UNITED STATES

NUCLEAR WASTE TECHNICAL REVIEW BOARD

TRANSCRIPT

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

Wednesday

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150 Anza Boulevard
Burlingame, CA 94010

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PROCEEDINGS

BAHR: Good morning, that's the traditional music to start the Nuclear Waste Technical Review Board meetings. Good morning and welcome to the U.S. Nuclear Waste Technical Review Board's Workshop on Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations.

I'm Jean Bahr, I'm the chair of the Board, and I'll introduce the other Board members in a moment, but first I'd like to briefly describe the Board. 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 organization. The Board was created in the 1987 amendments to the Nuclear Waste Policy Act to perform objective, ongoing evaluations of technical and scientific validity of DOE activities related to implementing the Nuclear Waste Policy Act.

The 11 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 to Congress and the Secretary of Energy. The Board also provides technical objective information on a wide range of issues related to the management and disposal of spent nuclear fuel and high-level radioactive waste.

This information can be found on the Board's website www.nwtrb.gov along with Board correspondence, reports, testimony and meeting materials including websites of its – webcasts of its public meetings, and copies of some of the Board's most recent reports can be found on the document table at the entrance to this meeting room.

Now, I'll introduce the Board members and then tell you why we're holding this workshop and a little bit about our schedule for the next two days. First, the introductions. I'd ask that as I say their names, the Board members raise their hands so that they can be identified. I'll begin. I am Jean Bahr the Board chair. All of the Board members serve part-time, so we all have other jobs, and in my case, I'm professor emerita of hydrogeology in the Department of Geosciences at the University of Wisconsin-Madison. Dr.

Steve Becker is professor of community and environmental health in the College of Health Sciences at Old Dominion University in Virginia. Dr. Susan Brantley is distinguished professor of geosciences and is director of the Earth and Environmental Systems Institute at the Pennsylvania State University. Mr. Allen Croff is a nuclear engineer and adjunct professor in the Department of Civil and Environmental Engineering at Vanderbilt University.

Dr. Tissa Illangasekare is the AMAX Endowed Distinguished Chair of Civil and Environmental Engineering and director of the Center for the Experimental Study of Subsurface Environmental Processes at Colorado School of Mines. Dr. Lee Peddicord is director of the Nuclear Power Institute and professor of nuclear engineering at Texas A&M University. Dr. Paul Turinsky is professor emeritus of Nuclear Engineering at North Carolina State University, and Dr. Mary Lou Zoback is consulting professor in the geophysics department at Stanford University.

I've just introduced 7 Board members plus myself, not the full complement of 11. Due to other commitments, Dr. Linda

Nozick is unable to join us today. Dr. Nozick is a professor and director of civil and environmental engineering at Cornell University. Also Dr. Efi Foufoula-Georgiou is unable to be with us because she's under the weather, but I believe that she's following the meeting on webcast and she may be emailing some questions in during our discussions. Dr. Foufoula-Georgiou is distinguished professor in the Department of Civil and Environmental Engineering at the Henry Samueli School of Engineering at the University of California Irvine. And the Board currently has one vacant position.

I'd also like to introduce two experts who are serving as consultants to the Board during this workshop in specific areas that we will be discussing. First, is Dr. John McCartney, he's professor and chair in the Department of Structural Engineering at the University of California San Diego and Dr. David Bish is professor emeritus of geology in the Department of Earth and Atmospheric Sciences at Indiana University.

As I usually do at Board meetings, I want to make clear that the views expressed by the Board members are their own not necessarily Board positions. Our official positions can be found in our reports and letters which as I mentioned are available on the Board's website. If you'd like to know more, sorry, if you'd like to know more about the Board, a one-page handout summarizing the Board's missions and presenting a list of Board members can be found at the document table at the entrance to this room. And you can also visit the Board's website as I mentioned at www.nwtrb.gov.

At the end of each day of the workshop, members of the public will have an opportunity to make comments. If you want to make a comment, please add your name to the sign-up sheet that's outside on the registration table and time for each speaker may be limited according to the number of people who want to speak, but any written comments or other other written materials that you want to submit to one of our staff members today or by email or by mail to the points of contact in the press release for the workshop which is posted on our website, these, any of these documents submitted by the public will become part of the meeting record and will be posted on the Board's website along with the transcript of the workshop and the presentations.

If you make a comment during the workshop, please use one of the microphones that are available, there's one in the center near the front of the public area, state your name and affiliation so that you'll be identified correctly in the meeting transcript. This workshop is being webcast live, so you'll see some cameras around the room. Depending on where you're sitting, you might be part of the webcast. I encourage presenters to speak loudly enough so that those in the back of the room can hear you, and it will also be helpful to those who are watching the webcast if the presenters will summarize each question that's posed to them before answering it.

