from international activities into the more lab-focused R&D program that are described in the five-year plan. For argillite, priority is given to engagements in the international activities, so DECOVALEX and HotBENT. We'll hear more about HotBENT in LianGe's presentation later, and others. Integration, experimental and modeling activities of barrier materials, interactions at higher temperatures for generic disposal concepts in argillite, and the use of novel approaches to evaluate barrier material, dynamic behavior and stability under repository conditions. So that's where the priorities are.

What are the near-term thrusts in the one-to-two-year period? We want to keep looking at the coupled thermal, hydrologic, mechanical and chemical processes that can affect repository performance. The way those are coupled makes that a difficult and challenging activity. We want to develop multi-fidelity approaches for integration of process models into the GDSA framework.

What are the longer-term thrusts for argillite? We want to simplify those coupled THMC process representations and continue to emphasize international collaborations with an emphasis on field testing and process understanding.

What activities are we involved in now for argillite? There's a big list of them here. I don't know that I need to go through all of them. Barrier material interactions at high temperature, PFLOTRAN, which is a very nice open-source flow and transport code that we use to model and implement these process models in. We want to model the long-term integrity of the argillite host rock barrier. We're also looking at machine-learning approaches and thermodynamic database development. Molecular dynamics simulations of water transport phenomena in smectite. Integrating coupled THC processes for radionuclide transported to GDSA, and then HotBENT, which is a very neat experiment that we'll hear more about later.

And as I said, here you see the way those activities are spread out across the control account, there's a piece for four of the national labs. So Los Alamos, Lawrence Berkeley, Lawrence Livermore and Sandia. And for each piece there's also the ... an international component that we've talked about.

What accomplishments have we done? So each year there's what's called a level 2 milestone report, that is produced as part of the argillite scope of work. This is a big, substantial document, typically hundreds of pages long, where a lot of the ... well I would say essentially all of the activities and results for the given year can be found in there.

And there's the cover of the title page there. You'll hear from people on this title page later in the meeting. For example, Carlos Jove-Colon is there, Florie Caporuscio is there and Jonny Rutqvist. So almost all the folks you'll hear from later have fingerprints on this report. It's talking about some of the accomplishments, specifically, developing a comprehensive suite of experiments focused on hydrothermal interactions of bentonite clay, steel materials and argillaceous wall rock.

Integration of characterization studies with thermodynamic modeling, including engineered barrier solids and host rock material.

Simulations of bentonite swelling and model development to look at the way the excavated damage zone, when there's a room or a drift that's been excavated, how that permeability changes after that.

And then thermo-hydrologic and chemical modeling of bentonite barrier fluid interactions with PFLOTRAN, the code I mentioned a minute ago.

And then thermodynamic database development that contains parameters for properties of aqueous, solids ... aqueous, solids, and gas species.

Okay. So I've uncovered argillite. Now we'll move into the engineered barrier system work package control account and the way it crosscuts with argillite. The activities for engineered barriers are also contained in the five-year plan. Priority is given to HotBENT Field Test and supporting complementary activities.

International activities that I talked about for DECOVALEX 2023 is a thermal hydrologic and mechanical modeling of validation activities using data from the ... the Swiss Mont Terri full-scale heater test experiment. And integration between hydrothermal experimental methods and cement-host media studies.

So that's the priority of activities in the engineered barrier system 5-year plan. The near-term thrust in the next 1- to 2-years, are analysis of thermal, mechanical, and chemical processes that influence performance of EBS design for each host media, and then understanding bentonite buffer drying and re-saturation processes. So those are the two things that we're looking at near term.

More further out, 3- to 5-years, we want to continue in our involvement in international collaboration on underground research lab studies for engineered barrier system performance and design materials, particularly cement.

Here's the way engineered barrier crosscuts with argillite: Fundamental process understanding, so shaft seal development and integrity. Degradation evolution, especially the way the permeability may change, depending on if that ... if it's in an excavated damage zone or not. Engineered materials and the disturbed rock zone, which is the same thing as excavated damage zone, it's just a different acronym that means the same thing.

Waste package materials and backfill/buffer. And there are lots of ... several processes that we're looking at to representing and understanding better chemo-mechanics of chemical and geomechanics, how those coupled process are represented, and THMC, that's the really the Holy Grail of what we want to get that was four processes coupled: it's a very hard problem, but we're making progress on it.

Multi-phase flow, multi-scale phenomenon. And as we saw for argillite, here when you look at that control account for engineered barrier, you see there's a piece for each of the three labs: so Los Alamos has a piece, Lawrence Berkeley has a piece, Sandia has a piece. It's a very cohesive team, and for each piece of work there's a corresponding international piece that the same lab is involved in. So Alamos has a piece; Berkeley has a piece and Sandia has a piece.

So the highlights of the EBS R&D accomplishments, we have model development for thermal, hydrologic and mechanical of the full-scale emplacement heater test at Mont Terri; extension of clay swelling thermodynamic modeling to higher electrolyte concentrations; reactive molecular simulations for modeling of bentonite radionuclide retention; and THMC evolution of bentonite via analysis of large-scale field experiments.

Now as I mentioned for the argillite control account, for engineered barriers there's also a big level two milestone that's produced every year. Here's the title page from it, it's also typically hundreds of pages long, and has many of the speakers that you'll hear from in this meeting are on the title page of that report. Ed Matteo, for example; Florie Caporuscio, who we'll hear from later; LianGe's on there. So we have representatives from all ... essentially all the labs that contributed to this report, there's someone here to help talk about what's in there.

And not only are we doing lab work and international collaborations, we also have a significant outreach to university partners which is contained under the Nuclear Energy University Program, NEUP. And since I made this slide not very long ago, a week or two ago, this is even outdated a little bit. There's been two more awards that we're getting ready to make for activities related to argillite and engineered barrier system.

But since 2020 there's been 14 NEUP Awards to teams investigating disposal aspects significant to argillite and engineered barriers. Doing a lot of fundamental research and development, backfill material advancements, high temperature effects, which is very important for what ... it feeds into a lot of things at the labs and the international partners are looking at. Database development and engineered barrier material.

So there you see the different logos from the universities. They really span across the country. We have a lot of good, a lot of good participants in that program. And I should, before I move from this slide, so each award that is made to NEUP, there's a person on the DOE side that serves as a technical point of contact for that, for that NEUP activity.

So for each one of these NEUP Awards, there's a lab, either from Berkeley, Sandia, Los Alamos or Livermore that serves as a technical point of contact to advise that work as it moves forward.

So conclusions, the argillite R&D activities are extensive in scale, everything from bench lab work, and we'll see some of that coming up later today, to underground research lab field testing. We'll also hear some more about that.

Collaborations are very extensive, everything from along the labs themselves to universities, to international partners.

The engineered barrier system R&D is very complementary to the R&D...done in the argillite control account, it's done to develop a technical understanding of the barrier argillite host rock system.

As I said in the ... one of the earlier slides, it’s sort of motivating how, how the goal of this work is to eventually feed into the geologic disposal safety assessment representations. The work done in these work packages provides the technical underpinnings for that.

And our in-depth milestone reports that contain detailed summaries of the R&D activities and results.

Here's a handful of references. And that's my last slide. Thank you.

BAHR: Thank you, Chris. We're well ahead of time, so we have plenty of time for questions. And do we have someone from online?

Steve Becker, who's online, so we'll get Steve to unmute himself and ask his question.

BECKER: This is Steven Becker, NWTRB Board Member. Thank you, Chris, for a very interesting presentation. Your discussion of international collaborations was very useful, and it called attention to a lot of important work. You noted the role of underground research labs in helping to attract a new generation of waste disposal scientists.

CAMPHOUSE: Mm-hmm.

BECKER: I was wondering, is there any work going on that explores the role of URLs and other research facilities in community outreach and public information? And along those lines you mentioned, at least briefly, that work was taking place toward developing a common set of best practices and lessons learned, vis-a-vis, risk communication, and could you tell us just a bit more about that effort as well?

CAMPHOUSE: Yeah. So one part that I meant to mention and different ... and didn't mention is that this year there's a new, kind of a pilot program for, for loss of a better word, that's ... that is actually focused on work force development for geologic disposal. There are two labs that have a work package related to that: one is Sandia, the other is Lawrence Berkeley. And the goal for that work package is to bring in, for example, undergraduate student interns that are interested in geologic disposal, but maybe don't know a lot about it, get them involved with lab personnel that do. So there are a handful of interns at Sandia, there's a handful of interns at Lawrence Berkeley. And we brought on the last summer, and have extended, I would say the majority of them, to year-round interns. So we're really bringing those in to participate with the lab staff and really get them involved in these activities.

There's also a post-doc that's been brought on at Lawrence Berkeley and we're still working on getting the post-doc brought on at Sandia. And we're ... well the plan is we're going to continue this program for workforce developments and expand it in the coming year.

So it's a really nice way, you know, there's not ... there's not an easy way for undergraduate interns and graduate interns to really get involved in geologic disposal science, and this is a good way to bring them into the labs, let them learn hands-on.

And the way that feeds into the underground research lab, what ... part of the question that you had, we are getting them more involved. That part of the program is still in its early stages. We want to start having a seminar ... a series of seminars that the students will be able to attend, the post-docs will be able to attend from these different things, but that's still sort of young.

Did that answer your question or did I ... do you have any follow-on questions?

BAHR: Steve?

BECKER: I ... yes?

BAHR: Steve, go ahead. You have a follow-on question?

BECKER: Yes. Can you hear me?

CAMPHOUSE: Mm-hmm.

BAHR: Yes. Go ahead, Steve.

BECKER: So yes, Chris, I would say that it was very useful to hear more about the role of ... the developing role of URLs and attracting that next generation of waste disposal scientists. What I was wondering is, is any thought being given to exploring the role of URLs and other research facilities in community outreach and in public information?

CAMPHOUSE: Yeah, I may pass that one on to Dr. Sassani. He's approaching the mic right now, I think.

BAHR: I think we have Dave Sassani ...

SASSANI: Yes.

BAHR: ... to answer that.

SASSANI: Dave Sassani, Sandia National Laboratories. Steve, good question. We have ... in leveraging the international work for the URLs, we have the efficiency in that in terms of the R&D value. In addition to that, in ... we have a ... an interesting underground system at WIPP, which we've been accessing for the Brine Availability Test in salt, and doing an underground research project there as part of the SFWST Campaign. And that is also being used by the international community, in particular, as one of the DECOVALEX programs now.

We have also been thinking about other possible sub-surface testing in unsaturated media that could be done to utilize facilities underground but haven't actually sited that at any location. Part of the discussion we're having in planning involves the very large expense of starting a new underground research laboratory versus taking advantage of existing facilities.

So that's in discussion currently. And I'm thinking that over the next year we'll probably move forward with a couple of aspects of that into at least the planning stages for the following fiscal year, but that's ... we are looking at those sorts of aspects.

BAHR: Dave, this is Jean. I think what Steve was asking about was not engaging with the scientific community but engaging with the broader public in terms of ... and this gets to perhaps the efforts that are going on in terms of consent-based siting for storage. But when you think about consent-based siting for a repository, the URLs have been, in internationally and other countries, have been a tremendous asset in some of those activities. Is there any current activity by DOE related to public engagement through the URLs?

SASSANI: Yes. Thank you, Jean, that is a good clarification. And I will say we have some discussions of that. We don't have anything ongoing in the R&D side of the house on that yet, but I will hand that over to my DOE counterparts to talk further about some of those aspects.

BECKER: Thanks, Dave.

BAHR: Is there anyone from DOE who wants ... it looks like Bill Boyle is coming to the microphone.

BOYLE: Yeah. William Boyle, DOE. I don't think the mic's on though. With respect to your clarification, Jean, I'll focus in on my experience with Yucca Mountain, which did have a very active program for letting people, even the public, go take tours of Yucca Mountain. And I think every country that has an underground research lab experiences the same thing. They get a lot of visitors at their URLs, both from the people Dave was talking about, the technical people, but also local people that live in the community and just get interested, and people from all over the world.

So I think that's a well-known phenomenon. If you build it, they will come. I can tell you that right now. And so even setting aside an explicit effort on consent-based siting, if you have a URL, it will act as this draw for people that want to see it, including the local community.

But more specifically, in a couple months, the Government of Japan and the Nuclear Energy Agency are going to have a workshop on the utilization of URLs in this joint fashion. For the people Dave was talking about, and for the purpose you clarified about. They want ... Japan and the NEA want to learn from the other countries that have had underground research labs. So

I hope that helps.

BAHR: Steve, do you have a follow-on from that?

BECKER: I think that got a good discussion going and I think maybe we can allow others to ask their questions. I think we certainly started the discussion of URLs and public information and community outreach. So thanks everybody.

BAHR: Do we have another question? I'll ... so Dr. Peddicord from the Board has a question.

PEDDICORD: Yes. Lee Peddicord. Thank you very much. Great introduction. Great discussion. I wanted to go kind of all the way back to one of your earlier slides where you're talking about some of the attributes of the material, and particularly that of it being self-sealing, which I think is very attractive.

And the question comes to my mind ... and of course Dr. Boyle pointed out there's a variety of these materials, there's a continuum. But in terms of a nominal or effective lifetimes for a repository to self-seal, if you will, what are those in terms of years, decades and so on, and how does that compare to other media like salt, which is very attractive as a self-sealing material as well, too?

CAMPHOUSE: Okay. I may pass that to ...

Do you want to take that, Carlos?

So I know for salt, the salt case I've been involved in pretty extensively, and they're looking at, for example, on the Waste Isolation Pilot Plant, when there's a damaged rock zone, they're looking at healing within 100, 200 years. Argillite, I think, is about the same time schedule.

JOVE-COLON: I'm happy to ...

CAMPHOUSE: Yeah.

JOVE-COLON: All right. In regards to the self-sealing properties ...

BAHR: Can you identify yourself first? Thanks.

JOVE-COLON: I'm sorry. Carlos Jove-Colon, Sandia National Labs. And with regards to the self-sealing properties, yes, it's something that is observed. Clay, for each rock, et cetera. Your question, I think, is more specific in terms of the order around time scales within tens, hundreds, thousands of years. We can see ... I mean, there are actually experiments at an URL, and I have to defer that to Jonny Rutqvist from Lawrence Berkeley that probably is more familiar with it, and they're doing full reactivation experiments, but ... in which they inject pore pressure into the ... an existing fault and they, they let it, you know, sit and observe what feedbacks on this. And apparently they can, you know, see that there is actually some effects of both: percolation of fluids, but also, let's see, something that represent self-sealing in the system, and that's expected, especially when you have fractured a rock, et cetera.

Now, with that said, how long it takes could be in the length of experiments: days, months, and it's something that actually had been observed for clay-rich material in lab scale experiments as well.

Short-term scales, but also applies to long-term scales. Does that answer the question?

PEDDICORD: Well one thinks about when they ... you had the situation with WIPP, where you were down for a couple of years or so.

CAMPHOUSE: A few years.

PEDDICORD: And really when you put back into those drifts, a lot of them really had started to move.

CAMPHOUSE: Right.

PEDDICORD: And moved towards self-sealing. So that was a fairly fast timeframe. And I'm assuming for the clays, it's quite a bit slower. And so I was kind of after a comparative number of values of say, salt and apparently sealing fairly quickly in the order of months, maybe years, as opposed to the clays, the argillite, which I'm assuming, having been in some of those underground research laboratories, looks like it's a much longer process.

CAMPHOUSE: Yeah.

PEDDICORD: But still effective.

CAMPHOUSE: Mm-hmm.

JOVE-COLON: This is Carlos Jove-Colon from Sandia National Labs. Yes, I agree with that. Creep processes, which are, you know, in terms of, you know, time, it's very ... it's an inherent property of the salt rock itself. And of course clay is a different rock, it deforms differently.

But yes, at the end of the day, the process is the same. Maybe it's slower. But again, there are argillites that are clay rock, and they're different kinds. Some of them are harder, indurated. Others are softer. And so the gamut of properties can change considerably, when it comes to time scale, which is specific to your question.

BAHR: It looks like we have someone else who is going to ... Jonny Rutqvist or Dave Sassani?

RUTQVIST: Yeah, we actually do some ...

BAHR: This is Jonny Rutqvist.

RUTQVIST: Yeah, this is Jonny Rutqvist, Lawrence Berkeley Lab. So I work doing model simulation, both in salt, host rocks, and also in clay-based, like argillite. Yeah, for salt, host rocks, you get very fast, I mean, sealing or the ... for example, of the excavation disturbed zone, especially if you're high, you know, higher temperature and it's accelerated. And also of the ... you have the crushed backfill which can actually consolidate within 20 year, or, I mean, it takes like 20 years, I mean, for a section, I think to consolidate, but ... at least.

And then in clay, it depends, of course, on the ... in argillite it depends on the clay contents, they vary, whether is there more brittle or more ductile. Shale, actually, I will show in the next presentation, some simulations with it.

And I will also say in like, at Mont Terri Underground Research Laboratory and they look at the excavation disturbed zone. If they have such a disturbed zone and then they have the bentonite, or they put pressure on that disturbed zone, you also have a swelling of the clay and then you can seal it very quickly, just by the pressure, because you have ... because it's a kind of a ductile shale.

And also, there is long-term creep processes that will kind of seal it while it's got more. So I think it depends very much on the type of shale you have. Mm-hmm. Thank you.

BAHR: Looks like Dave Sassani wants to add to that.

SASSANI: Yes. Dave Sassani, Sandia National Laboratories. Just to add really quickly, just to ... kind of summary item. And Bill has talked about this before. At ... in the Belgium system at Mol, and their URL, their clay is like modeling clay that you would go pick up at, you know, Home Depot and add a little water to, and it oozes. So you can see it oozing out of openings in the wall. And this is why their engineered barrier system isn't simply a bentonite backfill. But they're also looking at concrete for structural support for operational purposes to keep the drifts open. So that's on the one end, which is much more like the salt aspect.

But as you get into the more brittle varieties, which have better structural properties, you also have longer periods of time over which it occurs decades to hundreds of years. Where for some, you really get into the end member that's more like a crystalline system for like a slate that's fractured, and it ... well those fractures potentially will stay open, and you may have fractures occurring later. So you might have the end member that's more like a crystalline case with fast fracture pathways.

So the trick there is of course targeting a clay or an argillite that has those properties that allows you to operate reasonably and then put in your engineered barrier and close and seal, and then let it systematically seal over the hundreds to a thousand year timeframe.

BAHR: Thank you. This is Jean Bahr from the Board. A sort of broader question, one of the things that we were interested in is a summary of what ... what are the big things you've learned in terms of processes over perhaps the last decade? Both the U.S. and the international community, and the experiments in the underground research lab work that you ... you mentioned development of a lot of models. But what have been the process understanding advances that have been made in that time scale?

CAMPHOUSE: Okay. Yeah. So I can give a, kind of an overview answer, and then maybe funnel into more technical specifics, I'll have to hand it ...

But thermal is obviously very important. So HotBENT is looking at that. The BATS Test that was talked about already is looking at the impacts of heat on how brine stays available in the salt host rock.

BAHR: I'm asking about the argillite rocks.

What have you learned about thermal processes and what are some of the remaining gaps and knowledge that you're really trying to target?

CAMPHOUSE: Okay. Yeah, I'm going to have hand that to ... maybe Jonny.

RUTQVIST: This is Jonny Rutqvist again, Lawrence Berkeley Lab. So thermal processes, I think temperature we can predict pretty well in the ... most host rocks because it's dominated by conduction.

CAMPHOUSE: Mm-hmm.

RUTQVIST: And that's kind of a quite simple process to model if it ... if you have the right thermal conductivity. In shale you have the anisotropic thermal conductivity you have to consider. And so we usually see that we can predict temperature quite well; whereas, other processes, like pressure and mechanical responses are more difficult to do ... to deal with.

So I think ...

BAHR: So are there some sort of milestone things that you've learned in tackling that pressure prediction over the last ... or is it just a hard problem and you're still working on it? We heard, when we had our fact-finding meeting, that you've learned a lot over the last 10 years. So I'm trying to get a feeling for a little bit more specifics of things that you've learned that you can point to as improved understanding.