The webcast will be archived for a few days and then will become available on our website. To assist those watching the live webcast, the workshop agenda has been posted on the Board's website and that can be downloaded, and the presentations will be visible as part of the webcast and they will ought to be posted separately on the website right after the workshop.

So, I'm not sure if I am on the right slide here. Whoops, I managed to hit the wrong button. OK, that's the information, OK, I'm at the right place now. So why are we holding this workshop? Well, a number of countries including Belgium, Canada, France, Finland, Germany, Japan, Korea, Sweden, Switzerland and the United States have operated underground research laboratories in different types of rocks to support the development of deep geological repositories for the disposal of high-level radioactive waste and spent nuclear fuel. There are some examples of rock samples from some of these laboratories on a table somewhere in the back of the room that Bret is pointing to, and you're welcome to examine those during the break, and I think you can pick them up and look at them and feel them and touch them.

Underground research laboratories or URLs for short enable research and technology development activities to be conducted under conditions and scales relevant to specific repository environments. Since 2012, the Department of Energy has engaged in active collaborations with the geological disposal programs of several countries, including participation in research conducted in URLs in Europe, Japan and Korea.

DOE's international collaborations now form a considerable portion of its geological disposal research portfolio. According to DOE, these collaborations have been beneficial to its own disposal research program, because they provide access to decades of experience gained in various disposal environments in a cost-effective manner. They enable DOE-funded researchers to gain research experience and take advantage of established URLs in a short period of time, and they provide opportunities of peer reviews of DOE data and analyses by international experts.

The Board has in the past in both our letters to DOE after our public meetings and in a variety of reports encouraged DOE to maintain awareness and take advantage of opportunities for international collaborative research, so the Board is very pleased to see DOE actively engaging with international partners and participating in the research of the URLs.

The workshop objectives are to review DOE research and development activities related to URLs and to elicit information that will be useful to the Board and its review as well as to DOE in its implementation of those research and development activities.

The workshop begins this morning with an overview presentation on the purposes and types of URLs and the R&D activities that are conducted in those facilities. That introductory presentation will be by Mick Apted of INTERA who has extensive experience working in geologic repository research on both in the U.S. and throughout the world. Mick’s presentation will be followed by a series of presentations on international R&D programs in Switzerland, Sweden, France and the United Kingdom. These presentations will then be followed by a facilitated panel discussion related to the international URL programs. Then, DOE representatives will provide an overview presentation on

DOE's geologic disposal R&D program and its integration with the international URL research.

The remainder of the two-day workshop will include technical presentations on DOE's URL related research and development activities focusing on natural barriers, engineered barrier integrity, hydrologic flow and radionuclide transport, salt research and the geologic disposal safety assessment framework that DOE is working on.

A poster session is scheduled immediately following today's adjournment. Adjournment is scheduled for 5PM, and I will try to be keeping us strictly on time so that we can make that deadline and have plenty of time to discuss the posters. At the end of the day tomorrow, we'll have a final plenary session that will identify key issues and lessons learned from the underground research laboratory R&D programs. And the workshop tomorrow will also end at approximately 5PM.

A lot of effort went into planning this workshop and arranging the presentations. I want to thank our speakers who travelled here, particularly the speakers who have travelled here from other countries. I will also want to thank Drs. Mary Lou Zoback and Tissa Illangasekare, the Board members who acted as Board leads and who coordinated with other Board members and Board staff to put this workshop together. And I want to thank the DOE and national laboratory staff who supported or made presentations at a Board fact-finding mission meeting that we held in February of this year in Las Vegas to help prepare for this workshop. And the presentations that were made at that fact-finding meeting will also be posted on the Board's website along with the presentations from today's workshop so that you have a more complete picture of the information that we've been reviewing.

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

APTED: Well, thank you, Jean and thanks to the Board for inviting me to participate in this workshop on international underground research laboratories. What I'm going to give you today is about a 10,000-meter-high view of the issues associated with URLs. I want to mention that my co-author on this is Neil Chapman. Neil is preparing, and I've been contributing to an IAEA course on URLs, and so a lot of the information here you'll see is sourced to that IAEA presentation short course that is being prepared. In other cases, hopefully I've identified other sources of information that might be interesting to the Board and other participants in the workshop.

OK, my talk is divided into four parts. I'm going to talk about the role and objectives of what I call underground research facilities. You'll see why I'm using that terminology in the next slide. Evolution of URFs over time, history of URFs, a little bit of down memory lane trip and then a short tour, I think of these almost like postcards of very quickly going through a number of the URLs that are out there that have already been mentioned.

So, definitions and meanings. Now, the different countries have come up with different names for things that relate to this general category of underground research laboratories, and what I've done and Neil here with me is sort of collected the different terminologies you'll find in the literature, URL, underground research laboratory, the word laboratory in our view implies more of the main emphasis on experimental work and really early fundamental processes. You see underground research facility, Onkalo is often referred to in Finland as an underground research facility.

Here, research applies more to the idea of applied research of what's going on, particularly in demonstration of emplacement, rock excavation and so on. A rock characterization facility, that term is used in other countries as well. So, what we've come up with and we see this term, we think, evolving more to the forefront in terms of collective term for all of these types of efforts is an underground rock facility. It's a more generic term. It's a facility basically for research, characterization and demonstration, excavation and emplacement of engineered barriers.

This is, I think, more in tuned with the international views. I think today, what we would say the emphasis on characterizing host rock for design, design optimization and providing information to the safety case along with testing and demonstrating constructability if you will and feasibility of that is really at the forefront. The era of fundamental experiments and research into basic processes we feel has long passed.

OK, I'm not going to read all of these, you've got I think the presentation itself. I just want to quickly point out some of the key words in terms of the value, training, verification of earlier site-based characterization of a site, development and testing of special rock excavation techniques, permitting full-scale demonstration of realistic in situ demonstration, particularly what you get at depth is pressure. Is pressure important? Well, it often is if you think of in a lot of the chemistry situations with volatile species.

It allows basically, if desired, a pilot disposal type of facility that might be built early and emplaced and monitored over the time of the multiple decades of which an underground repository is constructed, and then dismantled to learn information about what has happened over multiple decades.

Public demonstration, I think this is, to me and I think to a number of people here is really it's a key and often an overlooked topic of how to engage to the public, how to build that confidence and social acceptance in terms of what is geologic disposal, what does that mean? I think the first point, the general public is not particularly well understanding of what does the underground look like, what are the issues associated?

They're just – it's vague, it's out of sight. So, the importance here and I'm sure later, Patrik is going to talk about the Äspö, the demonstration of emplacement of canisters in that facility. Again, this is an important thing to show to people, these stakeholders. I'm sure the Board has visited some of these same URLs and so on to see what is being done, how is it being done, what is the confidence that it can be done, very important.

Early stages, basically to show these stakeholders what does the deep rock look like and at later stages really show at increasing scales both temporal and spatial for the purpose of demonstrating that these concepts and these disposal approaches can be confirmed.

OK, when does a URF play a role? This is again basically think of a time sequence, early going, very much in terms of providing training to staff. This is after the host rock is perhaps selected, in situ characterization, after-site selection, test characterization, developing specialized rock machinery for excavation, eventually in some of the more mature programs are going to hear later this morning, full scale demonstrations, in situ demonstrations to stakeholders and as I say possibly a pilot disposal facility.

The Board had a question on generic versus site specific URFs. I'll give you my take here and maybe later when we're, as a panel, we'll talk a little more about this topic. The generic URF, again, training, developing specialized excavation methods, sealing systems, how we're going to seal shafts and ramps in which we get the waste from the surface to the underground. And then site specific as part of a repository here where the underground characterization and demonstration work is done, sort of building on site characterization, demonstrating the capability of emplacement and if possible retrieval if that's required by the national laws.

And in addition, all these activities in the next slide which is very long, and I won't read. But basically, all this work is done in the generic URF, if it can be done later in the site-specific site laboratory should it even – is it really needed to do it in a more generic location or not. I think it's a question that has to be considered in terms of the context of each national program.

OK, what are the typical activities, again, I'm not going to read all these, I'll point out some of the issues we're going to hear later tomorrow's and later this afternoon, thermal, hydrologic and chemical, THMC impacts on emplacement of these engineered barriers within a geologic setting. So, if you have questions and want to amplify or edit or suggest onto to this list, this is a list Neil and I sort of put together consulting a wide range of national programs in terms of how they see the typical activities and roles for a URF.

OK, so this is a single slide for part two, evolving objectives. Again, this is time zero here, early program planning, eventually leading hopefully to operation and final closure of a geologic repository. In the early going, perhaps the roles here are very limited until we actually get to a site and there may be benefits instead of a program in its early going tying up with other international programs and learning what's going on in URFs in other countries for example. So, in early stages, this idea of perhaps rather than doing one locally in a country, tying themselves into other countries might be a preferred approach.

But later, I'm not going to go through the whole flow diagram here, but you can see a lot of attention we thought of being put into this in terms of what are the various activities that need to be addressed and how a URF is providing and meeting some of those inputs.

All right, history, probably most, hopefully many people realize we're this whole geologic disposal originated, in a 1957 National Academy of Sciences report. You notice it was sold for a dollar, it's a very interesting, again, step back in history in terms of the cost. But the group here was focusing primarily on looking at liquid radioactive waste, so it wasn't looking at spent fuel or high-level waste, or metallic components. It was looking at liquid radioactive waste how to dispose of those safely within the environment.