RUTQVIST: Yeah. I'll be presenting in the next presentation about the thermal effects and the ... I mean it'll be from this field experiment, large-scale field experiment, we sometimes ... we noticed that we sometimes, like looking at the pressure, we didn't ... couldn't capture exactly what happens, so we then tried to find what's the reason.

And especially, and the mechanical effects, so especially the mechanics, usually very difficult to measure because we ... sometimes you have a ... the measuring devices, I know the ... you have this kind of a mechanical extensometer, and some things like ... tried to measure the formation and the slip and things like that. So it's just difficult to measure. Nowadays you have ... start didn't have any fiberoptics, so I think we would get better measurements of the mechanics in the future, but ... so I think that's ... and we have seen that ... we saw that for the pressure evolution, that there might be some reason to be ... we see that it might be an overly long term, it's ... was more difficult to actually predict the pressure responses, and you know, we are trying to figure out the ... this is ongoing work to figure out that. Yeah, so ...

BAHR: Okay, thank you.

Are there questions from other Board members? Tissa.

ILLANGASEKARE: Yeah. Thank you for the talk. So you mentioned ... this may be a detail, but it will come up later in the DECOVALEX. You can model comparisons.

CAMPHOUSE: Mm-hmm.

ILLANGASEKARE: But I wonder, from most of these models, and some of knowing that there are so many parameters. So in your comparisons, do you still try to come up with a ... some sort of a calibration process?

CAMPHOUSE: Mm-hmm.

ILLANGASEKARE: So based on ... like, you know, calibration is sort of an art in some of these cases, that are science, so ... so we've got to make, like a process. Part of this comparison, this project, it's a way of coming up with some sort of a calibration processes when you come from different scales, but you also move inside of different scales.

CAMPHOUSE: Right, right. Yeah, that's a lot of what the DECOVALEX Project is about. So we'll take a set of data ... well not "we," but I'm on a multinational team ... we'll take a set of data generated from a real URL and then look at how well their parameters and models match that data.

And then, as you described it, begin to calibrate those implementations to see where, maybe the parameter specification isn't quite right or other ways they can refine and improve their model to capture that data better. That's the way I think ... what one of the big thrusts of DECOVALEX is.

ILLANGASEKARE: That's what I'm trying to say. So see if you can focus on those calibration issues.

CAMPHOUSE: Mm-hmm.

BAHR: And I'd like to welcome Paul Turinsky, who, finally arrived, and I think he has a question.

CAMPHOUSE: Okay.

TURINSKY: Took four tries to get a flight that actually made it. And I think I drove as many miles to and from the airport to my home. I could've been driving here directly from ... with my car to Washington.

But in asking these questions, know that I'm a nuclear engineer.

CAMPHOUSE: Okay.

TURINSKY: So okay. There's been some questions Tissa just asked on parameters. As you go across the different clay types, do you actually have to change the model forms themselves? In other words, not just the input to the code of some parameter value, but the actual form of the models.

CAMPHOUSE: Yeah, so at least the parameters will change, right, so the permeabilities and things and the porosities will be different. And the model implementations, I'm not as familiar with.

Maybe Dave might ...

BAHR: This is Jean Bahr. For example, for the mechanical properties and processes are likely to be quite different in a very plastic material compared to a more brittle one.

CAMPHOUSE: Mm-hmm.

SASSANI: Hi. This is Dave Sassani, Sandia National Laboratories. I'm going to speak to the generalities, and I'll leave the specifics of the mechanical to Jonny, perhaps, to speak to. But it's a great question. And we do want to capture those parameter ranges, and the uncertainty, the variability that go into the safety assessment models for those pieces that eventually would go into the safety assessment. But one of the aspects that is a large change across these is what we talked about just previously, which is in the clay systems you can go from rocks that are very mushy to malleable to brittle. And when you go into the brittle stage, you introduce potential fast fracture flow pathways into the clay, into the formation. And those are a conceptually different aspect. And those are the major pieces that we're looking to figure out what are those major conceptual pieces that change so we can put those into the process models, evaluate them there and see, okay, do these impact the safety assessment side, and do they need to be included explicitly.

The thermal mechanics are a good parameter value exercise and investigation. And I'll let Jonny perhaps talk to that range of parametrics.

TURINSKY: So it would seem like you would need a ... it would seem like you would almost need a model then for cracking.

SASSANI: Yes, absolutely.

CAMPHOUSE: Yeah.

SASSANI: Because you want to consider potential future crack formations in the formation, particularly due to the thermal mechanical coupling. In general, as I said, this range of behavior in clay repository systems, argillite systems, it takes you almost from the salt case all the way to the fractured crystalline system cases. And you would adjust your engineered barriers as needed.

In many cases, if you have a healing clay formation, the bentonite barrier plays less of a substantial role in the safety assessment because the rest of the clay system is there doing almost the same thing. But if you have fracture, fast fracture pathways that you're going to be expecting to be in your expected case for safety, you really want to have a very robust engineered barrier system performance then.

TURINSKY: All right. I have two other questions, Jean, if okay. How similar are clays that we're doing the experiments on versus the clays in the U.S. that we would consider as potential host rock sites?

CAMPHOUSE: Yeah. I'll have to give that to ... I don't know the answer to that one.

JOVE-COLON: This is Carlos Jove-Colon, Sandia National Labs. So your question is what is the similarity of the clays that actually were studied versus the one that we are really considering in putting a repository on.

TURINSKY: Mm-hmm.

JOVE-COLON: And well, that's kind of a siting question. And right now, we don't have a site or a siting process. So we don't ... for me it would be hard to answer, or probably I can give you a general answer about what the similarity will be. We're looking at an entire range. For example, in ... what I do is bentonite, which is more an engineered barrier system, and sometimes bentonites are different from the host rock clay. So I can talk, like, more about those.

In terms of the host rock, they're going to be different clay rocks with different levels of induration, you know, some of them are going to be more ductile or more brittle than others.

So at this point, we're looking at, you know, various types of rock, mainly from the international program perspective. But basically, they're going to be some differences, but unless we have some target sites, with a specific rock, it's kind of hard to answer that question.

TURINSKY: Okay, well I'll ask a different one. Are there host rocks in the United States that are very similar to the host rocks we're doing the experiments on?

JOVE-COLON: I would say in general there's some similarities. Again, we have, for example, you know, I will ... we forgot Chris Neuzil here in the audience, but he's more of the expert on the shale rock. But there are host rocks, either pure shale, and it's going to be ... some parts of that particular formation that are going to be very soft clay, I mean, but there are others in which they're going to be a more level of induration. They're harder and brittle, so it depends.

Yes, the answer to the question would be yes, we can cover ... and I think Ed Matteo, later, is going to give an idea of how these different shale formations, in terms of the brittle versus ductile look like in a, kind of an ternary diagram. So it gives you a general flavor of the range of clay host rocks, in terms of their properties, brittle versus ductile, here in the U.S.

TURINSKY: My last question is heterogeneities; it's something that I assume you really can't characterize in detail.

CAMPHOUSE: Mm-hmm.

TURINSKY: So I'm, again, talking host rock here. So how does the model account for something that I think is not totally known for a site when you're looking at it? What's the approach to that? Or maybe it's not important. I, you know, again, I'm a nuclear engineer.

CAMPHOUSE: So one thing that we work on is to characterize the uncertainty associated with each material that's included in the model. And that's where that piece would fit in from.

TURINSKY: Yeah.

CAMPHOUSE: So you'd have a range of material properties to try and capture those different material characteristics.

TURINSKY: Are the experiments large enough, though, to cover the, you know, a large enough area where they ... you wouldn't know it's necessarily there in detail.

CAMPHOUSE: Yeah, that's a good point.

TURINSKY: In other words, if you did the experiment and went into what looked like the same type of clays.

CAMPHOUSE: Mm-hmm.

TURINSKY: But, would you expect to see some differences if you did the experiment in different locations in that, you know, that mine?

CAMPHOUSE: Yeah, you would expect to see difference in different locations. That's what I was trying to get at with the way you would characterize the uncertainty in the parameters. You want to take ... at least for now, when we're doing a sort of a generic geologic implementation in the GDSA, you want to take information from different sides to build that uncertainty distribution. So you'd take, you know, if there are changes in the permeability or what have you, from different locations, you want to build that into the uncertainty.

BAHR: And Tissa has a comment.

ILLANGASEKARE: Yeah. Tissa Illangasekare. So I think just to follow up, but you mentioned, that part of the DECOVALEX research is upscaling, looking at upscaling issues. My assumption, the answer seems to be that even though you don't know exactly what the heterogeneity in the field is, but if you look at both from a material and practical point of view probably can make this issue of upscaling associated with heterogenous systems in your model uncertainty analysis in some way or another?

CAMPHOUSE: Mm-hmm.

ILLANGASEKARE: I think that's probably what ... maybe that may be what you are looking at when you look at upscaling, I assume.

CAMPHOUSE: Yeah. I agree.

BAHR: Are there questions from staff members? We're running a little ahead of schedule, so if there are any questions from other people who are here in the room, I'd welcome those. Or comments.

BOYLE: Yeah. William Boyle, DOE, not a question, but a comment. Back to Paul Turinsky's question.

But, you know, there's measurement error that can give a spread in results. And then there's, well, we measured a property here and then a hundred feet over. We measured ostensibly, the same property and got a different number.

Both of those effects are completely taken care of in the analysis of a site. It's, first of all, it's good science and good engineering to take into account the uncertainties.

But in the United States, it's also required by the Nuclear Regulatory Commission's regulation. We have to be aware that human knowledge is imperfect, and on top of that, Mother Nature is dealing from a very big deck and gives out different values sometimes for seemingly the same thing.

So all that's ... it's through a Monte Carlo simulation that we scientists and engineers try to encompass all these different types of uncertainty and make sense of it. So it ... we are aware of the uncertainties and the different types, and there are methods for trying to come to grips with those uncertainties.

BAHR: Other comments? Questions? Anything else from the virtual land?

LESLIE: No.

BAHR: Okay. Well then, I guess we can move on to our next speaker.

Thank you, Chris.

CAMPHOUSE: Thank you.

BAHR: Our next speaker is Jonny Rutqvist, who's going to be talking about modeling the long-term integrity of the argillite host rock barrier.

RUTQVIST: Okay. Thank you. So I'm going to talk about the long-term integrity of argillite host rock barrier. So the argillite host rock is one important barrier of the multi-barrier system as we can see here. Starting with the waste canister that should isolate the waste, and then you may have a bentonite buffer surrounding the waste canister in the tunnel that is placed maybe 500 meters deep in the bedrock.

So the bentonite buffer then should provide mechanical stability of the canister, retard the arrival of water and corrosive solutes to the canister; retain and retard migration of radionuclides if they're released from the canister.

And to this I also would add that it's very important, actually, for supporting over the excavation role, in the case of such ... in argillite, actually to ... this is important to sealing the excavation disturbed zone, so it's important to have the fully-developed swelling, stress, in the bentonite buffer to actually interact with the host rock as well.

And then you have the bedrock that should provide a stable chemical and mechanical environment and retard radionuclides if released.

So in this presentation, I will focus on coupled thermal, hydraulic and mechanical couplings of processes as you can see here, and how they can impact the barrier integrity. And at the end, how they impact the contaminant transport. So I'm not going to ... I'm not working on the contaminant transport, because that's taken care of in the performance assessment, the safety assessment or GDSA.

So I'm only focusing on the coupled processes and how they meet ... may impact the barrier system, permeability and so on. And that ... then that can be taken account in the performance assessment.

So in a nuclear waste disposal, the processes ... coupled processes tends to be thermally driven. So you see down there you have the temperature. So if you have a temperature change, you may go up to the mechanics through thermal expansion, and that will then change the stress and strain field in the host rock.

And if you change it too much, you may get failure of the rock, and that can then, in turn, change the permeability if it goes down to the hydraulics. And that could then impact the ... the barrier performance.

If you go from hydraulic to mechanics, we have a moisture swelling of the bentonite buffer. This is a very important process for the performance ... for the bentonite buffer function.

And then you have effective stress. So that means if you reduce ... if you increase the pore pressure ... you can change the stress field by changing the pore pressure and you can even get hydraulic fracturing that would not be so good. So this is complex coupled processes that we actually need to understand better to actually reduce the uncertainties in our prediction of the long-term behavior.

And this figure shows ... illustrate thermally driven coupled thermal hydromechanical processes in the near field over bentonite backfilled repository tunnel.

So you have in the center, you have the heat releasing waste canister. And then number one, you get the heating of the bentonite and the host rock.

And then close to the waste canister you have a number two drying and shrinkage of the bentonite because of evaporation. These are quite short-term processes happening in the first few 10 years or so.

At the same time, number three, you have the wetting and swelling by inflow from the surrounding host rock into this bentonite buffer that is initially partially saturated when they emplaced it.

And then, number four, you have thermal stress and deformations; that, in number five, can give a thermal mechanically induced changes in the permeability.

So number six added ... this is thermal pressurization, which is important for a low-permeability host rock such as clay or shale where you have actually thermal expansion of fluids that is trapped in this medium and that can increase the pressure quite high, so this can be quite important in this kind of a medium.

So as I say, this is maybe short-term here. It's sealed to 1,000 meters ... this is 1,000 years.

This is when you have a high temperature from the heat released from the canister. And then the question is what is the long-term impact of this? What is the impact on the bentonite buffer function?

Number two intact ... impact on the rock bentonite interface; impact on the excavation disturbed zone, and the impact on transport properties.

So ideally you would have a situation where you have got fully saturated the bentonite buffer within recent of time like 20 or 30 years or something like that.

And then you have a fully developed swelling stress and can actually tighten the ... all the interfaces and the host rock as much as possible.

This is ... illustrate actually a case where you ... if you have a breach of the barrier. So this is a case if you don't develop the swelling stress in the buffer and you get the support against the excavation roll and you may have fractures open. In this case, in the hypothetical case, you have a release of radionuclides that could provide some pathway for transportation of the radionuclides.

So this is something we want to avoid, and we want to learn more about this coupled processes to actually reduce the uncertainties to actually make sure that we do not ... that this will not occur.

Also seeing in model simulations actually that ... actually the large-scale coupled processes can be important. So thermally driven coupled thermal hydromechanical processes. And this means that this is illustrated. You have many, many emplacement tunnels here in the repository in a row. And you would heat up this whole region because of release of heat from the waste canisters. And this will also then ... could also induce thermal pressurization over a large area.

So this kind of increase in temperature and pore pressure would then change the stress field, and preferentially it would increase the stress field in horizontal direction because you have ... the rock is confined versus in the vertical direction, the stress field is determined by the ... actually by the weight of the overburdened rock and then the free-moving ground surface. So you would not change the vertical stress field much.

And ... but increasing the horizontal stress will then lead to increased shear stress in this area, and the question is whether you can actually induce shear activation if you have fractures. That may be more relevant in brittle shale. Or if you can induce hydraulic fracturing. If you ... if this kind of thermal pressurization is high enough to exceed the vertical stress, it would actually induce other rock fracture. So this is something we ... needs to be studied and avoided.

So to study these effects we have a modeling framework we have developed, so we are using the ... our TOUGH2 multiphase flow simulator developed at Berkeley Lab and linked it to a FLAC3D geomechanic simulator.

And so these are actually kind of two established codes with each thousands of users. So this also provides some confidence in this model simulations ... model simulators. And they are both developed and continuously applied in their respective fields. You have a large number of fluid and mechanical constitutive models that can be utilized.

So this was first developed and applied in the Yucca Mountain Project. Then we expanded it to bentonite and argillite host rocks, and also to salt host rocks and salt backfill by adding new capabilities to the existing model and framework. Basically adding new constitutive models ... mechanical constitutive models, or THM models, that can model this kind of behavior of the bentonite and salt and argillite; it has also been used by other teams internationally, this model framework.

For argillite host rock, so it's important to consider the anisotropic THM properties. So that means, for example, you have these bedding planes. And so you have different properties across the bedding and along the bedding.

For example, mechanical model considering those as weak planes to reduce shear strength in ... along the bedding. Higher thermal conductivity along the bedding, higher permeability along the bedding. So these are important to have into the models to actually model this accurately.

Then you have the excavation disturbed zone, so you can see on the picture there, down below there, these are measurements of permeability around the tunnel in Opalinus Clay. You can see that the permeability around ... adjacent to the tunnel is several orders of magnitude higher than the host rock. So this is due to creation of fractures. And those fractures are being unloaded against the free surface.

So could be after excavation, you have this kind of increase in permeability. Hopefully when you put in the bentonite and it swells, it will close those fractures and seal it off. It's also important to consider where you have brittle versus ductile sealing argillite because in the brittle shale you may have more permanent changes in permeability.

Models can be ... you know, you can do model simulations of these experiments and actually calibrate the model that could actually model this. So you can use like a stress-dependent permeability model, for example, to model these kind of effects. But could be site-specific. Could be different from, even in argillite, if you go from Opalinus Clay in Switzerland and the Bure site in France, there may be some difference, and also depending on the direction relative to the stress field ... local stress field and zone.

We have done a lot of model verification and validations over the years. So you can use, first of all, analytical solutions to do verification if they exist. There may be some thermal pore elasticity existing. You have laboratory experiments. These are often used to actually determine the properties of the material. Sometimes you use numerical modeling of the experiments to actually infer the underlying properties of these materials, including bentonite or shale.

Then we have the important, I think, the field experiments where we have ... through the DECOVALEX Project, we have access to this multi-year, multi-million dollar experiments ... experimental data. And these are very important because we model ... we can model the processes at the relevant scale of a tunnel or an emplacement tunnel.

And here it's listed the number of experiments. So we have data from two different shales here, or the Opalinus Clay at Mont Terri and Bure in

France, the COx claystone. So for the Mont Terri, we have the HE-D, which was the thermal pressurization. This was part of the DECOVALEX 2015, looking at the thermal pressurization in the host rock.

Then it's the HE-E, which was a half-scale bentonite argillite interaction. So you have the ... you have a tunnel, it was half-scaled sized tunnel with a heater inside. You heat up the rock and the bentonite and look at the THM responses.

Then there was a fault slip experiment where we injected ... where they injected the active way to the fault that crosses the Mont Terri and laboratory. You look at the permeability changes and the creation of the slip of the fault and how permeability changes and how it evolves over time. And then long-term sealing.

So this is something we modeled part of DECOVALEX 2019. Currently we are modeling the full-scale emplacement experiment. This is DECOVALEX 2023. This is the full-scale, large-scale experiment, a 50-meter-long tunnel; it's a full-scale of the Swiss concept of radio over emplacement over waste disposal.

And the heating, the heating has been going on for 5 ... more than 5 years, and it will go on for 15 to 20 years. So here we can get more longer-term data.

Then for the Bure, you have the COx claystone. DECOVALEX 2019 we looked at the borehole heater thermal pressurization experiment again. And then using, actually parameters determining ... calibrated from that experiment, we then go on to our bigger scale experiment, which was the ALC Micro-Tunnel Experiment. This is an experiment using a micro-tunnel ... I will present that more detail in the next slides ... where they actually using the concepts of the French nuclear waste disposal system to emplace nuclear waste.

Currently we are working on modeling a thermal fracturing experiments conducted. This is ... structurally increase the heat more and use a fracture and see the changes in the permeability.

So here we can use this for the validation and verification of the code for argillite to THM models and bentonite THM models. We can compare with data, but we can also compare with other codes within the DECOVALEX Project, as well as compared with other conceptual models that are used in the DECOVALEX Project because each team may use slightly different conception model of applied, you know, boundary conditions and so on. So this is good to actually ... actually, by this we can actually identify some uncertainties and quantify some uncertainties by doing sensitivity studies and looking at these processes.

So now I'm going on to the modeling of the ALC, the micro-tunnel experiment at the ... in claystone at the Bure Underground Research Laboratory in France. So this is a micro-tunnel that is heated so the micro-tunnel is open, 7 meters in diameter, 25 meters long. So this is the concept of a nuclear waste disposal in the French system. So they're going to emplace their nuclear waste in these kind of micro-tunnels. And it's a 4-year heating up to about 50 degrees C, if you go a few meters away from the heat source.

There are five DECOVALEX 2019 modeling teams who are using different models and the properties for this modeling was, as I said, it was taken from ... we did previously modeling a smaller Borehole Heater Test and did calibrate the model there. And they also used the data from laboratory scale measurements that was kind of validated against that small scale heater experiment. But here, then we took those parameters here and we did ... first did a blind prediction of what could happen for the temperature and pressure evolution for this case.