Excuse me, while I get it, catch myself up here. And perhaps many of you have heard in early 1960s, Project Salt Vault in Kansas in bedded salt was one of the early programs, putting heaters in salt to look at what would be the impact of radiogenic heating on if waste was put into salt formations. Actually, before Project Salt Vault we were digging around in literature, that was really the first documented underground experiments in salt were 1959 in Hutchinson, Kansas. One of the key findings basically at that point was that direct disposal of liquid radioactive waste was not looked to be feasible, partly because of issues particularly around gas generation and corrosion.

This is the snake diagram we put together. It's basically showing the long history here. We had to sort of loop things around in terms of the number of URFs that have been developed overtime, again, starting here in the 1957 National Academy Report and now looking at some of the very recent ones in China and Czech Republic and so on that are currently being put together.

OK, historical evolution of activities, in the early going and by early, 1960s to 1980s, so that's well before my time, demonstrate basic technical feasibility of geologic disposal, formulate techniques, understand transport of nuclides in host rocks. Then a national repository program started being put together in Posiva in Finland, SKB in Sweden, the early OCWRM work here in the U.S. and here basically in the '80s up until the 2000 study of this coupled process THMC, I defined that earlier, demonstrating technical feasibility, trying to formulate the design, optimizing design and detail.

And then over time, you can see different activities have really started emerging and eventually now, we're getting into the era of full-scale testing of in situ systems basically dress rehearsals, can we actually build it as we draw up in our wonderful perfect computer screens and everything looks perfect. And we find, maybe it's a little more difficult than that.

OK, part four, I'm going to talk a little bit about some examples, and I'm going to take Stripa which is one of the first URLs on that snake diagram you'll notice and delve a little bit deeper and look a little bit, that's sort of a bad pun, but look a little deeper in terms of what was being done at that time, what were the results at that time, and what evolved out of that very useful set of activities that was done in the 1980s. I'm somewhere in this photograph, I can't, I'm a much younger person at that time.

One of the activities was rock characterization studies and very forerunner, actually the Swedish and American cooperation, the so-called SAC project started, between the early organization of what SKB evolved into and Lawrence Berkeley, looking at fracture hydrology and fracture apertures, geo-hydrochemistry in service of doing hydrologic modeling, in situ stress, permeability, or you can read these various stages in terms of the phase one and phase two and phase three. Particularly phase three and the latter part was getting to the important issues of trying to understand the undisturbed rock volume and the heterogeneities at what scale were occurring because in the early 1980s, the hydrologic models and I think Patrik will maybe speak more to this, were very simple or sort of deterministic. And one of the things that quickly emerge from the Stripa is a need for different conceptual models to try to capture that spatial heterogeneity that actually is present in fractured rocks.

So this got the site characterization and validation, the so called SCV project, again, well organized, a lot of different activities all feeding together in a flow diagram looking to try to derive some important insights into the topic of how do we characterize a block of rock that we have not yet intruded into and then intrude into that to see if those models and our predictions actually were in a sense validated, although I think that word validated has sort of fallen off best usage in our programs.

One of the more particular other aspects of Stripa is multiple flow conceptual models were developed basically on the Stripa data. The data that was collected basically raised doubts this deterministic equivalent porous media flow modelling, were not going to work. It really didn't capture the, again, the heterogeneity at different scales of this kind of rock. And so instead that began the development of one conceptual model that looked at the discrete fractured networks which, again, I think Patrik may talk a little bit about from the SKB perspective, stochastic continuum models, the so-called Dershowitz Fracman modelling. And more recently this idea of sparse channel models for hydrologic flow built by John Black in the UK.

So, all these basic models, were conditioned to the data from Stripa and they all basically agree with the data from Stripa, but partly because there's a number of adjustable parameters in all of these models. It's not surprising that it's more of a calibration than any sort of verification or validation. Basically, they are using the data to say can we develop models that will basically reflect back the data that we've actually measured.

But to me, the important discriminating result from Stripa was in 1991, actually it came out in 1992, so-called SKB '91. It was a very important report and basically, they concluded using results from the Stripa data, that shows that the safety of a carefully designed repository is only affected to a small extent by the ability of the rock to retain escaping radionuclides, meaning the hydrologic setting of the system.

The primary role of the rock is to provide stable mechanical and chemical conditions in the repository over a long period of time, so that the function of the engineered barrier system is not jeopardized. This is the heart of the conclusion of that main report. In a takeaway of a key finding, hydrology and basically associated uncertainties in hydrology in fractured rocks and particularly for spent fuel, the case may not be the same for something like intermediate level waste but for spent fuel, really have a low risk significance with respect to long-term safety.