To the right you can see the model we used, and you can see the horizontal bedding orientation. So we have anisotropic properties here.

So now I'm going to show kind of movie of the evolution of the temperature and the pressure. So to the left you can see the ... you will see the evolution up to the left the contour, you will see a contour of the evolution of the temperature.

And to the right, you're going to see the evolution of the contour of the pressure. So here, this picture is taken just right after the excavation of the micro-tunnel. So you can see there is a blue ... if you look at the figure to the right, there's a blue color in the micro-tunnel. This just means that the pressure is very low there, it's more less atmospheric.

And then the blue area ... the blue contours on the edge of the ... with that, the model is actually two tunnels where you also have atmospheric pressure.

You can see also there is some reduced pressure there around where you have 25 meters. So that's actually a monitoring borehole that's ... that intersects into the system. And it's very important to consider those monitoring boreholes also in this modeling of this experiment because otherwise you cannot ... you cannot model the pressure evolution.

So you know, not only you need to model the rock itself, you actually sometimes need to model the experimental equipment or boreholes to actually do this. So this is not very easy.

Then you'll see, on the bottom you'll see, two graphs. You'll see the ... to the left you'll see the temperature evolution. And this is the black lines here. The black line is for one monitoring point: 1616-2 shown up there. You can see that the ... that's to start the heat there after 200 days and you get the increase in the temperature up to about 50 degrees.

And then you look to the right, you can see the pressure versus time in days.

So as soon as you turn on the heater, you turn on the heat source, you get the increase in pore pressure and this is caused by the thermal pressurization.

And then there is a peak, and then there's a reduction in pressure and this is because you have fluid diffusing against the ... towards the open borehole that is open at the atmospheric pressure.

So let's see. So what you're going to see now, you're going to see first the excavation of the tunnel, of the micro-tunnel. And then, after some time, you're going to see the start of the heating on the picture to the left, for the borehole, and then you're also going to see the thermal pressurization evolve in the one to the right.

So now you have ... here you have excavation, blue, and then after, and coming to 200 days, you got the heating starts, and then you get the thermal pressurization evolving in the figure to the right. And this is ... you can also see that close to the borehole, there is not much pressure changes because that's kept at atmospheric pressure, and you have flow into the borehole.

BHAR: This is Jean Bahr. What's the ... there's a little low-pressure zone that heads off perpendicular to the micro-tunnel.

RUTQVIST: So that's a monitoring borehole.

BAHR: Another one. Okay.

RUTQVIST: That has also ... you need to consider that in the model. It's a monitoring borehole that is open. It ... you have some fluid going into the borehole, so that impact the pressure, yes.

BAHR: Okay.

RUTQVIST: Okay. Now we can look in more detail about the comparison between the measurements and modeling team. So in this figure we show ... I show to the left, we can see results for one point that's located above the heat source; it's about four meters above the heat source, across the beddings.

And then to the right, you'll see another monitoring point that is located on the side of the heat source, it's about 2.5 meters away from the heat source.

So as you can see, the ... for the one to the right, you can see that the temperature increases more, up to 50 degrees versus the temperature for the one to the left increases to 40 degrees, so this increases to higher temperature on the right because it's closer to the monitoring point. And, you know, this shown the thermal conductivity is higher in the direction along the bedding.

So what's shown here, the black line is the measurements, and the different colored lines are the model predictions. So this shows, again, as I said, you can predict the thermal ... thermal temperature quite well, usually, because it's dominated by heat conduction. Doesn't matter if you have a very complex processes, maybe in the near field it's over pressure and so on. It's dominated by heat conduction. So if you have a correct thermal conductivity and the heat source ... model heat source, you can predict temperature evolution quite well.

So this is done using the thermal conductivity values that we had determined from a previous experiment, a nearby experiment.

PEDDICORD: Could you remind us the different models there, Andra is the French?

RUTQVIST: Oh, the different models?

PEDDICORD: Yeah. The sources or the organizations.

RUTQVIST: Yeah. So these are different modeling teams. So Andra is the French nuclear waste agency.

PEDDICORD: Yeah.

RUTQVIST: You are asking what kind of models they have?

PEDDICORD: No, no, no. What the organization and country is.

RUTQVIST: Oh, okay. NWMO is the Canadian Nuclear Waste Organization. Quintessa is a consultant from U.K., they work for the British, for the British Nuclear Waste Organization. UFZBGR; so BGR is the German Geological Survey, I think. And UFZ is a university in ...

PEDDICORD: Yeah. And then is it correct that in the left one, all the predictions are uniformly high for that position; and the right, they're uniformly low?

RUTQVIST: I think in both cases they are a little bit high, but ...

PEDDICORD: I mean, they're all close.

RUTQVIST: A little bit, but still I think it's good. I mean ...

PEDDICORD: Yeah.

TURINSKY: These are blind predictions.

RUTQVIST: Huh?

TURINSKY: These are blind predictions.

RUTQVIST: Yeah, it's a blind prediction. Yeah, yeah.

TURINSKY: Okay.

RUTQVIST: It's a blind prediction.

TURINSKY: And are there any ...

RUTQVIST: So if you ... if to ... yeah, if you slightly change the thermal conductivity, you can get it exactly on it. On the ... yeah.

TURINSKY: Okay. And the measurements; there's no error bars shown. Are they so small they're not worth showing?

RUTQVIST: Hmm? The ...

TURINSKY: The measurements have no error bars on the plots. Are they so small that ...

RUTQVIST: No. No, they're ... not in this case, yeah, yeah, yeah. Yeah, I mean, temperature can measure in a point and with a device I think ... yeah.

TURINSKY: Okay.

RUTQVIST: But ...

TURINSKY: So the difference is a real difference ...

RUTQVIST: But sometimes you can see some things happening in the ... not in these plots, but you can see that our measurements error for some reason.

TURINSKY: Okay. But the differences then between prediction and measurement are real differences because the measurement ...

RUTQVIST: Yeah.

TURINSKY: ... uncertainties are so small.

RUTQVIST: Yeah, yeah, yeah, yeah. I guess so, yeah.

TURINSKY: Yeah. I ...

BAHR: This is Jean Bahr. Did each team use the same thermal conductivity or is it ... are the differences because they used different values of thermal conductivity and ...

RUTQVIST: I think they used a slightly different thermal conductivity. Because we did the, as we said, we did the model calibration against another smaller-scaled field experiment in another part of the same mine. I mean, I don't know exactly how far away it was. And the different teams then came up with ... I mean, quite similar values, but not exactly the same values on the thermal conductivity.

BAHR: And this is Jean Bahr, again. Were there any significant differences in the underlying conceptual models or constitutive relations in these models or are they all basically based on the same heat conduction formula?

RUTQVIST: Yeah. The heat conduction models are very similar, the anisotropic. But how do you model the ... I mean, how do you model the heat source? How do you put in ... the borehole into your model and that can ... maybe some slightly differences in the ... in the models and ... how did they put boundary conditions. You have boundary conditions on the tunnels and things like that, so could be some differences, yeah.

Okay. I better continue. Okay. So in my opinion, it's a, I mean, good enough prediction. But when it comes to pressure, it's more complex. Here we can see some deviation between measured and modeled anisotropic pressure evolution.

So if you look to the right, you have the pressure versus time for the ... for the point located about four meters above, across the beddings. And you can see that the black line is the measurements. And you can see that most teams actually ... you get the pressure increase, roughly the correct peak pressure.

But then, over time, the ... the modelists predict that the pressure start to declining. We are seeing the measurement is kind of ... continues to increase with time. If you look to the plot to the right, so this is for the point located along the bedding, only 2.5 meters from the borehole. Here we can see that many teams, you predict the peak pressure quite well, around 7, 8, megapascals.

And then you have a pressure decline as a function of time that is also ... this kind of pressure decline is quite well predicted. And this is more ... it declines faster here because you are closer to the tunnel that is held at anisotropic pressure. And also the permeability and the horizontal direction is higher because it's along the bedding.

And then you can see some deviations if you look closer to the figure to the right, for example, the red line ... the red dotted line, yeah, they predict pressure increase when you get the heating, but the starting point was a little bit different.

So this is ... this starting point is affected by how you model the excavation of the tunnel. And then they put in the heaters. So what is really the permeability of the ... of this tunnel, I mean, and the ... how does it work. And then this micro-tunnel is connected to another tunnel, to the big, big tunnel. So you have a flow along this borehole. So it's very complicated, actually, to model this because you need not only to model a host rock, but also the experiment itself.

And then you measure the ... you measure this pore pressure in boreholes that are kind of packed off, maybe some section, and the ... maybe this is not completely considered in the model simulations where we maybe monitor the pore pressure in the point.

So what you can see also here, you can see the blue line. So this is actually after the fact that the one team, the Quintessa, did a model calibration to try to match the pressure results. And what they did, so they reduced the permeability of the host rock, especially across the bedding. So then you get better match to the pressure evolution on the figure to the left. You can see this continuous increase in pore pressure as a function of time.

Then they also had to ... in order to, at the same time, simulate the thing to the right, they had actually to include an excavation disturbed zone along the borehole that extends a little bit on the two sides. And this is something that they have seen it at the ... at this ... at the Bure that you have this kind of excavation disturbed zone that extends more in the horizontal direction.

So that's why by considering such effects, you may be able to better fit the values.

BAHR: This Jean Bahr. So that suggests to me that the calibration exercise that the Quintessa group did, revealed aspects of the system ...

RUTQVIST: Yeah.

BAHR: ... that were not accounted for in the other models.

RUTQVIST: Yes.

BAHR: And so would that suggest that maybe the other ... if the other models went back and included those same effects, they would be a better match?

RUTQVIST: They ...

BAHR: And do they ... do you do that when you see that there are ...

RUTQVIST: We ... yeah.

BAHR: ... characteristics of the site that haven't been adequately included?

RUTQVIST: Yeah, we did the ... some of the teams actually did the trial very different. Many different things to actually explain this. And this is by Quintessa, they succeeded to fit, at least in these points.

And so if other teams would use the permeability and put in this kind of excavation disturbed zone, you would ... we would get the better fit matched to the data also, yes.

ILLANGASEKARE: Tissa Illangasekare. So previous slide, so the conductivity ... generally in your conduction equation you can capture these nicely like you show earlier, but the spacing suggests that the grid refinement is needed to capture this layering, or that's what you are saying, that some ... if you don't capture the layers, that isotropy to grid refinement, the pressure cannot be matched or that's what you are saying or ... not like if ... so basically the Quintessa group, did they refine the grid ...

RUTQVIST: No.

ILLANGASEKARE: ... to make it smaller so they could capture the interfaces? How do you get ...

RUTQVIST: No, there are no change in the grid as far as I know. They just ... most importantly, you reduce the permeability. Then you would be able to match the ... that left thing better.

ILLANGASEKARE: The permeability of the whole ... not the permeability of individual cells, they are in the permeability of the whole system or ...

RUTQVIST: In the whole system. In the ... around this ...

ILLANGASEKARE: Oh, I see. Yeah.

RUTQVIST: Around this, in the whole model around this area. Yeah, yeah.

ILLANGASEKARE: I see. I see, so one whole ...

RUTQVIST: So the, as I said, the original permeability values was from another site calibrated.

ILLANGASEKARE: Yeah, yeah.

RUTQVIST: So this shows that you have some spatial variability in the permeability over this site.

ILLANGASEKARE: Yeah, yeah.

RUTQVIST: And this kind of ... so then we can identify this for ... and that kind of variability can then be applied to ... when you do a long-term prediction.

ILLANGASEKARE: Yeah. So that means that if you go to ... veer off of that variable, then you had to go to a smaller grid, so you are ... change the permeability value from grid to grid. Is that correct?

RUTQVIST: Sure, we can ... yeah. We can change the permeability at each grid point.

ILLANGASEKARE: Each grid point.

RUTQVIST: If you want. This was not done here ...

ILLANGASEKARE: Done in this instance.

RUTQVIST: ... because we didn't see ... I mean, that's another ... do we have any changes in permeability because of some stress changes here, but I ... I don't know. These are small stress changes; it's not we create the fracture or ... in this case.

ILLANGASEKARE: No. Yeah, I'll have a question later, follow up later. Thank you.

RUTQVIST: Mm-hmm.

TURINSKY: While we're talking about ... this is Turinsky. Was change in permeability, would you believe the value that they had to change it to, is it within the range of expected values?

RUTQVIST: If the change in permeability is

... how much to change the permeability?

TURINSKY: Yeah, yeah.

RUTQVIST: It's quite small, actually, because I mean, here you increase the pressure slightly from ... so I don't ... I forgot the number. Oh maybe, I think the ... okay, they reduced the permeability by one order of magnitude if I remember right. Which is ... yeah.

TURINSKY: Isn't that a large change?

RUTQVIST: I mean, the permeability in the rock can vary many, many orders of magnitude.

TURINSKY: Okay. I'm just wondering if there's like a ...

RUTQVIST: Especially if it got fractured ... a fractured rock or ...

TURINSKY: ... a fudge factor or ...

RUTQVIST: ... but for shale, of course, maybe shale that's a substantial reduction, yeah.

BAHR: I see that Dave Sassani has a comment.

SASSANI: Thank you, Jean. Dave Sassani, Sandia National Laboratories. I just wanted to add, because this is an excellent example of the question that Paul raised earlier regarding heterogeneity in the geologic field. And what's really a big takeaway from this, in my frame of mind is, what we try to focus on are not so much the random heterogeneities in the host rock. You want to do measurements in different locations and find what is the range of behavior of properties in the host rock so you can capture that range of variability in your modeling. But if it's random, you're not too concerned about it unless it's doing something at ... as a scaling issue. But generally, those random fluctuations, they average out when you go to bigger and bigger scales. Systematic heterogeneity in these systems is our focus in general, and this is a case of two of those.

One is the systematic variability of the thermal conductivity in the vertical versus the horizontal, i.e., the layering direction. And so you can see that effect here.

But the other is the introduced systematic variability of the boreholes, the monitoring boreholes, which are big impact, as well as the potential disturbed rock zone around the borehole itself. And those aspects, those are what we try to focus on because they introduced these conceptually different variabilities that are systematic in the system and can lead to the differences that we're observing.

So I think Jonny's discussion way more spot-on with the details of what's happening in those variabilities in the change in the heterogeneity and the variation and the thermal conductivity parametrics.

But it's really these conceptual aspects that we want to capture in the models to assess whether they're important to performance of the system over the geologic timeframe.

RUTQVIST: Okay. Yeah. So in this case as we ... you have pressure changes up to about 8 megapascals. So these are not enough to actually ... far from being able to create hydraulic fracturing because the least, depends on a stress field here is about ... I think it's about 15 megapascals or something like that. So neither would need much higher-pressure changes actually to cause fracturing. And this is something they are studying currently, where they try to heat more abruptly up to 100 degrees

C. And then actually to try to create a vertical fracture to see ... to see how such ... if such a fracture would be created when they increase the pore pressure about this principle stress ... these vertical stress, and whether this create a fracture and whether this fracture will be sealing over time, after the pressure is released.

So here they will put up ... temperatures up to 100 degrees C. And we have five DECOVALEX 2023 teams ... modeling teams and models. And we compare ... we will compare the temperature pressure, stress, I mean, stress between the modeling teams and the potential for fracturing. So this is ongoing. I will not present any results on this.

So the summary of the Bure argillite modeling, so the key parameters is the anisotropic thermal conductivity and permeability to predict the pressure, thermal and pressure responses.

And then important thermally, like fluid ... fluid thermal expansion is very ... it's very, very important. You need to consider that the ... correctly, the temperature depends on the fluid thermal expansion and, and you have solid thermal expansion of the medium. And then you have some storage properties, and tensile strength if you look ... going to look at the potential for tensile fracturing.

So temperature and pressure can be predicted, I think, more confidently than mechanical responses. Nor, I didn't even show any mechanical responses actually in this ALC experiment. They did, they had one measurement in that borehole you saw that was some ... in the figure were showing some pressure decline. They had some mechanical extensor meters there, but they just ... their measurements are not good enough to, to actually do ... reliable they said. So they ... we didn't do any comparison.

And the ... as I said, I think this maybe will improve in the future where, where the fiberoptics ... you can measure strain and maybe with better quality. Yeah. You ... we can study the ... and quantify this special variability of properties and this can then be applied in, in a long-term simulation to mounding predictions.

Then I want to go over to show some results for modeling the long-term repository behavior. This is the THM of the argillite barrier, and then the impact on the near-field EDZ THM responses, and finally, some new work on the impact of creep in the argillite barrier, here looking at the ductile and more brittle rock.

First looking at the ... this simulation showing ... illustrates the evolution of THM over kind of a repository scale. But this is conducted with a repetitive symmetric model looking at ... could represent the interior of a repository. You're looking ... we're looking at one repository tunnel. We have in place a heat-releasing waste package in place in the bentonite buffer that is initially saturated at 60 percent when we apply a heat source, which is shown there, below.

Looking on the temperature evolution up to the right, so you have temperature on the vertical axis and time, log time, on the horizontal axis. Looking at the red, the temperature ... temperature curve, you can see that you go up to about 91 degrees after about ... after about 50 years. And so this is where you reach the peak temperature and then it starts to decline because you have the decline in the heat power input.

Then you look at the purple line, in the temperature curve. You can see that temperature increases here to about 65 degrees after about ... happens after 1,000 or 2,000 years. This temperature is much lower, it happens ... this is the point, 10 meters away from the tunnel. It more less represents the overall temperature in the repository.

But as I will see ... show later, this peak temperature is actually more important from the THM viewpoint than the higher peak temperature in the other waste canister because this kind of temperature evolution, a peak temperature in the host rock actually dries the thermal mechanical and thermal pressurization effect in the repository.

Down below you can see the evolution of the liquid saturation as a function of time. And the important thing is when you do get full saturations. In this case, you have, after 25 years, you have some initially drying near the ... the waste package, but after 25 years, you get the full saturation, and this is when you have the full ... fully developed swelling stress and fully developed support of the excavation walls.

Then looking at the more coupled thermal ... THM effects, so up on the top, you'll see the pressure evolution, its function of time, and this is for one point within the bentonite buffer and one point 10 meters away from the repository tunnel. You can see the ... the pressure becomes similar and it's ... it is caused by thermal pressurization in the host rock. You reach a peak pressure after about 2,000 years. So this is when the peak temperature in the host rock was peaking.

So again, you'll see the importance of the repository temperature evolution here. And this is high pressure up to 8 megapascal, but not high enough to cause hydraulic fracturing.

Then you can see the stress evolution down below. This is the stress evolution, even in the buffer, in the point V2. You can see the upper graph, "Total stress" it says. That one is very well correlated with the pore pressure evolution on top. So this means that this kind of a stress evolution is driven by this thermal pressurization. So very important process, thermal pressurization here.

And then you see a graph that says, "Effective stress." So the effective stress is equal to the swelling stress in the buffer. So this is caused by the swelling, and you see that this peaks at 5 megapascals, after about 25 years. So this when you had full saturation in the buffer, and this provides the mechanical support to the excavation wall. Then it goes slightly down because of the cooling shrinkage.

So these are important to see this kind of a ... how this happens in time. You want to have the sufficient swelling in the bentonite buffer before you get the maximum thermal peak stress in the system, which is happening here. Maximum thermal peak stress, you have 1,000 years. The buffer is already fully saturated after 25 years.

BAHR: Jonny, this is Jean Bahr. Can you go back just a second?

RUTQVIST: Okay.

BAHR: So what's happening at 10,000, 20,000 years when it starts to repressurize and the total stress also starts to go back up?

RUTQVIST: Yeah. So what happens is first the pressure goes down because you have a cooling. You have a cooling and that cause kind of a negative thermal pressurization. So it actually goes down below the hydrostatic pressure at that depth because this is located at 500 meters depth.

So the hydrostatic water column pressure would be about 5 megapascal. So that's where it ... when it goes to the far end, you get to 5 megapascal because that's driven by the hydrostatic water column. But temporarily at 20,000 years it goes down below that, and that's because you have ... I think because you have kind of a ... you have a cooling on the system, you get the ... kind of a negative thermal pressurization. You get the thermal depressurization, I'm saying, yeah. Yeah. It's all ...

BAHR: So then it goes back up but it ... it's hard to tell ...

RUTQVIST: Yep.

BAHR: ... whether it's going back up and it's going to level out or is it ... continue to go back?

RUTQVIST: Yes, it's going to level out at 5 ... about 5 megapascals because that's the water column going from the ground surface. So ground surface you have a constant pressure, and then you have the weight of the water column going down to 500 meters depth. So the ... that will be 5 ... around 5 megapascals for water, which the density is 1,000 ... let's see ... yeah, 1,000 kilo per cubic meter, right?

BAHR: Thank you.

RUTQVIST: Yeah.

Yes. So you saw this, again, I'll come back to this again. You have this large-scale; you have this temperature evolution in the repository results in high pressure, shear stress, potential fracturing. So that may then become the limiting factor in the ... in the thermal management. So thermal management, often that they look at the temperature in the bentonite or a waste ... waste package sometimes have a limit of 100 degrees C, and sometimes maybe higher.

But actually this analysis shows that the temperature in the host rock may be could ... need also to be considered in the ... in that kind of thermal management. And to reduce that temperature in the host rock, you would have, for ... you could, for example, increase the distance between the tunnels or increase the distance between individual waste packages. That's a part of the thermal management and design.

And those kind of large-scale stress changes would also act on the tunnels. So if you're having increase in horizontal stress, you can get stress concentration on top of the tunnel that potentially could lead to mechanical changes, and because I said, these kind of things happen, peaks at 1,000 years after the emplacement. So that means that this kind of near-field effects could also happens.

But if you have developed the sufficient swelling stress, you get ... you will have the confinement against the tunnel wall structurally prevent such a failure; this have been shown in simulations. So it's important to have this supporting buffer stress at that time.

Finally, I'm going to this graphic. It's not come up as it should, but anyway.

So finally I'm going to show the ... some simulation results on the long-term creep and the ... so this graph shows the different kind of argillite or shales in the world, and you have a diagram where you look at the mineral content. You can see on the bottom, you can see the clay content. So going from zero to 100 percent if you go from the right to the left.

And looking at the dashed line, so this is the clay content about 30 percent. So this is ... has been sometimes used to actually distinguish between more brittle shale and more sealing shale. You can identify the Opalinus Clay. These are the purple squares. So these are far into the sealing shale category. We can also see the COx clay, those are the brown squares, those are little bit towards the middle, but still in the sealing shale.

And then if you look at the ... up. Up, you'll see the blue point, for example, up to the right. So that's Barnett shale. So this is one ... these are these kind of shales that are used for shale gas production. And this is because these kind of shales can actually be fractured and stimulated; whereas, those sealing shales may not be easily stimulated for ... for increasing the permeability for production.

Yeah. And you may also look at the ... some of the U.S. shales, the Pierre shale for example, those are circles down there, the purple are very, very, very high clay content. So it would be very sealing.

And then you have the ... those called the Paleozoic Eastern Interior U.S.A., those are a little bit more brittle, but still, they are in the category of kind of sealing shale.

So what I'm going ... what we ... we did some simulation, so long-term creep and we'll ... we used the data from where we have some crosses called Caney shale. So one white cross is within about 40 percent ... 40 percent clay content and another is outside, is about 20 percent clay content. So we ... there was some existing laboratory tests there on the creep and we implemented a creep model to actually simulate the creep behavior and we did the ... applied that to a repository simulation to see what happens. And because in the previous simulation, we did not include the creep, we used the elastoplastic model, but not with a time dependent.

So you can see what happens here. So if you look on the top, you have the one with the more brittle shale. This is ... shows a contour plot after about 10,000 years. It shows the shear stress in the system. And then you can see that you have shear stress developed close to the tunnel. And this could actually lead to damage that could be maybe permanent permeability increase in theory at least in this case. And then you look to the bottom, where you have the ... what we call sealing clay, 40 percent clay content.

So in this simulation, we show that the stress field becomes completely isotropic after 50 years. So this means that the ... no creep, the deformation tends to even to ... to even out any anisotropic stress would be by creep. Deviatoric creep you would make stress field completely isotropic over time. And this took about 50 years, and after that you even get some compaction of the tunnel and stress increase on the buffer, so you get completely uniform stress fields, so kind of a sealing.

So this actually shows ... this will be, I think, very beneficial for ... for the isolation will look more like a ... almost like a salt rock in terms of sealing. So high clay content, we have soft high creep and self-sealing.

To summarize, so repository coupled thermal-hydromechanical processes can have a significant impact on argillite barrier integrity.

If you are ... if you have too high thermal pressurization, you can get fracturing or you can get impact on the excavation disturbed zone and so on. So this is something we try to learn more, but the ... but this process is ... by modeling these kind of large-scale field experiments, we can reduce the uncertainties for this kind of a ... for modeling argillite, and that will be useful when we do the long-term prediction.

So field experiments in underground at the research laboratory have been developed and designed to study this phenomenon such as thermal pressurization and fracturing. So then modeling of these experiments provides confidence in the models applied when you predict these for a repository.

You can use these modeling these experiments by sensitivity studies. You can identify, you know, uncertainties and actually quantify it also. And that could be then applied in a ... for the long-term analysis you may use Monte Carlo simulations and so on.

So the type of argillite, whether it ductile or more brittle, could have a significant impact as I show. If you have a more a brittle rock, you may have a more ... if it's very brittle, you may have more like a granite fractures, right? And then the question is if that's ... if you have such a rock, that is more like a granite, maybe this kind of model I'm using now is not suitable. Maybe you will need kind of a discreet fracture model or something to model the ... at least for the migration and things like that, so ... if it's very brittle, but I didn't see any ... such a highly brittle rock.

So high, yeah, high temperature would cause a strong ... could cause stronger thermal pressurization, but could also accelerate creep if you have a clay-rich shale, because the creep processes are temperature-dependent. If you're high temperature, you're accelerated. So that's good, especially near their excavation walls.

And coupled THM modeling can be applied in the thermal management repository design for ... so if you perform such analyses, you may apply ... looking at different uncertain sensitivity studies and make sure that we are below the temperature changes that would cause unwanted mechanical changes in the repository.

And that's my last slide.

BAHR: Okay. Thank you very much.

Do we have any questions from the virtual?

How about Board members? Paul has one, and then I heard Lee and then Tissa.

TURINSKY: Okay. What about the weight of the package? How does that influence ...

RUTQVIST: The weight.

TURINSKY: Yeah, the actual weight of the package.

RUTQVIST: We have a, actually in the case of salt, we actually looked at the ... like about the potential for ... actually by creep, the waste package would move down, the long-term creep.

But in the ... it's, of course, it's included in model. We put in the weight of the waste package ...

TURINSKY: Yeah, because it's going to impact the stress field.

RUTQVIST: I mean, that ... that would be impact locally, below the waste canister in the bentonite buffer. You would have ... maybe some ... the weight, yeah, would impact.

TURINSKY: Yeah, so have you done ...

RUTQVIST: But it's still ... I think it's still small if you compare ... if it build up stress of 5 ... 5 megapascal, that's huge, I mean ...

TURINSKY: Yeah.

RUTQVIST: So ... .

TURINSKY: Yeah, I'm just thinking direct disposal in some of these very big packages.

RUTQVIST: Yeah. Oh, yeah. I mean, we ... yeah. I mean, that may be something one should look at

... also looking at the ... and maybe it has been looked at. A potential for the ... if you have a weight ... very high weight waste package in the bentonite, whether that could move down with ... over very long time with the creep.

TURINSKY: And ...

RUTQVIST: I know they looked at it. I know, I ...

TURINSKY: Yeah, I'm thinking also cracking.

RUTQVIST: Yeah, yeah.

TURINSKY: The onset of cracking.

RUTQVIST: Yeah.

PEDDICORD: Yes. Lee Peddicord from the Board. So on your very interesting ternary diagram, say slide 24, as an example, it's kind of intriguing. You know, we heard, I think from earlier, you know, the boom clays in Belgium are fairly plastic. I think Silly Putty was the description. Yet on this diagram, it's fairly close to the Opalinus Clay in Switzerland.

So there ... is it correct to say there are other factors that really go into determining the properties of these materials and suitability or behavior in a repository? I'm looking at the kind of light green boxes ...

RUTQVIST: Yeah.

PEDDICORD: ... and the pink boxes, and their relative proximity to each other in this diagram in the, in the lower left.

RUTQVIST: Yeah. Yeah. You are right. I ... I do not know what's the ... why this ... why the boom clay has a ... yeah.

PEDDICORD: Yeah.

RUTQVIST: Maybe you have a ...

BAHR: I think Dave Sassani might be able to ...

PEDDICORD: Dave is going to clear it up.

SASSANI: Dave Sassani, Sandia National Laboratories. I'll make no promises yet. Wait.

But the one aspect we didn't talk about ... we talked a bit about minerology of the clays, and then clays' particle sizes. Bill did a really nice introduction there. Another part are the ... the various minerals that are in the clay. But then there's also the geologic history of the material.

And so some of the ... and I can't speak to these specifically, but when I saw the boom clay in ... at Mol, it ... it's a ... it is a very unlithified clay; it's young, it hasn't been ... my guess it has not been buried very deeply or heated very much. And so it hasn't undergone any hydrothermal processes or any metamorphic processes. The more you heat it and cook it, just like putting it in the kiln, when we ... you know, you fire it. Well that happens at much lower temperatures, but over much longer time scales.

And so you're metamorphosing these things. You're lithifying them. The boom clay almost isn't lithified, you know, it's on its way there, maybe in another, you know, few million years if it gets buried, whatever. But it's a much younger version and a much less ... less driven version than some of these other rocks.

PEDDICORD: So there's kind of another axis here, history, that you would overlay on top of this.

SASSANI: Yes. Pressure temperature history.

PEDDICORD: Yeah.

SASSANI: Yeah.

PEDDICORD: And of course in our part of the world, the Eagle Ford, it's brittle, it's good for fracking, things like that.

SASSANI: Exactly. Yes.

PEDDICORD: Thank you.

ILLANGASEKARE: Yeah. So I want to sort of continue the earlier discussion. So this question has to do with the ... so when you are trying to ... seems like that you said the ... one of the models you were able to change the permeability and get it a little better.

RUTQVIST: Mm-hmm. Yeah.

ILLANGASEKARE: So then the explanation was that still not the spatial variability, but the average permeability, it was sensitive. So in your ... in the sensitive generality, does it show that in your model? Did you do a sensitive generality to show in priority that it is going to be sensitive to small changes in permeability?

RUTQVIST: Yes. Also ... so the thermal pressurization is very sensitive to permeability.

ILLANGASEKARE: I bet. Yeah, yeah.

RUTQVIST: So if you have a very high ... highly permeable rock, you'll not get any, any change in ... due to thermal.

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: So you have to ... to increase the pore pressure, and then at the same time you have the ... when you increase the pore pressure it tries to flow away.

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: So you would tend to decrease it, so it's ... yes, it's very sensitive to permeability.

BAHR: Following up on that, is ... are there are sort of ranges of sensitivity? Is it ... is there kind of a threshold at which it becomes important and then below that value of permeability it's all pretty much the same?

RUTQVIST: No. No.

BAHR: Or does it continue to change ...

RUTQVIST: Yeah. Yeah, I've done ... I didn't ... I didn't really understand. So you're ...

BAHR: So under ... at some range of permeability, you see almost no pressurization.

RUTQVIST: Yeah. Yeah.

BAHR: And then as you lower the permeability, you start to see it be quite sensitive to permeability.

RUTQVIST: Yeah.

BAHR: As permeability decreases. Is there some permeability lower limit of ... over which the pressurization is about the same, even if you continue to decrease permeability?

RUTQVIST: So you ... only if you have a impermeable rock you will get the thermal pressurization just by fluid thermal expansion. And then it would stay ... would stay there.

And if you have a very highly permeable rock, you cannot get ... it cannot ... you cannot get any thermal pressurization because the fluid will diffuse away from that area, so ...

BAHR: I'm thinking for some processes there's sort of a narrow range in which the behavior is very sensitive over some range of permeability, and outside of that range, either above or below, it may make less difference exactly what the permeability is.

RUTQVIST: I cannot define ... I don't think there is such a threshold. I mean, there is a ...

BAHR: It's a continuous ...

RUTQVIST: I mean, yeah. I mean, of course if you need to reach to a certain level of ... you need to have a certain level of low permeability. I mean, it should be where ... until you come to that limit you will see no ... very, very little thermal pressurization. But in this case, the rock is very low permeability and so ... yeah. So ...

BAHR: Thank you.

RUTQVIST: Yeah.

ILLANGASEKARE: So continuing. So eventually you had to go to large-scale simulation like you said. You had to look at much larger rock, like in Figure 22.

So the question is that when you go to that scale, then you had to deal with the ... more like the structured heterogeneity, not the random heterogeneity, but the heterogeneity of the ... of the larger-scale heterogeneity.

RUTQVIST: So when you go to the repository scale?

ILLANGASEKARE: Yeah, repository, okay.

RUTQVIST: Yeah. So then you go to the repository scale.

ILLANGASEKARE: Yeah.

RUTQVIST: Yes, it's important where you have the layer.

ILLANGASEKARE: Yeah.

RUTQVIST: But then you have ... next, what you may have a permeable layer on top.

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: And it's very important to include that.

ILLANGASEKARE: Yeah.

RUTQVIST: Because that actually helped to relieve the ... these pressure changes.

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: So if the shale layer where you are in is very thin, and then you have a permeable layer next to it.

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: You will not ... you will get much less thermal pressurization. So that ... that's important to include those ...

ILLANGASEKARE: Yeah. So then my question, and you ...

RUTQVIST: And you may also have stratigraphy within the ...

ILLANGASEKARE: Yeah. Yeah.

RUTQVIST: Within the formation itself.

ILLANGASEKARE: Yeah.

RUTQVIST: So that ... we did not include it. I mean, we didn't ... we don't include ... in this model we used homogenous anisotropic properties.

ILLANGASEKARE: Yeah, yeah. So that means that ... I'm thinking more in terms of upscaling theory. So if you ... you'll never be able to capture the heterogeneity at the larger scale. Any measurement, it has to be somewhat determined indirectly.

So if that is the case, there are two approaches: one needs to ... develop upscaling theories so that you can get your ... some effective parameters of that scale. Or, if you know exactly where these layers are, then you can do the grids itself to look at those transitions.

So yours seems like your approach is ... seems to be you are getting into more looking at the structured layer than going to the grids, doing this upscaling. Is that ... not upscaling ...

RUTQVIST: Yep. I'm sure at the real site, they will have ... we'll have to consider those layers and stratigraphy and ... yeah, where you have it.

ILLANGASEKARE: Yeah. So next question is that in this research I ... we heard that ... we talk about scaling, but you are looking at multi-scaling. But basically the work you are doing in these experiments is one scale, then the 3D larger scale. So I'm sort of proponent on the side of intermediate scale.

RUTQVIST: Mm-hmm.

ILLANGASEKARE: So there will be some testing you may need at the intermediate scale too, because you kind of jumped from that scale to the field scale. Do you have something either modeling or some experiment where you look at this scale?

RUTQVIST: So I mean, for ... in this particular case, we actually started with the properties determined at the lab scale, kind of.

ILLANGASEKARE: Yeah.

RUTQVIST: I mean ... or what they had, the ... what they had at their ... at that site in Bure and where they'll do a ... I've done a lot of large-scale tests.

ILLANGASEKARE: Yeah.

RUTQVIST: And then we apply those properties to that previous experiment.

ILLANGASEKARE: Yeah.

RUTQVIST: What I called HD experiment. So the ... I mean, like thermal conductivity is almost the same.

ILLANGASEKARE: Yeah, yeah. That talk ... okay, yeah.

RUTQVIST: And the ... yeah, and the permeability of the matrix.

ILLANGASEKARE: Yeah.

RUTQVIST: But maybe ... but then you have the bedding planes and things like that that impacts.

ILLANGASEKARE: Yeah.

RUTQVIST: That is important. I don't think it's ... I think it's maybe slightly easier to upscale in this kind of medium compared to a granite, for example, in granite.

ILLANGASEKARE: Yeah, yeah.

RUTQVIST: Where you have fractures and ...

ILLANGASEKARE: So your thinking is that when you upscale this problem, because we'll have enough computing power to get these layers into your model and the stratifications and isotropy into the model itself, without looking for parameters at that scale. You could have all the constitutive models aside, they will have ... going to be on a smaller ... smaller lab scale.

RUTQVIST: Yeah. But we did apply those constitutive models on this scale when ...

ILLANGASEKARE: Yeah.

RUTQVIST: Right. Yeah, so ...

ILLANGASEKARE: Well that, that scale constitutive ... yeah.

RUTQVIST: I mean we have our mechanical constitutive model, for example, or the other models for thermal conductivity and so on, but ...

ILLANGASEKARE: Yeah.

RUTQVIST: Yeah. We ...

ILLANGASEKARE: Yeah. The thermal conductor, I wouldn't worry. I'm more worried about flow and permeability.

RUTQVIST: Permeability.

ILLANGASEKARE: Yeah. Thermal conductor, I'm ...

RUTQVIST: I mean, in this case we used the simple anisotropic permeability model.

ILLANGASEKARE: Yeah, yeah.

RUTQVIST: And we have ... and that, maybe, it's difficult to ... yeah, I agree, maybe that's difficult to determine from large-scale tests for this.

ILLANGASEKARE: Yeah. So okay, yeah.

RUTQVIST: Even for this case, yeah.

ILLANGASEKARE: So these ... so my point I'm trying to make is that I think you need to have some intermediate scale between the field and the lab scale.

RUTQVIST: Yeah.

ILLANGASEKARE: Because some of the work I'm doing is showing ...

RUTQVIST: Yeah. Would that be a smaller scale field experiments? Or block scale experiments?

ILLANGASEKARE: Yeah, block scale experiment.

RUTQVIST: Yeah. Yeah, that would be used for the ... yeah, yeah.

ILLANGASEKARE: Block scale and meter ... meter scale.

RUTQVIST: Block scale experiments where we can control the ...

ILLANGASEKARE: Yeah. Yeah, yeah, yeah.

RUTQVIST: Control the block manipulations.

ILLANGASEKARE: Yeah. Yeah, that's my point.

RUTQVIST: Yeah.

ILLANGASEKARE: Thank you very much.

BAHR: Are there any questions from the staff? Yes, Chandrika.

MANEPALLY: Chandrika Manepally, Board Staff. Jonny, thank you for the nice presentation. I have a couple of questions for you. First one was on Slide 8 you indicated that you started working on improving your numerical that is the TOUGHFLAC model of ... since 2011.

So I just want you to take a look back on the history since 2011. All there improvements that you have made, and all they tasks that you've been involved with in DECOVALEX, what do you think are like the main accomplishments? Like you are able to better predict your pore pressures.

RUTQVIST: Yeah.

MANEPALLY: And if so, I ... so can you kind of just give us a gist of all the activities in a historical perspective?

RUTQVIST: Sure. So the first thing we did ... so I have ... I mean, so the first thing we did was actually to develop the bentonite model. So before we have a just very simple modeling of the swelling using just as the function of saturation and no real ... so then we implemented the ... we implemented the ... we started with different models, the straight surface model, and also the Barcelona basic model.

MANEPALLY: Mm-hmm.

RUTQVIST: So that's a model that can model the bentonite behavior to consider the effects of a ... when you have a ... for example, when you have a dry bentonite, it's very stiff. And, and it's also high ... strength is very high, you know, in the clay, like, stiff, then the dry is very high. Very ... it just becomes wet; it becomes very soft and ... and weak.

So this is considered that ... this can be considered in that basic Barcelona model. So that, that we ... we did a lot for ... and modeling of the bentonite behavior and even got to more complicated model where we have the Barcelona expansive model.

MANEPALLY: Mm-hmm.

RUTQVIST: Where they consider dual structures in the bentonite, and that model actually has a lot of parameters, like, too many parameters.

MANEPALLY: Yes.

RUTQVIST: So it's very ... yeah.

MANEPALLY: So I guess my point was, what is that improving? You're able to better predict your temperatures, you're more closer to what was measured by what ... all your pore pressures, you were off before by 30 percent.