Probably there are other factors that show proportional impacts, but hydrologic and if you think about it, it's fairly obvious why if your far-field transit time or distance is 50 or 100 meters why hydrologic flow was not going to provide the basic great isolation capability that was initially thought of the early 1980s.

So, my also takeaway is that this focus on hydrologic flow models early illustrates a problem with conducting R&D when not guided by a top down safety assessment of the entire repository system. Idea, now what you see in more and more programs and modern approach is a safety function approach, a top-down approach of looking at what can happen to a repository system and making judgments about that.

OK, stealing a little bit of thunder maybe from some of my co-panelists coming up, just we’re now into the postcard type of showing, but I'm going to point out and read some of the key findings that come out at some of these URFs that you can look at. Here is the Äspö currently going on in crystalline rock. And when you look at all of the current planned efforts, I mean there's the emplacement, there is basically looking at alternative buffers and buffer tests, sulfide experiments and other sort of geochemical, really the focus now is more in geochemical and emplacement and performance of EBS components in the underground. This is really where the modern URFs are at now.

This is the Onkalo facility, I think, Irina, it's about 3 kilometers of underground tunneling that they've done from the surface all the way down, all of this before they got their construction license approved by the way. But basically, to get down to what they were looking to be the repository depths here but then look at a number of sort of issues on constructability. One, their first deposition tunnel, they looked at, excavated six vertical deposition holes, they found three that were not going to qualify because of intersecting fractures, that's a 33 percent rejection rate. If that rate continues there is not going to be enough volume unless they build tiers at Olkiluoto Island to put all of the Finnish spent fuel there. So, it's a big deal to get down there and find some of these issues that they're going to have to confront.

They've also looked at tunneling here and basically trying to level this floor because that becomes a very important aspect in terms of how fast can one backfill these tunnels before they start swelling and creating problems. So, can that be done robotically? How smooth can we make that floor become important questions for the Finns.

In Canada, during early 1980s and early '90s, basically at the Lac du Bonnet, the batholith, one of the key findings is the rock mechanics, people enjoy this, is there was actually very high anisotropic stress ratios. Basically, there's lensing as they went down and rock spalling. So, one of the conclusions that came from that saying if we're going to be in that kind of environment, can we come up with engineering counter measures or workaround. And one of it was basically now instead of actually depositing canisters in vertical or horizontal deposition holes, the Canadian approach is to put their waste in large emplacement rooms, vaults.

I mentioned just Asse because it was one of the early ones in terms of demonstrating trial canister emplacement. Mol in Belgium has done a number of tests. You can see that they're fascinated with Greek and Roman mythology in terms of the names, Archimedes and Orpheus, but there's been a number of important tests done at the Mol site.

Grimsel, I'm not sure whether Irina will talk much about that a little bit which is presently going on, but it's in crystalline rock, high in the Alps. Daniel will be talking about the Bure and in France, wonderful location, and again, some of the type of planned underground laboratory work and characterization that's planned. China, we – I mean China, like in a lot of other areas, it's in early stages, you might say it's in our rearview mirror compared to a lot of other nations, but it's coming fast, very fast for a number of reasons.

So, they're planning now to build a URL which is what they call it. They're basically, the China Atomic Energy Authority has approved it to be built somewhere in the overall Beishan site which is a granite batholith out here in the Gobi Desert. Nine current candidate sites that are being explored and basically, they plan to start sinking shafts in 2020 and they've been pretty good at meeting their schedules. So, pay attention to that.

My summary slide basically let's roll this up and where we've been and where are we now and what might be going on. So, the current global status, these are a bar-chart basically showing that are currently inactive or decommissioned, currently in operation and here's are ones that are under construction. And then here they're basically showing in type of rocks what has been done in salt, crystalline rock or sedimentary, basically clay, argillitic type of formations in terms of what has been done and what are planned to be done in those type of host rocks.

So, thank you very much for your attention and I welcome some questions.

BAHR: OK. Thanks, Mick for keeping to the schedule. We have about 15 minutes for questions, so that's great. I want to start out, you said a couple of things that were interesting to me as a hydrologist. One is that the hydrology is not important in…

APTED: In fractured rocks.

BAHR: In fractured rocks. So that's what I wanted to probe a little bit is one of the things, I guess that we've learned is that in fractured crystalline rocks a repository really relies on the engineered barrier system rather than on the geologic setting itself. Do you think that that's going to hold true for other types of lithologies, clay and salt that people have investigated? And it certainly was true for Yucca Mountain as well which is another fractured rock.

APTED: Yes, you put your finger on exactly the right question to consider. The clay rocks, basically the far field there is thought to be a diffusion type of boundary condition. So, if you have 90 meters of clay like in the Opalinus report in Nagra and you look at diffusion calculations there, very little gets out even over a million years because it's diffusion based.