RUTQVIST: Yeah.

MANEPALLY: Now because you implemented all these improvements in your numerical code, now you are much more closer to the answer. So that is the kind of feel that I'm trying to get at, like ...

RUTQVIST: Yeah, yeah.

MANEPALLY: And this goes to the one that Jean was asking in the morning.

RUTQVIST: Mm-hmm.

MANEPALLY: You've been working on this area for almost 11 years, 12 years now at '22, 2022.

RUTQVIST: Yeah.

MANEPALLY: So what are the ... what are the key insights or key improvements that you've made?

RUTQVIST: Yeah. The bentonite model, this ... well using that we could fit the laboratory data much better. Some of the data. And for the argillite, I mean, argillite model we ... for the ... for the, I mean, we ... when we started in this, within our time on isotropic thermal conductivity model, and anisotropic permeability, even in the tough to code, this is a finite volume model, and it's not easy actually to model anisotropic behavior. So we had to actually ... sometimes we used the ... we had to orient the mesh along the beddings to actually model that correctly.

So this is something, I mean, without ... including these kind of features into the model, we could not ... we could not match any data on temperature or pore pressure, actually, without including the anisotropic effects on temperature and ... for thermal and ... and the permeability.

And then for the mechanical models, we are using actually an existing constitutive model in FLAC3D for the ... for the mechanical and isotropy that is kind of developed for ... orthotropic model developed for modeling of this kind of layer formations.

And it's ... that one, yeah, that one we use as a ... it's not ... that's for the mechanical changes and we don't ... we don't actually have a lot of good mechanical data.

MANEPALLY: Right.

RUTQVIST: So that's something that we want ... I want to have more mechanical data, that's my main point.

MANEPALLY: Right.

RUTQVIST: And that's also ... okay, now we look at the temperature and pressure, but then what is the consequences on the stress field?

MANEPALLY: Mm-hmm.

RUTQVIST: So ... we want to have a ... if we can measure the changes in the stress field, and if you can measure the deformations more accurately and over longer term. So that's also important, too, if you want to look at the time dependent effects, like the mechanical creep behavior and so on.

So these are the thing that always ... throughout. Also, I remember in the Yucca Mountain Project, the mechanical measurements were ... had some problems.

MANEPALLY: Right. So this lack of geomechanically data is because of lack of development in sensors? Or it's just an issue about these tests are not able to, you know, have as many thermocouples as geomechanical sensors? What is the issue about getting this data?

RUTQVIST: I think, yeah, I think this maybe sensors. So temperature you can measure in a point very easily. Pore pressure you have to maybe back off a section and that's complicated, but ... and then mechanics. Sometimes they use these in a borehole extension meter, maybe they're in there with anchors and then sometimes these anchors slip.

MANEPALLY: Mm-hmm.

RUTQVIST: And then the high temperature is ... they're all impacted by high temperature, also. So sometimes they don't get reliable measurements. They, also when they try to measure stress in the bentonite buffer, sometimes they ... they don't get very good data of the swelling stress.

MANEPALLY: Okay.

RUTQVIST: So that's something from my viewpoint I would like to have more data on. On the mechanical response. So ... but now with the fiberoptics, I think that we are going to get better data because then they can measure, you know, very detailed, the strain, and should be some improvement there, I think.

MANEPALLY: Okay. Thank you.

RUTQVIST: I'm not an expert in measurement, by the way, so ...

MANEPALLY: No, that's okay.

BAHR: Okay. Well we're at time for a break now. So thank you, Jonny.

And if other people have questions for him, maybe they can catch him during the break. And we will reconvene at 2:45, Eastern Time. So that's about 12 minutes from now.

(Session break.)

BAHR: Welcome back from our break. And before the break we were focusing on the argillite host rock itself, and now, we're going to be ... the next two talks are going to look at the engineered barriers that might be constructed from bentonite in ... and how they function in an argillite host rock setting.

And so the first speaker is Ed Matteo from Sandia National Labs, and I'll turn it over to him.

MATTEO: Thank you, Jean. I'm Ed Matteo, I'm the engineered barrier systems work package manager and technical lead at Sandia National Labs. And I'm going to talk today about ... give an overview of the engineered barrier system, both discussing the function and design aspects for an argillite host rock.

As we've discussed at length, I'd say, or at least touched on this morning, there's ... argillites are a broad rock category, and we've had some discussion about sealing versus brittle, and Jonny went through a nice detail of this ternary diagram, which illustrates where we draw that dividing line at the one third; that dash line that we see in the figure.

I don't think I need to add too much to this other than to say that a lot of the host rocks that we talk about fall into the sealing category, which I think was already mentioned.

In terms of, from a design standpoint, we could say that the ... in argillites, especially in the sealing types, we place a high reliance on the natural system, because it's a diffusion-dominated system, and also because it's reducing, we expect slow migration of the radionuclides.

That said, because the natural system retards migration so much, we do have a scenario where we have effective transport, say, via the EDZ or some other failure in the seal system itself.

So, the EBS design will be a function both of the inventory and the geologic setting. A key parameter of the inventory will be the thermal output. This has a significant impact on the layout of the repository, and it's typically one of the earlier parameters that we want to get a handle on in the preliminary design phase.

The geologic setting will determine the chemical and mechanical environment that we're working in, and there's several engineering decisions that need to be made in the design process. One is the constructability, how will we construct the repository, can we construct the repository, and then the emplacement, as I mentioned, is a critical aspect taking into account the thermal output of the waste packages; it will determine the spacing.

And then we have other questions about emplacement where we use a vertical versus horizontal emplacement, and then what materials will we use. In an argillite repository, there are questions like, well, will we use pelletized or compacted bentonite, or some sort of prefabricated engineered barrier.

And then there's material selection. What will we select for the overpack? If we're in a sealing shale, for example, we ... we wouldn't necessarily need a corrosion allowance material, we would just go with what we had. But if we were in a brittle shale, as was discussed, it would ... which would look more like a crystalline repository, we might be employing the use of a corrosion allowance material.

And then there's all these operational safety aspects to the EBS, like ground support to keep the excavations open.

This is just to give you an idea of the multitude of design options we have to choose from. I don't need to go through each one of these items, but it's something you could look at, at a later time if you wanted, or just pick out some key points here of, we have the waste canister design decisions there, waste package, including the overpack. Do we have a long containment lifetime, as would be in a brittle shale or are we looking at a short containment lifetime where we would have a different set of material selection. And then of course as I mentioned, the emplacement mode and other elements.

So, the argillite type will have a big impact on the design. So we discussed the sealing versus brittle. Another thing that also came up in the questions was the mechanical properties, and that is a function of the degree of induration, and I think this also came up, the burial history of the formation.

And so, you know, you could have two sealing shales, and I think this also came up, the Callovo-Oxfordian or the Opalinus and the Boom clay are all ... would all fall into that part of the ternary diagram, what we would call sealing clays, but they have very different mechanical properties, and as such, the designs are drastically different.

So, in the ... the French concept, for example, which you have a more indurated, competent clay, you ... you would use a bentonite buffer, and as Jonny explained really well, how it provides mechanical stability over the long term. But in the Belgian concept, where you're in a Boom clay, you actually have a cementitious buffer, you could say, the super container concept, where you don't employ bentonite clay, but rather you need some ... you need a buffer with more mechanical integrity to account for the very plastic nature of that clay.

Another thing, we talked a little bit about heterogeneity. So even within the Callovo-Oxfordian, for example, you know, the upper COx has much different mechanical properties, or different mechanical properties, so there is that ... there is vertical heterogeneity in that formation. And an example of this is, you know, in the design, the shotcrete would be removed in the upper COx because you don't need it for the long-term mechanical integrity, whereas in the lower sections, it would be left in place.

So now I'm going to go through all of the EBS system components. We have the waste form, we have the waste canister and overpack, buffer/backfill, drift seals, which could be the access seals and the emplacement seals, shaft seals. And these together create what we call the seal system, or the geotechnical seals. And then we have the ground support, which could be the liner, the rock bolts, et cetera. And then we have the EDZ or the DRZ.

And you know, an important thing to note here is that the seal system or the geotechnical seals have to take into account the existence and the interplay that could occur between the EBS and the EDZ. This is just a blow-up picture of what I just said in words, it just illustrates the different components of the engineered barrier system, and it also has some of the natural system on it. And then, in the dash line, you see the disturbed rock zone, or the DRZ.

So, the EDZ explicitly needs to be taken into account in the design. And typically in these drift seal closures you'll have these breakouts or water stops, as they're sometimes called, and this is illustrated here.

You'll have varying elements, you'll have a shock; for example, you could have a shotcrete containment plug, and then a clay swelling core within the closure, but you have these breakout areas which are pointed out in this figure, and those account for that excavation damage zone.

Jonny described this really well, so I don't need to go into a lot of detail on it, but you know, these would ... these design elements could help arrest any advective flow pathways that might develop along that EDZ. And of course, in a sealing shale, of course we would expect that those defects, that damaged zone, would heal over time.

The shaft seal also needs to take into account the EDZ and will have different breakout zones and water stops incorporated into the design. So here we have what is considered sort of the state of the art for shaft seal design, which is the WIPP Shaft Seal Design; it's a multi-barrier concept, and it has alternating layers. You can have cementitious plugs, compacted swelling clays, some salt backfill, and then you have these asphalt water stops incorporated into it. And then, again, it has to account for the EDZ in the shaft seal as well.

Cement liners. So, these primarily will provide ground support, especially in a weaker system where you have a less competent rock. So in a crystalline formation, for example, you would not typically need a cement liner, but in most argillites, you do.

So one problematic aspect of having this design feature are some of the unknowns that get introduced. So cementitious materials, we don't have as much confidence in their ... you know, long term, or on the geologic scale of their long-term behavior. These are materials that can degrade and crack and most importantly, allow for the development of preferential flow pathways, just adjacent to the EDZ, or even worse, work with the EDZ to create some kind of preferential flow pathway.

We are also talking about an environment where there's a lot of heat generated from the waste package. So we expect, and I think Jonny showed this pretty well, you know, as long as that thermal period is lasting, there's going to be an intense dry-out in the near-field environment in the buffer and surrounding rock, well into the EDZ and beyond.

And cements are normally saturated materials, so we're not exactly sure how they will behave under those conditions as well. One ... one remedy for this concern would be fiber reinforcement, and these could be glass fibers or metal fibers, or some other material that would arrest the crack development.

There's also a chemical effect that we would be concerned about with these materials. In the Yucca Mountain, this arose. The alkalinity that would be contributed to the system from the cement matrix itself, there's a lot of concern what this would do to colloid formation and transport of radionuclides.

So one of the developments during Yucca Mountain was these low pH cements, which, really are not low pH at all, they're just lower pH cement. In actuality, they ... you know, a typical cement would have a pore solution above pH 13, and these low, low pH cements would be in the neighborhood of 10 to 11.

One other issue related to these cementitious materials would be the sourcing and/or variability of the materials. We see already a push for a low CO2 material, especially cement being a rather carbon intense material. So it's not clear if the sourcing that's available today would be available at some future date.

This was a big lesson learned during WIPP when they had developed an expansive concrete for grouting and plugging, only to find that the company that produced the expansive agent went out of business.

Moving onto the buffer and backfill. As I mentioned, these could be bentonite, or as in the Belgian concept, cement. And Jonny kind of covered this, but I can kind of reiterate it now, can extend the waste package lifetime, and can ... and can secure the package in emplacement, which should help couple the thermal conductivity to ... to the surrounding rock.

And in the case of bentonite, this is a functional barrier, right, that will swell to fill any gaps, and will retain the cationic species. And lastly, it can deter microbial activity, which could have some unwanted contribution to the near-field geochemistry.

So the ... if we're talking about a bentonite buffer would be self-healing, similar properties to the host medium, assuming that's a sealing clay. It has a proven durability and robustness in a geologic environment, right, we have clay formations that are hundreds of millions of years old. We know that they're very stable over the very long-time scale that we're talking about in a repository.

Very low permeability, resulting in a diffusion-dominated system. Of course, there are concerns of fracture or channeling, in a more brittle case where we talked about it may resemble more of a crystalline, and then you have to worry about things like erosion possibly also.

And swelling behavior, retention of cationic radionuclides, and then there's, as I mentioned, some crosscuts between argillite and crystalline because of some of these similar issues between bentonite in both cases.

So one area of particular interest are high temperature effects, and we have a range of lab- and field-scale tests. We're going to hear, I believe tomorrow, from LianGe about the HotBent test to characterize the behavior.

Typically, there's a limit of 100 degrees C in a clay ... in a bentonite buffer, because then we'd go over the boiling temperature for water. And so, there are a lot of tests to see what ... what would happen if we did exceed those temperatures. What would be the effect on the swelling properties, for example, or what would be the effect on the radionuclide retention?

Another area that is a fertile area to explore is, can we tune the thermal conductivity of the bentonite buffer? Are there materials that could be added? Graphite is one that has been suggested to improve the thermal conductivity, and more efficiently conduct heat away from the waste package and reduce the peak temperature of the waste package surface and beyond.

And then there's a lot of interest in using pelletized bentonite in the buffer because of the ease of emplacement. It's quite an involved operation to use compacted bentonite to fit the pieces together, so to speak, in an engineering sense, and when we have thousands of waste packages using some sort of augured system, which has a little bit more automation to the emplacement, it's quite an attractive option.

So that brings up the question of homogenization. So this is ... how does that ... over time, how do the spaces or intricacies between the blocks or the pellets, how do they come back together? What's the rate, and how well do they ... do they heal?

And there are several crosscuts with the NEUP Program, the Nuclear Energy University Partnerships. On the right of the slide here, we have some results from one of these projects in the Lab of Marcelo Sanchez at Texas A&M, where we're looking at the effects of temperature on swelling pressure, and we're actually first ... first off, we're looking at the swelling pressure of compacted bentonite versus pelletized mix. So we have swelling pressure on the Y-axis, and then time, and you can see the evolution over time.

In the lower figure, looking at thermal conductivity of a pure pelletized mixture, and then a mixture that is ... has graphite added to it to try and improve the thermal conductivity, which apparently, it works pretty well. There are some pictures of the apparatuses here.

Dry-out and re-saturation damage is another emerging area. What is going to happen to the bentonite during the thermal period? We expect that cracks could form, and understanding the extent and the rate at which this happens, and how these cracks behave in the re-saturation period, could be an important investigation.

And also, gas flow through bentonite when the ... before re-saturation, both channeling and fracturing, and again, when the clay re-saturates, how will these features evolve over time?

Buffer erosion, again, for a brittle argillite, this is an important topic in crystalline repository design. There's concern that the ... with the ... with effective transport by fracture networks that buffer material could actually erode and be carried away and create effective transport through the buffer region.

Another area of interest is, can we add getter materials. You know, the bentonite buffer does a really good job of trapping cationic radionuclides, but we know that anionic species, which typically don't interact with any of the engineered barriers, or many of the host materials, drive the performance.

So, Iodine-129, is one of these materials.

So, there is active research in looking at anionic sort of materials that would trap things like I-129, and then thus, give us another knob to turn in the ... in the engineered design space.

The waste form, we have a set ... a set of fixed characteristics that we basically inherit in the design space, right, we have the radionuclide inventories, the thermal output, the materials within it, the cladding, and then even the things like criticality and other aspects, the in-package chemistry. These are things that are all inherited and have to be taken into account in the repository design, and can have effects on the EBS.

The waste package itself, again, we could use ... we imagine for sealing shale, you would just use, like, a steel canister, because you're putting that high reliance on the host itself. We don't ... we don't spend the extra money, so to speak, on a long-lived canister; whereas, in a brittle shale, again, behaving a little bit more like a crystal repository, you would have ... you would want some sort of long-lived overpack material that would allow you to put more emphasis on the waste package itself.

Multi-purpose canisters present some interesting design challenges, DPCs are a good example. A higher thermal output is a big challenge, which, as you'll hear about with HotBENT, and needs to be taken into account.

We also ... you know, a question came up about the weight of the package. Heavy packages introduce all sorts of engineering challenges. Just getting them into the underground, you know, they're ... you would need, in certain repository concepts, you'd have to ... the operational constraints of getting a really heavy waste package need to be taken into consideration.

And then corrosion rates are always kind of a big question mark. They're very sensitive to the material, and to ... to the ... the ground water that we have. In a generic mode this is harder to get a handle on, but it's ... it's another aspect worthy of consideration.

So one thing to mention here is, how do all these engineered elements tie together with ... with the buffer, for example? So, the material that you'd have on your waste package, for example, if it corrodes, you would get some kind of secondary mineralization.

And so, it won't necessarily directly affect the buffer, but you'd have this interplay between ... at the interface of the waste package and the buffer. And in general, there's always questions about how the near field of geochemistry is going to evolve as all the engineered materials degrade over time, and we'll hear more about that in the next talk, I believe.

So as Chris Camphouse spoke to you earlier this morning, and obviously Jonny spoke to you as well, the international field tests are very important. Both for proof of concept, not only for the modeling capability, but for things like emplacement, some of the operational aspects.

But they also give this opportunity to improve understanding of complex processes. I think Jonny's talk illustrated this really well, how process model development happens from the ground up when you have a set of ... of data from underground field tests, you know, there will ... as Jonny illustrated, you know, the thermal aspects could be captured quite well, but the mechanical leaves something to develop, which tells us, what we need to develop better process models, and I think Jonny indicated that. What type of data he ... we would need to further improve the mechanical modeling at the process level.

And then there's, you know, this critical data to understand, you know, in the computational representation, to what degree are we abstracting the processes, and to what degree is that okay, and to what degree do we need to improve that representation overall. And of course the performance assessment can help us make that decision because we can understand which processes or parameters the performance assessment are most sensitive to.

So, for the Full-Scale Heater Test at Mont Terri, for example, it provides this platform, where we can understand the processes in the near field, especially the waste package, the bentonite buffer, and the host.

And so, again, the individual bentonite, for example, which is of primary concern in this meeting, is one piece of the puzzle, but it's really hard to just separate out each engineered barrier system component, because both the chemistry and the mechanics will be part and parcel of the entire system.

So to conclude, the design concept will include a preliminary EBS design. This is determined from the geologic setting and inventory. As has been said many times, argillite is quite a broad rock type, both the chemical and the mechanical characteristics can vary. The varying characteristics of the waste, differences in thermal loads, for example, can drive differences in the EBS design.

And I think that concludes my talk. Thanks.

BAHR: Thank you, Ed.

I think we have a good amount of time for questions at this point. Do we have any from the ... yes, Allen.

CROFF: Croff, Board. On your Slide 11, you had a bullet, "Helps conduct heat away from the waste package." I sort of had an impression that bentonite tended to be more of an insulator. Could you elaborate on that bullet as to sort of how that comes about?

MATTEO: Well if you had air there, for ... I mean, relative to nothing, to a void, it will help conduct heat away.

CROFF: I certainly agree with that, but if your argillite is sealing, I can't see air staying there for very long.

MATTEO: Sure, eventually. But yeah, there would be aspects, you know, as Jonny mentioned, you need to understand that you wouldn't want ... necessarily want that formation to just crush onto the waste package, right? Because you wouldn't be able to control the impingement. You could get point loading on the waste canister and fail it before you wanted it to. The buffer allows you to distribute it ... distribute that load from the subsidence evenly over the waste package and not unnecessarily damage or puncture or perforate the waste canister.

CROFF: Okay, thanks.

PEDDICORD: I have a follow on to that.

BAHR: Lee, go ahead.

PEDDICORD: Lee Peddicord with the Board. So a bit of a follow on to that. That at Mont Terri, the

Swiss were looking at a rather intricate and sophisticated system of augers to emplace bentonite particles around the package. And as ... if I understand correctly, that had kind of raised some issues in their mind in terms of getting all the way into the drift and sufficiently filling it, and then the reproducibility.

So a couple of questions come out of that. One is do you all feel that you can get sufficient reproducibility with this process and the variations it might lead to, does it make any difference, or how much difference or can you characterize it?

And I don't recall if they had decided this is now NAGRA, to go in a different direction from what they were going to do now that they're a preferred repository site. So do you have any updates on either one of those questions?