I'm not saying that hydrologic modeling is not needed at all. I'm just saying within the relative sense of all of the type of processes that need to be investigated, its risk significance, safety significance is lower than a lot of other factors. In the sense of the uncertainties associated with hydrologic modelling even if large may not have much of a consequence on the final safety analysis in terms of the uncertainty that's all captured within safety case analysis that's done.

So, I'm not saying all hydrologists go apply for another job or something like that. I'm just saying that within what's now known about what is important in fractured rocks for spent fuel, there are probably other topics and you're starting to see that in terms of where SKB and Posiva in particular and the Canadians are starting to look for their planned and current URFs.

BAHR: And yet on the other hand, you mentioned that at Onkalo, 33 percent of the tunnels had to be rejected because of fractures. So that suggests that in fact a significant amount of fracturing can compromise safety.

APTED: Oh yes, the fracturing is important, but there, I think and maybe Patrik will weigh in later as well. The issue there is buffer erosion into fractures basically. If these are very fast flowing fractures, is it capable that over time there basically a stripping out in expansion and remember the bentonite clay is expanding. Will it expand into those fractures and then be whisked away and overtime? You're starting to lose the density of the buffer which is basically an important characteristic for suppressing microbial activity and assuring colloid filtration and so on and stabilizing the canister, so it doesn't sink. So, in that case, rejection by the fractures is more based around this issue of buffer erosion.

BAHR: OK, thank you. And then finally, at the very beginning, you've said that the era of fundamental research in URFs is long past. Does that mean that we really understand all of the geochemical, hydrologic, mechanical, thermal processes well enough that we don't need to investigate them in the underground, the details of those are simply parameterizations of well-developed and well-justified models? Or do you think there are things that we can still learn about fundamental processes by going underground?

APTED: I say it would depend on where the program is. In the part two, I put out that sort of organizational diagram and so on. In early parts of a nation's program where they're trying to build up core competencies and studying how do approach this idea of siting and so on, there could be merit in terms of trying to be associated with programs outside of their country to learn about fundamental processes, what's been going on.

There's a lot of, looking back at Stripa, that's 40 years ago now, we've got new generations of staff coming in who are pretty ignorant of what went on and what was found and so on as we get grey hairs suddenly moving on into retirement. So, I think you're begging in a sense the, dragging me into saying, well yes, there's some fundamental processes to be done or something.

But I think it's a large part of something like diffusion in clay or hydrologic modelling of fractured rocks is a well-developed topic in which basically if you go that way, you have a site in fractured rock, then you can basically bring those existing models to bear on that. You don't necessarily need to start fresh and say, "I'm totally ignorant of what's already been done." So, I still say that's the reason for saying that era of really basic research is really coming to an end, has come to an end.

BAHR: OK, are there questions from other Board members? Tissa?

ILLANGASEKARE: Yes, my name is Tissa Illangasekare, Board member. So I want to start off, continue a little bit more on what Jean's question was, so you made the point that the rock actually has the mechanical and the chemical properties are used as barriers, but then you also mentioned that – so the point is that if you look at chemical properties, chemical issues, then you cannot avoid dealing with water. So, said that, you may be saying that the water flow may not be significant, but even a small amount of water may be the one that drives the chemistry.

APTED: Yes, that's fair. And again, I always go back to the more mature programs like in Sweden and Finland, one of the issues there is later glacial melt waters that are oxidizing, can those penetrate to great depth. If so then it can change for example the corrosion modeling that's applied for the canisters of copper and so on. It can also change the whole rate in which buffer erosion might occur.

So yes, there's some issues that are tied in and linked, you're absolutely right about that. Again, I'm not saying no hydrologic models, it's almost a question of sufficiency. We can always, Rod Ewing and I used to go back and forth on this topic, he used to say we need complete understanding and I said, but complete understanding, I mean tell me anywhere that's possible in science. Do we have sufficient understanding at different stages, in the early stages of surface base testing, can that give us an ability to go underground and collect more detailed information and so on? I think that's the right approach, sort of building up your competency in terms of developing a sufficient information to support a decision at each step over a multi-decade type of process.

Again, I'm not throwing hydrologic modeling away, I'm just saying a lot of it has been done and in certain contexts, the fractured crystalline rocks, by itself, it's that sort of transport from the buffer to the vertical fracture zone is not a very important safety function.

ILLANGASEKARE: But said that, if you look at generic sites, if you are trying to develop a model for a generic site, don't you think it's a good idea to consider this, because that way you can eliminate sites because you have a tool like that, it allows you to go through that process of elimination like you mentioned that it’s not a highly fractured site, and you can show that using this coupled model, so what the significance of these things are.