MATTEO: I would think that if you had to weigh the two options between the compacted bentonite blocks and augured system, you would ... if you think about the ... at a systems level, right, not just a single waste package where you have to emplace tens of thousands of these barriers. I would think that the ... there's going to be trade-offs to both systems, right? Obviously, the bentonite blocks, in theory, feel more secure because they're instantly compacted, there's no period where you have to wait for them to compact, you don't worry that there's empty pore space.

But then you have to worry about do they get emplaced. They're difficult, more difficult to emplace than auguring in a pelletized product. So then you have to weigh the trade-off, well if it's emplaced perfectly, then it's a superior or a better option.

PEDDICORD: I think there's a dose to personnel issue of placing blocks and ... as well, too.

MATTEO: Right. Right, there's that issue as well. You have to get ... there's no way to ...

PEDDICORD: Yeah.

MATTEO: I mean, you can push them in, but yeah. So I think that the pelletized ... I'll open it up to LianGe, because I know he's more involved with the NAGRA folks, and I think he even has a video of some pelletized bentonite being emplaced.

They moved the mic on you.

ZHENG: Yeah. LianGe Zheng from Lawrence Berkeley National Lab. So this has been ... I think all the machines has been used in Mont Terri, the FE Heater Test. And the latest, the HotBENT Field Test that Grimsel have, they use this ... almost the same machine, and I'm not even exactly sure where you mentioned reproducibility, what exactly you ... you mean.

As far as I know, in terms of dry density can produce is very reproduceable. So they can produce quite a similar dry density, which is one of the critical design variable for engineered barrier system.

And I find, for example, in the HotBENT Field Test, they have full heaters, and they fill the tunnel with no ... Wyoming bentonite, I know is always that type. But Czech Republic bentonite, that they ... they are able to reach ... no, achieve relatively a homogeneous bentonite with a density which, you know, is their target density, so yeah, that's ...

MATTEO: Thanks.

BAHR: I have a question. I think you gave us a really nice presentation of what these barriers do and the variety of them. What are the, some of the important technical gaps that we're still facing besides knowing a specific repository.

MATTEO: Right.

BAHR: You can't do a specific design without a ... but more generically, what additional things do we need to learn so that when a site is chosen, you can go and do that design?

MATTEO: Right. So the first way to answer that is to point to the international community and the things that are of interest. The HotBENT test illustrates to us that high temperature is one of those things.

Then if we look at some of the other topics of interest, this ... in DECOVALEX, for example, there's this gas flow through bentonite Task, I think it's Task B. And so that tells us that, as I pointed out, that the gas flow ... and there's a lot of intricacies to that process, right, and that slide from Paul Marschall sort of speaks to the different phases of saturation and, you know, how that could progress in terms of fracture opening, and then the worry of there being a fracture percolation and then the gas can flow through ... through that.

I think the other ... and there are other examples. Let's see if any others ... you know, the coupled processes in the ... in the buffer and the ... the near-field multi-phase processes, as well. And then this ... this issue of having to deal with these multiple length scales in that over relatively large domain where you have these microscopic effects, right, in the bentonite itself, down to the swelling itself.

But then you have these multi- ... you know, we've seen in DECOVALEX Task C, the multi-phase aspect, especially during the thermal period when the heater is hot. You know, getting the physics correct is difficult. And I think Jonny speaks to some aspects of that in his talk.

The other thing is the ... is understanding some of these, as I mentioned, like a ... this isn't an integrated system, right, we don't just have the bentonite buffer. We don't ... and then a shotcrete layer and then the host and the ... or the EDZ and then the bulk host.

This is an integrated system. And so we've partitioned it into these distinct units to simplify it to understand it. But they're really, when integrated systems, they're going to have complex chemistry where, as the waste package corrodes, if it corrodes, or ... then you're going to have secondary mineralization which can then ... then you get that coupling between the mechanics and the chemistry where, you know, you go down this rabbit hole of, okay, there's so many different directions this system can go in.

BAHR: Are there particular questions about what happens at the interfaces between those components?

MATTEO: Yeah. Yeah, so ... thank you for that prod. So yeah, so that ... those interfaces, I think, are almost more important than the ... we kind of understand the bulk materials, at least to a first order, if not better, but then those interfaces are where we really run into lots of issues. You know, the bentonite cement interface, where you have chemistry and mechanics happening, the waste package buffer interface is another one where, especially the further on in time you go, you're going to have a real ... several complex processes happening all at once.

BAHR: So can you comment on the, sort of the research program that is going on to address those questions? Particularly the interface that ...

MATTEO: Sure.

BAHR: ... if you think that needs to happen at the lab scale? Does it need to happen at the ... -

MATTEO: It needs to start at the lab scale. And so ... and we need particular capability developments. And so one thing we've worked on is to develop workflows to understand materials, interfaces. And that starts with things like Florie's experiments, which you're about to hear about which, you know, hydrothermally alter a milieu of the materials in a generalized way where you're just having that end solution, and see what geochemistry occurs to something very specific where you have an interface of bentonite and cement, and then you want to do a postmortem on some sort of a, you know, leaching experiment or interaction experiment. And that can involve things, you know, very cutting-edge tools, scanning electronic microscopy, elemental analysis, micromechanical analysis, and then pore characterization of ... at the interface zone in the region of interaction between the materials.

BAHR: And I guess another sort of prompt is the ... do ... does the lab complex have all of the equipment that you might need for those kinds of characterization and those kinds of studies?

MATTEO: We do. And the ... I mean, they're definitely there at all the labs, it's just, you know, recruiting these capabilities into the inter-repository science, right, is something we're ... we're actively working on to pull them ... to pull them together is ... can be challenging, right, because it's ... you have to develop a workflow and you have to develop a ... an analysis framework to understand their ... the data that you do get.

BAHR: Thank you.

Are there questions? Paul.

TURINSKY: Yeah. If you're in a clay rock form, is it really that important that the buffer material retain radionuclides? I'm looking at the picture of the ...

MATTEO: Yeah.

TURINSKY: The size of the tunnels versus getting back to the biosphere.

MATTEO: Sure. It's more important in a brittle, right, if you had a percolated fracture network. Then it would obviously be more ...

TURINSKY: Yeah, or a hard rock.

MATTEO: Yeah. It is important because, as I mentioned at the get go. So what happens in these really low permeability systems, and we see the same thing in salt, is that there's ... because there's no large fractures, you ... it's super low permeability everywhere.

The only way to get any sort of release from the system is through the geotechnical seals. And so that's through the ... you have to assume something really unpredictable, I guess, because as I mentioned, we have these water stops where you have these cutouts, you designed the seal system to prevent preferential flow at the EDZ, and you do the same thing in the shaft seal, so somehow you have to have a failure in this multi-barrier system through the geotechnical seals to have a biosphere release.

And there is always going to be a scenario that analyzes that, whether it becomes something that's gets stepped out or doesn't need to be considered, but you'll have that scenario, so ...

TURINSKY: Yeah. Plus if your rock is clay itself, it has good ...

MATTEO: You would ... yeah.

TURINSKY: ... absorption capabilities.

MATTEO: Right. Not for the anions though.

TURINSKY: Oh, okay.

MATTEO: And then ... so then that was one of the reasons that, you know, one of the reasons we're looking at, you know, can we create some high performance getter or absorbent that can, you know, absorb I-129 or ... or tech, or some anionic species that would be driving the PA, okay, in that scenario.

TURINSKY: But does the bentonite itself have better absorption capabilities of the ... for the species; it does absorb then, most of the clays? The naturally-occurring clays?

MATTEO: Well, you know, the naturally occurring clays are going to have some fraction of a smectite swelling clay. So of course the bentonite is going to have a ... a higher percentage, but it depends on the bentonite. And of course the cation specificity, like, a larger cation, like a radionuclide, which are these heavy metals, is going to preferentially replace your smaller cations, like sodium or calcium or magnesium in the ... in the interlayer during the swelling.

And so that's how that functions. But yeah, in terms of ... the bentonite would be more efficient. In most cases, I would say it would be more efficient than the ... than the host medium.

BAHR: Any questions from staff members? Chandrika?

MANEPALLY: Chandrika Manepally, Board Staff. Ed, you were listing out all the key technical gaps in response to Jean's question. I was just wondering, in those key technical gaps, do you have a feel for which technical gap has a bigger impact on the barrier capability of the bentonite versus something that has a lesser impact on the barrier capability?

MATTEO: Hmm. I think that the dry-out is a ... is probably one of the more important of the technical gaps just because we would ... and absent of something like that, we would assume that the clay is a homogenous intact material. But if you had cracking or fracture percolation then it would change our ... it would change the function of the barrier because then you'd have advection for example.

Yeah, I think that's ... that would, to me, stands out.

BAHR: I think Bret Leslie has a question.

LESLIE: Sure. Bret Leslie, Board Staff. I'm trying to think of how to pose this, but eventually a repository is composed of engineered and geologic barriers. And if you get to the point ... DOE gets to the point of submitting a license application, you'll have to talk about, and have the technical support for degradation of the engineered barriers. And so kind of part ... I guess partially what you're doing now is trying to develop that technical basis.

So even though the clay might be why the repository is safe, I think DOE probably will have to come and say, "Well if we put in a DPC, and it's at 200 degrees C, this is how it'd differ than at 100 degrees C."

Is that a fair characterization for kind of the motivation of some of the stuff that you're doing?

MATTEO: Well I can pull out a specific example. So what would happen if ... one of the worries is when you increase the temperature, you can increase the smectite to illite transition in a bentonite clay. And so that would change not only the swelling properties, it would also change the cation sorption capability of the clay.

And so this ... we know that this is a Arrhenius-like, temperature-driven process. And so at a higher temperature, it will be accelerated. And we also know that, you know, the near-field chemistry driving that would cause it.

And so we need to understand all the different scenario, right, it's not ... there's so many different scenarios in the near field, so we want to ... we're going to be asked to ... what our confidence is in whatever prediction we make. And so if we haven't explored certain aspects of the parameter space fully, then how can we say with confidence, "Oh, we know the bentonite barrier is okay at 200 degrees C," but we have to develop that technical bases.

LESLIE: Right. And maybe LianGe will get into this more, but ... so will the HotBENT experiment, is that the sole basis for developing the technical basis for these higher temperatures associated with the DPCs? In other words, you know, have you defined what the barrier capabilities you need to evaluate and support, and would that experiment do that for you?

MATTEO: Yeah, I think so. And LianGe probably, almost certainly will talk to this more and he can chime in if I fail to answer it fully. But yeah, I think the two ... the two functions that we rely on the bentonite most for are the swelling and the radionuclide retention. And so those are of primary interest.

In terms of the HotBENT test, those are the ... I mean, there are other aspects to the test, like, they're going to put metal coupons in the test, but the primary drivers are heat the clay. And there's also some cementitious ... there's a cementitious plug involved in the test as well, so that we can look at the interface between a bentonite and a cement as well.

But I do think that the main takeaways are there are other ... I mean, LianGe will speak to this ... there are all other nuances to the experiment as to like the ... the transport as the ... the packages heat up and, you know, how moisture gets distributed. And those are things that can feed into the modeling aspects of it as well, right, to understand how well our model is capturing the alterations that occur at a higher temperature.

BAHR: I think we have a question from Tissa.

ILLANGASEKARE: Yeah. Thank you very much. So I just want to understand conceptually. So you are looking at multi-phase flow. So basically the gas, there will be gas flowing through a saturated porous medium; is that correct to start with?

So when the gas flow through, you call it ... isn't the gas going to be a continuous medium where there are bubbles, or it's like ... like traditional multi-phase theory is you had to have continuous phases, so that in your conceptualization, the gases considered be always connected pathways, or they can be bubbles in the formation?

MATTEO: So which part of the ... where are we in the repository lifecycle when you ask this?

ILLANGASEKARE: Yeah. I mean, I just ... I just want to learn myself. I don't know. So I'm asking the question. When you say it's a multi-phase flow, it's complex for me to understand where the interface is, et cetera.

But my question is in the conceptualization, how the gas is flowing there. Is it flowing like a continuous medium or like a gas ... all the gas in connected or there are ...

MATTEO: Well yeah.

ILLANGASEKARE: ... bubbles, or how ...

MATTEO: Well you'll have ... yeah. I mean, you'll have a continuous phase, right, very close to the heat source, you imagine that there you have a continuum. But you're going to have some kind of a capillary fringe, I think they call it ... you would call this, where you have a ganglion formation.

ILLANGASEKARE: Yeah, yeah.

MATTEO: And as the gas has to percolate into a saturated medium or partially saturated medium, and that's where ... I don't ... yeah, that's where it's ... gets tricky, right?

ILLANGASEKARE: Yeah, that the reason for my question, exactly that, because when you have interfaces, like two material texture interfaces, then the multi- ... traditional multi-phase flow behavior complex itself. But I don't know where the ... we really understand what happens if you have bubbles there in this continuous ganglia on top of gas becomes an interface. I don't know how they behave actually, I just asking.

MATTEO: I mean, that's, you know, that's one of the concerns with the dry-out, right, in general, is like what ... how much are you fracturing and how much alteration are you doing to the microstructure, the fabric of the bentonite as that dry-out occurs. And then will it all be reversible when you re-saturate at the end of the thermal period.

So the ... you know, I think it's always important though, we don't have to capture every single phenomenon. We'll always ... the ... any modeling we do will always be an abstraction, right? Especially at the performance assessment level, there's always a degree of abstraction to the way that you're representing things.

And so there are certain ... we have to be able to know which phenomenon we have to capture versus which phenomenon we don't have to capture, right? We don't have to have a perfectly high-fidelity model at every point in the repository or even in EBS. We just have to capture the ones that the performance assessment will be sensitive to. So that one is ... we have to figure out some of the ...

ILLANGASEKARE: So the point being that in the conceptual model for this, two different systems are different. So that's ... that is you may not ... you will not be able to model a multi-phase scenario under this continued ganglia in this issue of continuous, so ...

MATTEO: Yeah, you would ... .yeah, you would have to ... for that case, right, you might ... you're going to have to have a ... you have a whole set of ... we try to just develop the tools that if we ... it comes to that ... this ... "Oh this is a driver in the performance assessment," that we're sensitive to this phenomenon, then we need to be able to address it, but not necessarily address it unless we know we have ... right? It's the conundrum when we're not site-specific, we have ... we just have to focus a little bit more on capability development and generalized fundamental knowledge I think.

ILLANGASEKARE: Thank you.

BAHR: Any other questions from staff, Board members? Bret Leslie.

LESLIE: Thanks, Jean.

Bret Leslie, Board Staff. Kind of ... if you can go back to Slide 5 for a second. And I hate doing this, because I'm a geologist and I love rocks, but this is kind of driven by the host rock and kind of turn it around and say, "What are your repository concepts and host rock requirements if you have a DPC?"

How would those figures change? Would any of them, you know, if you have a DPC the ... Switzerland would still work. I'm trying to get a feel for that, because yes, you have all sorts of rocks in the U.S., but right now, you have dual purpose canisters that are large and big.

So does that constrain the rock types? Does that mean you have to go to a sealing clay, and you can't do brittle?

MATTEO: Well the first question is can you get a DPC into this environment, right, can you get it to the repository level from ... and that's an operational issue to start with.

For the ... the super container, which is what they use in the Belgian concept is a pretty large container. I don't know off the top of my head how large and heavy it is, but it has a huge annulus of cement around it, right? It's kind of a ... it's almost like a pre-fabricated EBS because you have the buffer on the waste container as a shielding element. And then it emplaces that way, so it's a fairly heavy container.

So to me, for certain the super container type of concept is going to ... should be feasible. I mean, I shouldn't say for certain, but it should ... it could be feasible.

For the sealing, for the like, more of an Andra type of concept, then I think that it's really more an issue, can you get it underground? But it's for both of them, right, if you have the operational infrastructure, do you have the concept developed?

The Germans do a really good job on this operational side in their program. They go into ... you know, we know that we could put a DPC in salt because the Germans have developed all the designs for the hoist systems to get that large waste package into the underground.

BAHR: Just following up on that with the Belgian case. They've got a super container, but that includes a buffer around it. If you took a DPC and you had to add a buffer around a DPC, it would be a super, super container. Would that be feasible from an engineering standpoint?

MATTEO: I mean, you would ... I mean, I don't ... this is outside of my area of expertise, but you would have a shotcrete liner, right? Your biggest concern would be is the excavation volume or diameter too large to work safely in the underground.

But I think that the ... that's why you have the shotcrete in the first place. I don't know what the ultimate ... you know, there are heuristics for, you know, it's usually more how close you ... you place the drifts and the excavations, as opposed to like how ... right, we can put pretty large ... make pretty ... I mean, we've had discussions of vault-type rooms for disposal, for example, and in almost any media, so I don't think that there's a limit on the excavation size, it's really just ... because of the size, do you run out of aerial extent in the repository horizon where you don't ... you have too many waste packages to manage a thermal load correctly, for example.

I think Dave has a comment.

SASSANI: Hi. Dave Sassani with Sandia National Laboratories. I'll just add, dual purpose canisters in the U.S. is one of the areas in which the U.S. is leading the world. It ... we have larger and higher thermal-loaded canisters considered for disposal than pretty much any other country.

And so in fact, and this is just, I'm assuming, part of the question which is more the broadscale aspect, that consideration does make it a bit of a challenge to take the designs that are out there, in other countries, for their systems, and just put a dual purpose canister into them. There are a number of considerations which have been discussed very well.

But in fact, it also creates a challenge in terms of the modeling of the evolution and potential degradation of the canister and the engineered barriers because it pushes the thermal aspects of the system ... the local system around a canister which spacing doesn't help very much with; it does some for very long term, but you will have to consider temperatures that are much higher.

Our interaction with HotBENT is a really good example of international collaboration where I think our ... LianGe and everybody involved with that have gotten the temperature raised to a level which puts us in the realm of what DPCs will be doing to some of these if they get disposed in a bentonite backfill.

But lots of good discussion about the engineering aspects.

BAHR: Thank you. And I think that brings us to time.

So thanks very much, Ed.

And we'll bring up our next speaker. A pair of speakers: Carlos Jove-Colon and Florie Caporuscio. I hope I said that right. And Carlos is going to start out.

JOVE-COLON: All right. My name is Carlos Jove-Colon, and basically, it's going to be a tag-team talk between myself and my colleague at Los Alamos, Florie Caporuscio, and it's called, "A Review of High Temperature Engineered Barrier Systems Experiments."

And I'm going to be giving part one, which is "Modeling and Testing Activities of Bentonite Barrier Behavior." Mostly stuff that actually we are ... conducted at Sandia National Labs, but also in concert with other labs as well. Next slide.

Oh, sorry. Anyway, just to give you a quick gist of why we actually talk about argillite. So, on the left panel, we have a map of the U.S., and with some color coding in terms of distribution of argillaceous rocks and geologic formations in the U.S.

And one of the attributes of why we choose argillite is, number one, widespread geologic occurrence. They're found in stable geologic settings, and they also contain the appropriate thing that's do ... and depth to actually host a nuclear waste disposal concepts, and we talk already about the self-sealing properties.

Color coding in this vinyl is actually the depth to the top of the shale formation in meters. So if you look at the center part of the map, this is pure shale. I don't know if you can see that. Actually, that kind of light bluish color that's about 400 to 500 meter range in terms of depth.

On the right panel, actually we have a generic stratigraphic column, and in terms of something that we do to develop a reference case for argillite, and how it looks like in terms of depth, and also the different types of formations that are considered, permeability ranges, et cetera. Next slide. Let me do it myself.

Well, we actually have talked on various aspects of this in terms of an engineered barrier concept, particularly in the near field, but this is more of actually ... I'm just going to mention a few things in here, Jonny has talked a lot about this. Ed talked a lot about this, but I just want to focus on something that was mentioned previously, and actually, it's about interfaces.

A lot of the action and a lot of the degradation in terms of barrier materials occurs at interface. So we have heat generated by the spent fuel, but we also have, you know, canister overpack, et cetera, and then that in contact with bentonite.

So there's, especially for concepts, like, for example, high-heat generating concept, like DPCs, we were talking about that. So you expect to have some mineralogical changes going on at the interface.

The same thing happened between cement and bentonite interfaces. And also, of course, you can have fluxes of fluids, you know, where they impact pore solution chemistry, and of course in case of a breach, you can have also effects on radionuclide transport.

Also, we are ... have to consider, you know, the effects of bentonite swelling and shrinkage. And again, thermal phase stability, you know, are ... these things are going to be stable in the long term, even under high-temperature conditions?

And of course, chemical interactions with pore solutions in bentonite as well. It also includes, you know, things like canister corrosion and contact with the bentonite, et cetera, and every process that actually accounts for clay barrier degradation.

Anyway, this is some of the highlights of the disposal R&D program, experimental and modeling activities. Florie is going to be talking about part two, a lot of the experimental activities and barrier material interactions at high temperatures. We talked in some aspect on the international collaboration and disposal R&D.

In Sandia, for example, we're involved with DECOVALEX 2023, modeling thermal, hydrological, and chemical processes in bentonite. We're also involved with the SKB Task Force, Sweden, in which they actually have a modeling problem for cement-bentonite interactions; it involves more a reactive transport.

And of course, we hear about HotBENT already, and LianGe Zheng from Lawrence Berkeley Labs is going to be ... talk more in detail. Our side of that is actually looking at postmortem characterization on the column test of bentonite, but also, we will be engaging in doing a thermal hydrological modeling of that as well, as the data comes in.

In Sandia, we actually have been doing molecular dynamics simulation of water transfer phenomenon in smectite, which is essentially swelling clay.

Swelling is a thing, it's a phenomenon that occurs at the nanoscale, and actually this particular technique is very useful to know what's going on. We also been partnering with the universities, for example, for the modeling of ordinary Portland Cement, and the modeling of leaching. This is actually pretty crucial for model calibration.

Also ... well, actually, Jonny talked about this earlier today, the modeling of THMC processes and shale creep in argillite. So this is also something that we do in ... you know, their focus is more on thermal, hydromechanical, but we actually ... they're looking at other aspects of the other chemical interactions of bentonite as well.

Machine learning approaches for radionuclide mineral interactions, and surface complexation database development. This is an effort that Lawrence Livermore National Labs is actually involved in, in terms of applying machine learning approaches, and looking at the wealth of data that existed there for absorption of radionuclides in ... not only in clay material, but other types of surfaces, and actually tried to exploit ... essentially primary ... let's say parameter evaluation of surface complexation, and how they can actually represent such processes using machine learning.

And also, thermodynamic database development. Since the Yucca Mountain days, and probably even before that, thermodynamic databases actually allow us to make predictions about not only the feasibility of minerals, et cetera, when they're gone and there's processes of ... that are thermally driven, but also allow us to provide a lot of the rigor and feed our geochemical modeling tools to make those predictions.

In terms of international activities, basically DECOVALEX 2023, Sandia is involved with the Honorobe URL in Japan. We are actually modeling lab scale experiments, but also as a part of another step in that particular activity, we are actually doing ... modeling the full scale EBS experiments as well.

As I said before, SKB Task Force includes cement clay interaction modeling. We're actually looking at a 1D problem, a reactive transport. Fairly simple, but given the complexity of cement phases in the OPC on the Ordinary Portland Cement, this actually can be quite complex as well. But also, we are involved in the HotBENT experiments, as I explained before.

In terms of the things that we're doing, basically water transport in clay interlayers during dehydration. And this is kind of important in the sense that smectite clay, when it hydrates, hydrates differently than it dehydrates.

One of the reasons is that hydration and swelling comes hand in hand, and the same with dehydration. When the system actually ... water leaves the system, it shrinks, and that actually has some implications in terms of desiccation, cracking, et cetera, and all those things that actually ... we mentioned already.

Just like here, just to give a snapshot of what's going on, you have a dry montmorillonite, which is a smectite, and essentially has zero waters in it, that's in the leftmost ... the left most part of the slide. You start adding one water layer, and then the whole stacks of the dried-out layers in this mineral structure start expanding until you actually accommodate up to two water layers. So that's basically the phenomenon in terms of clay swelling, which is pretty much water absorption inside the mineral structure.

So, one of the things that we have been trying to do is to study this phenomenon at high temperatures. So we actually have to conduct these experiments in specialized equipment; for example, doing structural studies at high temperatures on the control and moisture conditions, which is ... can be kind of challenging. But also we have been doing thermal studies on this just to see, for example, dehydration is an endothermic phenomena, you'll see here in the lower panel.

There is a differential scanning calorimetry here, that red curve here, that's in an upward peak. That's actually an endotherm, and that's what happens when the actual mineral dehydrates. But it's actually a stabilized process, and that's one of the things that we actually can explain using a much smaller scale modeling. It's actually a fast process at the beginning, and ending, it's a diffusive process.

And another aspect of this is actually ... the reason is to ... to me, a key reason is to study thermal ... the stability of all the clay at elevated temperatures, and this particular techniques tell us a lot about it.

And another thing that we're doing ... well, this is not another thing. Actually, this is a part of DECOVALEX, is actually modeling lab-scale experiments from the Japan Atomic Energy Agency in which they actually saturate bentonite.

In this case, they actually have a bentonite block, they saturate it from the bottom, and essentially and progressively, they actually measure liquid ... water content or liquid saturation as a function of time, and as a function of location.

So, on the rightmost panel, actually you can see that there are a bunch of cords, and we actually have two ... two types of modeling cases in which, one, we have an interior unit's initial saturation. We can tell the model to specify initial saturation as a function of the cell in which we want to actually measure the whole thing in the ... within the model, but then also we can actually assign an initial saturation homogeneously across the sample.

Why we did that? We were actually looking at different cases in which by specifying the initial saturation as a function of space, and within the sample, we actually have a better fit to the data.

But what happened if we actually decide to have a homogeneous initial saturation? And basically, the difference in here are very small. This is up to

30 days. You can see more difference at the beginning of the experiment. But still, it gave us a good idea on how sensitive those parameters are.

We actually did it for a deionized water, and then also for a synthetic groundwater. And basically, we managed to feed the data by ... by adjusting permeabilities across the length of the sample.

We actually also ... going to the next step under lab scale experiments, again, this is in ... this is with the Japanese. And they actually have a bentonite block in the bottom that there's a constant temperature boundary condition of 70 degrees C.

On the top, it's actually a constant temperature of 30 degrees C, and essentially, where we're using the ... our tool, which is a PFLOTRAN model. I forgot to mention that in the previous slide. Basically, that's what we use to do this type of thermo-hydrological modeling. And essentially trying to see if we can represent liquid saturation as a function of distance at different times within the sample.

Well, this is still work in progress. We haven't been very successful, although we can actually ... we can manage to get the overall trends, but we can't actually ... it's very hard to actually fit the data. But we are actually working on that, and the way we're starting to, at least in this stage of the modeling, is to actually use different permeabilities and see how the parameter is sensitive, and how it represents the data as a function of distance from the bottom of the example.

PEDDICORD: A quick question. Lee Peddicord. So this slide and the previous slide were both done at ... with Japan; did I understand correctly?

JOVE-COLON: That's correct.

PEDDICORD: But they're two different experiments?

JOVE-COLON: They are two different experiments.

PEDDICORD: Okay, thank you.

JOVE-COLON: Yeah, one is actually isothermal, low temperature. This guy is non-isothermal.

ILLANGASEKARE: Tissa Illangasekare. What is the size of the block?

JOVE-COLON: The size of the block, I think is 10 centimeters in length.

ILLANGASEKARE: Oh, 10 centimeters.

JOVE-COLON: Yeah. I need to double check on that, but I think that that's correct.

Okay. Another thing that we're doing is, actually talking about interfaces, is modeling of the Ordinary ... Ordinary Portland Cement leaching; and again, using PFLOTRAN. And this is more of a reactive transport model in which experiments conducted at Vanderbilt University, this is Dr. David Carson’s group. They actually developed an EPA method for leaching of monolithic material.

So, we basically used their data. This is, I think, reacting OPC over ... this is actually ... I think it's, yeah, cure OPC over fifteen hundred hours. And essentially we managed to get a very good representation as a function of time of the leaching, and this is actually, it's ... can be kind of a quite complex, because sometimes we don't know the ... how much of the initial ... the volume fraction of all the cement phases actually present in the model; that information is almost not given. But we managed to actually, in collaboration with Vanderbilt, get ... agree about the initial cement composition, and actually, that allow us to gauge our model to pretty much provide this information.

And actually, I'm very ... I think we can claim a little bit of success in terms of how well we have ... not only feeding the process for calcium and silicates as a function of time, but also, all their solutes.

So, this is my last slide, and essentially, we are very active in doing PFLOTRAN thermal, hydrological, and chemical modeling.

Again, looking at both aspects of variably saturated bentonite under non-isothermal and isothermal conditions.

Reactive transport modeling of OPC leaching experiments. And again, these experiments are very key, because it's not only a way to calibrate our models, but it's also ... and not only testing our models and verifying them, but also, we need a baseline. And I think that actually, such kind of partnerships in ... with people doing experiments are key in my opinion.

We're also looking at parameter evaluations, sensitivity analyses, mesh refinement, et cetera, and all those things are actually part of the modeling effort.

We are also looking at reduced order models, and the goal is to actually ... how can we try to capture, for example, otherwise very complicated chemical process models, like for example, bentonite swelling effects on permeability.

LBNL HotBENT heated and unheated column experiments. Basically, we are actually working with Berkeley and doing, you know, not only a thermal analysis of bentonite on those column experiments, but also compositional and mineralogical characterization, and also continuation of the cyclical thermal analysis at high temperatures.

This is a way that we can ... something that we can do at Sandia in terms of by cycles, applying moisture and cycles as a ... at a constant temperature and as a function of time. And that tells a little bit of the shrinking ... sorry the, swelling and shrinkage, actually, of the bentonite, in terms of the thermal analysis at high temperatures, is something that doesn't get compromised.

Of course, it's a large-scale experiment short term, but given the ... the way it can be done, especially under unsaturated conditions, it can give us a lot of information.

We are actually moving MD simulations, molecular dynamics towards gas transport. For example in this case, H2 gas, which is kind of a ... it's being considered an important gas in repository sciences just because of the ... it's a biproduct of corrosion, metal corrosion. And one of the things that we want to do is to actually look into gas absorption and transport in the clay interlayer.

And of course, we are still looking at analysis of thermodynamic parameters from clay degradation modeling that we actually conducted already in these simulations.

Thermodynamic database development, it's actually something that still always under evaluation, and we actually expanding into it. We have Lawrence Livermore, Tom Wolery over there, working heavily on this, and ... just because it's a key feed to a lot of the geochemical and reactive-transport models that we do.

And also, as mentioned before, Nuclear Energy University Partnerships, NEUP projects, actually are key also to look at, for example, in the cases of amended bentonite. We're looking at, for example, in the case of dehydration, how using microfibers can actually arrest the formation of desiccation cracks, et cetera.

So this is my last slide. I don't know if Florie can come in and leave questions for later?

BAHR: Yeah, I think we'll take Florie's presentation, and then we can have questions for both of you at the end.

JOVE-COLON: All right. Perfect.

CAPORUSCIO: My name is Florie Caporuscio from Los Alamos. I want to thank the Board for asking me to give a talk today, and mine is going to be on high-temperature experiments. We're going to focus on the minerology of what happens to the clays, phase transitions, and especially these interface playoffs.

You've seen the schematic many times today. What I'll ... once again, looking at the mineralogic changes, and a little bit on the waste package corrosions. We also have started to do experiments that incorporate cement with the clays.

Go on from here. There we are. I'm going to try and really do just summary slides today, because as you'll see, we've done over 50 experiments. It's going to be a little hard to cover each and every one.

So, we have a range of temperatures that we worked at from 200 to 300 degrees Centigrade, and a pretty consistent 150 bar for our pressure in these. These are all done in rocking autoclaves, by the way.

So, the first set of experiments were the Wyoming bentonite, solo, 16 of them. I'm not going to read all these parameters. You can go back when you need to and check them out.

Then we did a baseline, Opalinus Clay. So, we had knowledge of what happens to just the Opalinus at 300 C.

Then we mixed the wall rock, the Opalinus Clay with the Wyoming bentonite which is the buffer material. Had a bunch of experiments there, and of course we added metal coupons to see what happens at the interface site: copper, low carbon steel, stainless.

Once we had those under control, we had some knowledge base. We then added Opalinus Clay ... sorry, Ordinary Portland Cement, OPC, and/or low pH cement as we went on.

The last one, the last 10 experiments were done in a crystalline rock, Grimsel granodiorite from the Grimsel site at URL in Switzerland. And I'll do a comparison of those experiments versus the Opalinus Clay at the very end of this talk.

So, the interface between steel coupons and the clays, and what happened. Most of these were run at 300 C, 150 bar. These ... we project these to be sort of repository conditions, that's why we're doing them.

And what we end up with, you can see in the equation at the bottom, stainless steel, water, montmorillonite produces iron saponite at the interface, and opal.

Next summary. If you look at, sorry, the interaction between the wall rock, Opalinus Clay, and the barrier material, Wyoming bentonite, we had ... now we're talking about 20-plus experiments, but there were 2 that really sort of stood out.

The one at 300 degrees and 6 months. And then a lower temperature, many fewer weeks, eight weeks, but the water was much more saline. So we ended up getting ... it was especially in the 6th month, we ended up producing illite-smectite, which we had not seen in any of the others, and that was because there was some pre-existing illite in the Opalinus Clay.

So we had a nucleation site for it to be developed in the right chemical conditions.

When we added Portland Cement, we saw that there was a swelling decrease. We saw that the clays degraded, and minerology, the montmorillonite went to what's commonly in the cement industry called a C-A-S-H mineral, tobermorite, which is a calcium, aluminum, silica hydrate. In the SEM image, you see some nice long acicular illite in with the smectite.

So, what else am I going to talk about? Some zeolites. They're in the Wyoming bentonite to the tune of about 11 percent, 13 percent clinoptilolite. So top bullet, you heat it up to 300 degrees C, the clinoptilolite transitions to analcime, very simple.

When we add Opalinus Clay, and the Opalinus Clay groundwater, both of which are calcium-rich, you push from the analcime member towards the wairakite, which is the second bullet, which is the calcic end member of that same zeolite.

When we add cement to the mix on top of everything else, that's where we encounter these C-A-S-H minerals, tobermorite, garronite. And if we had a different ground ... wall rock, sorry, the Grimsel granodiorite, we don't see any zeolites created other than the aluminum tobermorite, which is probably a meta-stable phase.

This is why I like zeolites; they make for great images. The far left is Wyoming bentonite only, where we heated it, and we got analcime. We got beautiful analcime. Once we added calcium to the system with ... being Opalinus Clay and Opalinus Clay groundwater, it trended toward wairakite, which are the clump of zeolites on the righthand image.

What makes that unusual? This is solid solution series line. Far left are wairakite compositions; far right, analcime. It was that middle zone that ... well, first time they plotted one there was 69 by Seki and Oki. They believed that there was a miscibility gap: that you had end members, but you had nothing in the middle. We've added, besides those four experiments, most of our Opalinus Clay experiments have compositions that fall in the center.

Once again, it just proves that the overall chemistry of the system drives most of the mineralogic changes to be expected.

So, I want to give a little bit on the C-A-S-H minerals that we formed. These are at 200 degrees C with Portland Cement as our beginning experiments. The montmorillonite broke down to make tobermorite. The C-A-S-H minerals are precursors we've seen prior to analcime and garronite.

Just go down to the lower bullets, the change in smectite was quite significant when ... with the addition of cement. We lost a lot of our smectite, and we gained zeolites. See there: 19 versus 14 weight percent.

The clinoptilolite was slightly reduced, but you'll see that we were able to produce more zeolites with the addition of cement.

Going to try and summarize quickly. Wyoming bentonite to Opalinus Clay added ... to then add Portland Cement. So in the first one, pretty simple system. Smectite is stable. No illite was produced. The clinoptilolite transitioned to analcime at 300 degrees C.

When we added Opalinus Clay as a wall rock, we were able to generate some illite-smectite, and that is because of the discrete illite in the Opalinus Clay acting as nucleation sites and having the right chemistry to provide for that illite-smectite growth.

Because of the calcium content in the Opalinus Clay, it shifted the chemistry. We were able to form wairakite now as part of that zeolite system. When we added Portland cement to it, start losing smectite, we were able to continue growing some illite-smectite. We generated C-A-S-H minerals, and at 200 C, lower temperature, we showed an assemblage of tobermorite, garronite, and analcime. We still have work to do, but we believe that the tobermorite is metastable, and it's going to, with time or more temperature, convert to garronite and analcime.

This is a slide where I wanted to make a little comparison between the argillaceous material on the right, the Opalinus Clay, and Grimsel granodiorite on the far left. So the experiments had temperature difference. Opalinus Clay, dominantly we did 300 degrees experiments; it's a sodium chloride-rich brine. Whereas the Grimsel is carbonate rich. Zeolites, analcime-wairakite for Opalinus Clay. Tobermorite and other C-A-S-H minerals with the Grimsel granodiorite without any cement added.

And then minor illite-smectite with Opalinus Clay and not with Grimsel granodiorite, and we created some bentonite colloids in the Grimsel granodiorite experiments. That happened when we cooled off the experiment. We never do a quench.

There are health and safety issues of trying to ramp these things down from 300 to 25, so we just shut them off and let them ride down the steam curve, so they're not really quenched. But when we extracted the resulting material, we had colloids in the Grimsel granodiorite experiments.

Here are summaries, pretty much what I talked about earlier. Alter the bentonite only, because we had restricted potassium supply. We didn't generate illite. We also ... the aluminum also was a cause for not generating the illite, and clinoptilolite went to analcime at 300 C.

Steel corrosion was a simple one. At the interface, we created iron saponite and opal. That growth at the surface of the steel produces a larger surface area, and it may help provide an increase in actinide retention.

When we added bentonite ... sorry ... Opalinus Clay to the bentonite, we were able to generate some illite-smectite, and that's because of pre-existing illite in the Opalinus Clay, and we were able to generate more smectites.

When we add Portland Cement, however, smectite goes away, typically 15, 20 weight percent loss, and the clay itself is degraded. Some of the montmorillonite became tobermorite, and we ended up with a significant increase in the zeolite phases.

My acknowledgments. Thanks to the Department of Energy, Nuclear Energy, and a whole host of characters who, without them, wouldn't have been able to do all these experimental studies.

BAHR: Thank you, Florie. Can you just comment on what's ... what are the implications of the ... both the clay phase changes and the production of the zeolites on barrier effectiveness.

CAPORUSCIO: So first and ... sorry. Sorry, Jean. First and foremost, we went into this 10, 15 years ago saying you heat up clays, you're going to get illite. Not necessarily. That really depends on the bulk chemistry of the system.

This being a closed system, you don't add potassium, you're not going to get illite. In a general geologic system, things come and go, that's where you get illite when you heat it up in temperature.

Something to be aware of. Especially if we go into design phases down the line of different barrier systems. Generating more zeolites from this barrier system. Zeolites have typically an order of magnitude more retention of radionuclides. We saw that in the Yucca Mountain studies. JAEA, the Japanese group, they have a huge database that shows that zeolites are more likely to retain radionuclides than clays. So now it becomes a balancing act of how ... what's the weight percent that you get of new zeolites and will it be beneficial or not.

BAHR: What about the swelling capacity? If you're not creating the illite, then you're not destroying that. But what does the zeolite content do to the ... to the swelling of the clay ... of the bentonite?

CAPORUSCIO: So there was one study in the '80s where clinoptilolite went to analcime at actually low temperature, and there was a reduction in size, and an expulsion of water; was by Joe Smith, 1982 engineering geology, something ... but it's not a significant change, otherwise, because the amount of zeolite generated isn't that tremendous: 10 weight percent. Something like that.

BAHR: So if we can bring back Jose, then I think we can have questions for both of ... Carlos.

CAPORUSCIO: Carlos.

BAHR: Should've said Carlos. Sorry. Sorry, Carlos. Jove-Colon, you're ... we're going to bring Carlos Jove-Colon back.

JOVE-COLON: Do I use the other microphone or ...

BAHR: Yeah, maybe ... maybe you can share that one and ... do we have any questions from the remote people on these talks? We have a question from Lee Peddicord here.

PEDDICORD: This is just for clarification. Is this your team at Los Alamos or from other laboratories as well?