APTED: Yes, I mean if it's a conceptual generic site and so on, there has been, in your analysis, you're putting in assumptions about what that rock is and so on. And again, yes, if you dial – for example in Canada, the crystalline rock there, they assume no fractures, they could not find any fractures. Their argument there for that granite was that it would be transport by diffusion, so it was very much like the clay situation where hydrologic modelling was not going to be the dominant transport factor, but diffusion.

So one could easily make that assumption that we're going to find a wonderful granite site where just like the Canadians did that it’s all transport by diffusion. So again, I think we're armed now well with enough between discrete fracture modelling developments and the frac man and sparse channel flow models, we’ve got a number of conceptual models out there that can help guide any future generic beginning point that a nation might find.

BAHR: Others, Paul Turinsky?

TURINSKY: Turinsky, Board and remember I'm a reactor physicist when I ask this question.

APTED: I like you already.

TURINSKY: Are folks considering repositories for materials other than nuclear materials, and if they are do they operate URLs and is there interchange between our community and this other community?

APTED: That's a wonderful question. I mean for example, at one time, and again, I have to keep deferring to some of my international colleagues who maybe have longer perspective. In Sweden that was issue about mercury from batteries and other things, could mercury be also disposed of in a deep geologic repository? Norway is currently looking at what they call acid rock, basically rock that's been out of tunnels that basically are creating a huge chemical plume at the surface and could they be used as backfill and so on? So yes, that consideration has been made.

On the other hand, for example, at one time SKB was thinking of filling their copper canisters with lead shot around the spent fuel until they recognized that pulse of lead might get out as well because it's never decaying. It's one of the advantages of radioactive waste disposals is that the hazard diminishes with time. Not true with mercury or arsenic or some of these other ones. So, it's a wonderful question too, but in general no, that people have basically focused on the problem at hand because it's basically, the utilities are funding what is needed to go on, so they're interested in their problem first.

TURINSKY: But in the chemical industry, they're not operating URLs for disposal?

APTED: I don't know of any, but maybe somebody else, Bret or Bobby, any of you guys might know. I don't know of any.

BAHR: Mary Lou has a follow-up.

ZOBACK: Mary Lou Zoback, Board. Yes, there's a huge body of information and operations on underground repositories for carbon dioxide.

APTED: Good point.

ZOBACK: And the Department of Energy has several of those facilities they're working on now, so maybe some of them. And Daniel, I believe much of your early career was working on gas storage, underground gas storage. Storage, right?

APTED: Yes, natural gas storage, correct.

ZOBACK: But the same thing, you need to understand if you want to keep – if you want to sequester CO2 and keep it out of the environment, you need to be sure it stays underground for a long time.

APTED: How long is long? OK, there was a question over there.

BAHR: OK, I think Lee Peddicord.

PEDDICORD: Lee Peddicord from the Board, also a nuclear engineer, we’re sequestered to this side of the room I think. So, following up on your comment on the Finnish experience, a third novelty of the drifts not meeting requirements due to fractures, is that unique to that site or is there a more generic observation that this might be more typical as you go underground and…

APTED: It's a small statistical sample of six holes and three that were, or two that were found unsuitable. Since then, and again…

PEDDICORD: I was thinking more of their national programs.

APTED: Well I was just going to say, they've extended that deposition, I think they have now 12 deposition holes, I don't know what the latest statistics are. But I'm not answering your question then, was I?

PEDDICORD: So, I wondered if a rate not unlike that had been found in other national facilities in the same medium?

APTED: I don't know of any. I mean, again, the Finns are the furthest along, they're the first to get a construction license approved and they have built Onkalo and so on. An experience from Äspö for example may not be relevant to the Forsmark in Sweden I would think and so you'd have to be careful about that.

PEDDICORD: Thank you.

BAHR: Other questions from the Board members? Steve Becker?

BECKER: Becker, Board.

APTED: It's Steve Becker from the Board.

BECKER: Yes, Steve Becker from the Board. Becker, Board.

APTED: Come up here.

BAHR: Wait, we're trying to get the microphone working.

APTED: Come up here.

BECKER: Becker Board. Thanks for that nice overview. I'm going to change gears ever so slightly. On one of your slides, you noted the value of URFs in demonstrating processes to stakeholders and on another slide, you described public outreach as essential. Has there been enough URF experience with stakeholder engagement and public outreach that we now have a sense of what the best practices are and what innovative approaches can be taken in this regard, and has anybody published anything along those lines?

APTED: I'm taking your last question first, I don't. I'm unaware of any, but again, Patrik might know more. I think it's more anecdotal at this time in terms of bringing people to the Äspö site and demonstrating, showing what's going on with the copper canister. And by stakeholders, that's everything from the elite, like the Board that visits these kind of facilities I'm told, down to the local municipality decision makers and even the general populace.