CAPORUSCIO: So I can see right off the bat there are three people that I need to acknowledge: George Morgan, Lindsey Hunt, they were the microprobe operators at University of Oklahoma.

PEDDICORD: Okay.

CAPORUSCIO: That I did work with, for seven or eight years. Steve Chipera did some early QXRD when we were not able to do it, when our machine failed. He was able to help us at Chesapeake Energy.

PEDDICORD: Okay. Thank you.

BAHR: We have Paul Turinsky.

TURINSKY: Yeah. Following up a little bit on Jean's question. How far does this propagate these changes, into the interface? It seems if it doesn't propagate very much, in most cases, it wouldn't ... wouldn't be that important. But if it does propagate more, it'll have more significance. So I'm trying ... you know, how much does this impact the performance model eventually?

CAPORUSCIO: Yeah. So these are batch experiments in a fairly homogeneous environment. So we don't have the actual layering or scaling of, you know, "Here's the cement. Here's this. Here's that." Hopefully LianGe will have some of that tomorrow for you.

We do know that the iron alteration at the interface is ... is very ... I don't want to say "short," but it's immediate. And you'll see this layer of iron saponite on the steel surface.

And then there are other experiments from a French group, Mosser-Ruck is one of them, but they saw this iron saponite throughout the clay system. So, cannot give you a definite answer.

BAHR: Is there ...

ZHENG: Yeah. LianGe Zheng from Lawrence Berkeley National Lab. So in the FEBEX test, a longer heating and hydration test, the Grimsel test site, you know, they dismantled the test after 18 years of heating high region. This is longest test. So at the canister and the bentonite interface, we saw change, runs from 4 millimeter to 12 millimeter.

So something about the 1 centimeter, you know, after 18 years. At the concrete and the bentonite interface, the impacted area, about a half-centimeter. So that's the best. But this is 18 years of a test. So you can get a sense, you know, if you have a repository, you know, 100 years, 1,000 years, of course this is not linear, so yeah.

BAHR: We have additional questions from Board members? Questions from staff? Bobby.

PABALAN: Roberto Pabalan, Board Staff. Florie, you have done a lot of experiments using different combinations of bentonite type, host rock type, water composition, temperatures. Have you done geochemical modeling to see if geochemical models can ... predictions? What geochemical models can agree with your experiment or the results? And that's really where the value of your experiments lie. Not only in being able to maybe validate these geochemical modelings, but also to identify where there's a need to improve thermodynamic databases.

CAPORUSCIO: So we've just gone that route very recently, Bobby, using PHREEQC. And the nice thing is it ... they match up well. And this is in the zeolites with analcime-wairakite and clinoptilolite. We’re going next into the C-A-S-H mineral system and see what the stability is, because doesn't look as clear cut there.

PABALAN: Okay. Because modeling, of course, will enable you also to extrapolate or predict what happens in other geochemical conditions.

CAPORUSCIO: Mm-hmm.

PABALAN: For specific repository environments. So yeah, I'd be looking forward to seeing the results of your efforts.

CAPORUSCIO: Good.

BAHR: Chandrika?

MANEPALLY: Chandrika Manepally, Board Staff. I was just wondering the temperature and the pressure values that you've used for your experiments; it's 300 C and 150 bar. Was that a reflection of the kind of repository conditions that you expect, or what was the reason?

CAPORUSCIO: Well, it always helps to generate new phases at a higher temperature, sort of accelerate the process. But there's evidence to show that DPCs, at the skin, can be as hot as 300 degrees C.

150 bar, lithostatic pressure is what we calculated, about 800-meter depth, typical depth for a repository, if at all closes up. Okay?

MANEPALLY: Thank you.

BAHR: Andy Jung?

JUNG: Yes. This Hundal Andy Jung. I heard that the previous presentation by the Ed ... Ed. So the ... this phase depth, for the waste package, it seems like copper could be ... could become material for its current clay-based repository or you are still considering the other type of materials? But basically that is for Ed. A question to Ed, basically, but I missed it.

For your case where you have a slide 4 ... you have some testing ... phase testing, is the steel. I suppose the waste canister you say, but sometimes, the others says that overpack ... so overpack or waste canisters is a little bit confused.

And the question is that you ... you have observed iron-rich clay, does it mean that some dissolved iron is incorporated [with] the clay or the ... what is the definition? Like, you say the iron oxide layers? Iron oxide layer because these corrodes can make a significant dioxide ... iron oxide layers.

CAPORUSCIO: Yeah. Let me give part of the answer, and then Ed will jump in. We did do some experiments with copper foil, okay?

JUNG: Okay.

CAPORUSCIO: The Swedes, the Japanese do use copper as the outermost layer in their ...

JUNG: For the Sweden.

CAPORUSCIO: Yeah.

JUNG: Yeah. That is for the ... the granite type of material.

CAPORUSCIO: That's correct.

JUNG: That is a good candidate. But the clay case, the other countries are Swiss and the other France is the carbon steel ...

CAPORUSCIO: Yeah, they don't. They're not.

JUNG: Yeah, carbon steel is the primary material.

CAPORUSCIO: We decided just let's ... let's take a look, okay?

JUNG: Okay.

CAPORUSCIO: And what we did find out is there's pyrite in the Wyoming bentonite, the buffer material, that breaks down hydrogen sulfite gas. We created chalcocite on the skin of the copper as a protective layer. So that's that one.

The steels. We develop iron saponite on the interface. We see minor amounts of magnetite also created. And then a whole variety of other minor, minor phases due to the trace elements and the steel. So we see ... I'm sorry, I'm blanking.

JUNG: Yeah. So I understand that basically the iron oxide have a very significant role to absorb the salt actinides from the ... based on the previous testing. So what is the ... how much efficient to, like, to hold, to retain the ... hold the actinides in that layer? What percent; can you tell me?

CAPORUSCIO: Don't have an answer for you yet. Yet. Because it's such a fine layer, we've been trying to recover enough to do some thermodynamic work on it. We're just not there yet. We'd almost have to set up a ... an experiment where we harvest iron saponite.

JUNG: Okay. The last question. Do you have a plan for the other type of materials such as carbon steel for testing?

CAPORUSCIO: Such as what? I'm sorry.

JUNG: Carbon steel.

CAPORUSCIO: Well we have been looking at low carbon steel.

JUNG: Okay. Do you have any reports or ... to publish?

CAPORUSCIO: I believe the Cheshire 2018, which is one of the references in there, talks about the steel. If it's not the '18, it's the '14. It's one or the other. Both by Michael as lead author.

JUNG: Thank you.

CAPORUSCIO: Okay.

Did you want to say any more, Ed?

BAHR: Do we have other questions from ... Bret Leslie.

LESLIE: Yeah. I'll ... I'll re-ask Andy's question, because I marked it. Ed, on your slide, you were talking about copper. And ... and it was a corrosion-allowance material, which ... don't you mean corrosion-resistant material?

MATTEO: Do I have to say my name when ...

LESLIE: Yes.

MATTEO: Ed Matteo, Sandia National Labs. So we typically just say "allowance" because we know it's going to corrode. And so we ... we allow for the amount of time that it would give us as a corrosion allowance material; it's synonymous with resistance.

LESLIE: Yeah, but it ... not in corrosion science. Corrosion allowance ... you know, a corrosion resistant, you choose copper because it's reducing and ... and doesn't corrode.

So characterizing it as a corrosion-allowance material suggests it's in a oxidizing environment.

MATTEO: It ...

LESLIE: So that ... I ... I'm just trying to understand your choice of terminology.

MATTEO: Sure. It ... it just depends. It just depends on whether it's reducing or oxidizing. Also depends on, right, it would only be an issue in a brittle shale where, again, it would resemble a crystalline system with the potential for ... for fracture percolation and effective flow associated with that.

JUNG: So in this case, yeah, for the oxidizing condition, you can maybe call that corrosion allowance even though the copper, but the short term. But the long term in anoxic condition, we usually call this that a corrosion-resistance material. It's categorized to that part, not corrosion allowance.

MATTEO: Okay.

JUNG: So that is only for like a brittle shale is kind of oxidizing condition for the short-term period?

MATTEO: That, I think would depend on the ... yeah, on the actual shale.

JUNG: So in this case, which material is for the overpack? Overpack is in this colonized copper, right?

MATTEO: Are we talking about just in a brittle shale now?

JUNG: Yes.

MATTEO: Okay.

JUNG: That is for the copper?

MATTEO: It could be copper if ... if that was ... if you needed corrosion resistance and like, to the extent that it was a crystalline formation. Or it could be corrosion allowance where you ... the performance metrics that you need out of the overpack weren't something like, you know, near infinite canister lifetime, as you would need in a crystalline formation.

JUNG: In this case, in like an oxidizing condition, usually we use ... we are supposed to use like a stainless steel. Have the ...

MATTEO: Sure. Yeah, that's ... that would be corrosion allowance, yes?

JUNG: No, it's corrosion resistance. In the corrosion domain, we call this corrosion resistance.

MATTEO: I think ... yeah, I ... we have this ... I'm not making this up. This is in several DOE reports on repository design and that's the nomenclature that's used and that's what I've adopted, like, I can send you the reports. Several of them by ... by Ernie Hardin.

LESLIE: Okay.

MATTEO: But it would be good to speak ... this is always an issue in these ... disciplinary fields to speak the same language, right, in terms of like, the terminology that we use. So thank you for that comment. So ...

LESLIE: Bret Leslie, Staff. So Florie,

basically, kind of a ... I'm ... let me know if this characterization is right.

So even though you're doing a rocking autoclave, you know, and ... and then if you look at feedbacks. These are pretty water-limited situations where you're getting relatively small amounts of corrosion of the metal waste package, as compared to something like Yucca Mountain, where water was much more available, relatively speaking, which allowed much more oxides to form. Does that ... am I off-base?

CAPORUSCIO: So I'm ... no, but maybe I didn't ... sorry. Maybe I didn't mention. Most of our reactions, the water-rock ratio was anywhere from 9 to 1, to 13 to 1. So these were water latent, and actually, more so than Yucca Mountain, which was non-saturated.

LESLIE: Thank you.

CAPORUSCIO: Okay.

BAHR: Thank you. I had a question for ... for Carlos. In your ... you were talking about your experiment S14 and you said you were primarily working with changes in permeability to try to match that, and you said it was a work in progress. If you're not able to get a good match by simply adjusting the permeability, what other factors do you think you might need to either add to the model or parameters that you might need to change? You ... you do list, in your computational approach, a number of things that aren't included in the model, currently. For example, no ... no swelling is simulated and things like that. So can you ... can you speculate on what other things might need to be added to ... to try to improve the fit of the model results to the data?

JOVE-COLON: Carlos Jove-Colon from Sandia National labs. A good question. Well once we ... you know, considering swelling in here, kind of a simplification, I know. But we, for example have, saturation model embedded, van Genutchen model, van Genutchen model already embedded in there. That model in itself actually has parameters in it. And we try to maintain those parameters constant. I mean, not changing them or not adjusting them; just permeability to see if we can actually get, you know, to where we're going to go with the trend.

But with this non-isothermal experiment, our next steps to actually trying to tackle using ... adjusting those parameters. In addition, to actually either do a finer meshing, closer to the heat source, and actually trying to adjust permeabilities close to it, just to see the ... there's a level of isotropy in the permeability that I actually ... we need to capture that we are not, just because our mesh is too coarse.

So two ... those are the two things. Or maybe three: the meshing, adjustment of permeabilities on a finer scale, and also the saturation model here for the van Genutchen parameters.

BAHR: Thank you.

Chandrika?

MANEPALLY: Carlos, Chandrika Manepally, Board Staff. Carlos, this is continuing along the lines of Jean's question. I'd like to understand the overall goal of you participating in this DECOVALEX Task. Is it to add capabilities to PFLOTRAN that are not there? Because I'm assuming, if you use TOUGH-FLAC, you will be able to model this without the chemistry part, right? What is the goal, you know, in doing this task?

JOVE-COLON: Carlos Jove-Colon from Sandia Labs. The goal is to actually ... I would call it ... I don't like to use the word calibration too much, because it's too ... covers too many things. But validation, verification of a TH model for a bentonite is ... I mean, the Kunigel bentonite has a significant proportion of sand, it kind of behaves differently from Wyoming, you know, but ... still, it's a bentonite.

But I think that the overall objective is, you know, baseline. Our multi-phased transport models, in the ... in both isothermal or non-isothermal case. So that's, you know ...Developing a new capability, I don't see ... I mean, I think I have to still try modeling the data that exists right now before moving into that direction. So, so far, I mean, it's still work in progress. We don't see that we need to add a new capability for now. Maybe we have to do something, you know, for example, on the non-isothermal cases, you know, capillary, you know, pressure modeling, I mean, could be quite complex, et cetera, you know, but PFLOTRAN as it stands today, is capable of, you know, handling a equation of state... water, the kind of key ingredients, I call it, to actually be able to model this. We can get an overall trend, it's just that we cannot match the data as good as we could. But before I actually go and answer your question, I have to do the things that I tell Jean to do, you know, try other things until I say, "Okay. I give up."

MANEPALLY: Okay. Thank you.

BAHR: Okay. So I ... I think that ends our technical presentations. So we do have time for public comment. Do we have anyone in the room? I don't think we have anyone who's signed up for a public comment who's here in person. But if not, then we ... we have several comments that have been added online.

LESLIE: Oh, Jean.

BAHR: Oh. Dick Parizek has a comment.

PARIZEK: I didn't sign up, but I'm ... thank you for taking me on. I had a question specifically with regard to this understanding of sealing versus brittle behavior of an argillite. Sealing, I kind of visualize like salt being plastic and deformed and if you get rid of the porosity before you re-saturate it, now you ... you can sort of get rid of your permeability.

But in argillite, what do we mean by sealing? And perhaps there could be a little more detail on that, because that's the rock itself, not necessarily the ... the backpack materials, the bentonite as an example.

BAHR: Thanks for that comment. As I said at the beginning, this is not really a forum for questions and answers.

PARIZEK: Oh, okay, fine. I'll just list ...

BAHR: But that's ... but that ... that is a ... something that we will add to the record ...

PARIZEK: Yeah, I raised the question, I'm sorry.

BAHR: ... as something to think about. Yeah.

PARIZEK: And then there was a question about the temperature information that was provided in the last speaker, extremely helpful. It went up to 200 to 300 degrees Centigrade, which obviously, changes minerals. And it has all kind of mechanical hydrological implications.

And the question from a design point of view, what would be a reasonable temperature for a shale repository or clay repository versus like, salt or ... or other rock materials because of the perturbations that that might cause. And it seemed like you could manufacture some good things by temperature, and you might get some bad things by temperature. So this was ... clarity is needed there, I thought, from my point of view.

There was a statement made earlier about the bentonite becoming fully saturated in 25 years. Well 25 years for the bentonite, does that mean that the repository itself becomes re-saturated in order to get the bentonite saturated? So then now we have a permeability effect of the constructed repository. So there's issues I could see there that raise some concern.

We looked at the stability of the rock and the layering in the rock. It was interesting; experiments showing horizontal bedding had an effect on the mechanical behavior, but as I understand in shales, in claystones, they could have residual pressure effects as a result of a offloading. A glacial offloading.

We saw that in the Opalinus Clay. There's suction effects that were being reported and water migrating from the bottom and from the top, and so this is sort of like a black hole, so there's a beautiful repository self-contained. And then Chris Neuzil, years ago, spoke of this on some of his shale experiments. Presumably, that'll be discussed tomorrow. But right away, a sucking shale is a fantastic host rock, because maybe ... how many years can you buy isolation in such an environment? But if you open up a repository in that situation, what does that do to the ... this beautiful system? And will the system collapse or have a shorter lifespan because of it?

But also, to say that the rock mass got back to equilibrium in 25 years, as a result, it became homogeneous and isotropic in terms of its behavior, what about this residual stress situation on the more regional scale for the rock mass? It seems like you have a residual stress field that's encompassing the experimental area of which you're studying, and it might have some impacts on the behavior of that rock mass. So there's some issues.

And then I have a question about surprises, you know, in repositories. I worked on WIPP for a number of years, and I was amazed when Pat ... Tom Pickford calculated fluid migration toward a heat source. And they ... they actually migrated and that was not in my thought process. I mean, I have trouble imagining weightlessness myself, and ... and zero gravity. But to have fluid inclusions migrate in salt was interesting.

And it was also surprising to have brine occurrences in embedded salt, flushing in on you when you're extracting salt. Wasn't exactly expecting that. But pressurized brine below the salt horizon was a surprise because you could now pressurize pockets and hit them with a real rig and bring fluids up through the repository to the surface. And these are not in the thought process at the time. And who expected the Asse Mine to be leaking water. Wait, this is Asse Mine, and it's now got a problem. They ... wasn't exactly a repository, it was over extracted salt, perhaps, I guess maybe why it's leaking. But there's always these surprises.

And so from a shale point of view, other than the surprises maybe of this negative pressure situation, you know, what other surprises that might come out of the shale rock? I mean, every ... every rock media has its own special behavior and things that we don't always understand. It takes years to figure these things out. But there must be some surprises in the shale, and surely in the design requirements and the whole overpack. All the issues that are ... brings to mind.

So these are some thoughts as I kind of listened to this. But early on, there were ... a lot of progress has been made on shale, and on argillites. And then the question is, you know, do we have at depths of how many meters I didn't know how deep the repository might be.

But isolation depths are kind of important, so that was part of the thought process and we ... here now, I guess 3- ... 300 meters to 1,000, or maybe 3- ... yeah, 3,000 meters were some of the notes, I think, so that's kind of deep. And at those depths, do we have anything that acts like the ... the clays over in Europe? I mean, most of our clays at that depth are probably, I guess, not that plastic. They're not like glacial clays, right? I'm not sure, you know, the range of conditions you might have to try to pick the rock site.

And there was an illustration that said the stable occurrences of shale. And the stable occurrences go up into the Dakotas. But it's not stable with irregular glaciation. Glaciation is going to come back and ... not in our lifetime, but it's coming according to the ... all the work that's been done dealing with what the mechanics are that drive the climate change. So glaciation in some of the regions of our country would clearly not be a stable effect in terms of the flow field effects and the mechanical effects as an example.

So ... and then to look at the Appalachian Region, we have 40,000, 400,000 oil and gas wells, they don't know where they ... many of them are. We have now some funds to begin to start plugging some of these wells. And there's thousands of them. And so there's certain areas that we've already kind of meshed up in terms of repository behavior. And we already have a lot of experience with this whole question about existing openings.

So there's a lot to think about in terms of shale as being the new magic rock, right? The granite was a great rock, but in ... when the Swiss got out of the granite and seemed to head for the shales, they had a good reason to do that, right, it was that whole permeability problem that has to be dealt with.

So shales are great, and clays are great, but they also must have some surprises. And so maybe Chris, tomorrow, Chris Neuzil's talk, may talk about some surprises, the unknowns he mentions. I'll be curious to hear what he has to say.

Again, I don't expect answers, but I ... I'd rather write all this down to you. I'd rather be able to list it this way. Thank you.

BAHR: Thank you, Dick, that will be included in the transcript due to our ... our great court reporter, who is making notes here.

And now we have comments that have come in online, I believe Bret Leslie is going to read those?

LESLIE: Yes. Bret Leslie, the Staff. There are only two that came in. During Chris Camphouse's opening presentation, Diane DeRigo, from Nuclear Information and Resource Service just stated, "Please expand on the validation of models." And that was her ... her comment.

The next comment came in during the Q and A on Jonny's talk. And this was by Stuart Stothoff from the Center for Nuclear Waste Regulatory Analysis. "The rapid thermal pressure response from the Bure Borehole Experiment was also seen at the Mont Terri site with heater tests. Our team interpreted that as rapid mechanical propagation of swelling at the borehole wall that rapidly changed the shape of the opening. In other words, the processes near-field T to M to distil P response." That's the summation of the ... of the comments today.

BAHR: Okay. Well, that's the end of today's meeting. I thank all the presenters and everyone who's been listening in, both in person and online. And we'll convene again tomorrow for another set of interesting talks. And that will start at 12 Eastern Time. So come back tomorrow, and we'll see you there. Thank you.

[Whereupon, at 4:55 p.m., the meeting for Day 1 of 2 was adjourned.]

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