How well it works, I don't know, but it can only, it seems to me, to benefit them. Our approach is to allow them to see what we're doing, that it's not all just waving a wand or something like that. We know what we're doing, they see the large equipment, they see the safeguards that are in place. I think it's just a cumulative experience for non-technical stakeholders to see that.

BECKER: And just as a follow-up, do you think that there will be a value to a sharing of those best practices and lessons learned in that regard across the different URFs so that everybody benefits from everyone else's experience?

APTED: Well, you're dragging the answer, absolutely yes out of me, yes. Of course, that would be something to look forward to, it might be a particularly useful area to promote it. I think.

BECKER: Thank you.

BAHR: Other questions from the Board, staff? Bret Leslie?

LESLIE: Bret Leslie, Board staff, thanks Mick. I want to go back to the science, I'm going to tie in Jean's question and Lee's question together. I think what you're trying to point out is constructability and knowing that you can actually do this disposal concept is a big deal compared to the maturity of the science associated with projecting close closure performance, is that a fair assessment?

APTED: Well said. I wish I'd said that. In fact, I will in the future.

BAHR: OK, thank you. Other staff?

APTED: There's somebody behind you, oh sorry.

BAHR: Consultants, do we have any?

LESLIE: Bret Leslie, Board staff again. You had a timeline of timing of activities, and it was linear, and it was linear assuming that a country has a program, and we have the example or a repository. So, we have the Department of

Energy that doesn't have a repository, they're doing generic studies. You have the UK that is doing generic studies.

Can you put yourself in their shoes and say how much should they be focusing on the basic science versus demonstrating aspects that are unique to their inventory? For instance, in the U.S., we have large dual-purpose canisters, do you think there's value for DOE now to look at some of the issues that would apply regardless of what type of repository or host rock there is?

APTED: You know taking your particular specific example, dual purpose canisters, that issue is coming up even in Europe. For example, Norway is looking at exactly that similar situation as they can avoid some of the issues and save cost quite frankly by looking at direct disposal dual purpose canisters.

To the extent that if you're in a program which is in neutral or just beginning, that part two slide basically has those white blocked area saying there's really nothing specifically maybe locally in your country to do, but you would benefit by trying to align yourself with programs elsewhere to learn what's going on. And that's really a lot of these national programs, SKB, Nagra, maybe even Andra have a lot of collaborators coming in. I mean there's a clay club for example, so anyone who ask looking and thinking about clay, they can learn a lot by looking at what Nagra is planning to do and what Andra is doing.

BAHR: Any other questions from the – Bobby?

APTED: We're about out of time, Bobby, OK.

PABALAN: Board staff, so temperature is a very complicating effect on a number of processes whether it's hydrologic flow, waste form performance, engineering barrier performance, so given the effects of temperature, for a hotter repository that may be for a U.S. program, do you feel the same way about not needing at a more fundamental research or do we know enough information about temperature effects or what do you think about that?

APTED: Temperature is an interesting question, again, I'm stealing a lot of probably useful stuff at other countries, arenas. I think the Nagra for example, they're planning to look at bentonite at 200 degrees and why not. I mean if you look at the facies diagram, the whole clay facies extends at 200 degrees centigrade. This whole idea of 100 degree maximum for bentonite, crazy.

I mean it basically was built in the 1980s, material scientists thought at 100 degrees water boils, the laws of physics and so on, but at those depths, water is not boiling at 100 degrees type of thing. So, I think the advantage of temperatures, you mentioned sort of, again, you're thinking scientifically, but temperature and the spacing of packages has a big impact on cost. Rock excavation costs are one of the real primary cost drivers in the system.

If you can tolerate higher temperatures than some of your early optimum – initial concepts and optimized to a higher temperature there can be important. Now, I'm not answering the scientific side of your question, obviously I agree that temperature is a driver on chemistry, on geomechanics, and hydrologic aspects as well. I think it's one of the important aspects that we considered. But I'm – now, one of my hobbyhorses is--forget a hundred degrees, let's – you know, let's be realistic, two hundred degrees is not the end of science as we know it.

BAHR: OK. Thanks Mic, we've got to move on to keep on schedule and I'm going to turn it over to Mary Lou to introduce our next speakers. OK.

ZOBACK: Mary Lou Zoback, Board. I'm really – I think we're all really honored to have such distinguished international speakers come here a great distance to talk to us about their experiences in their underground labs. Listening to Mick, I added up 200 years of underground experience and so we have a lot to learn.

Irina is the head of research and development at Nagra, the Swiss implementor for disposal of radioactive waste. And since 2017 she's been the interim manager for the safety base comparison of the siting regions in Switzerland for future repositories. She has a PhD in hydrogeology from the

University of Ghent in Belgium and she's worked for both the British Geological Survey and the French Geological Survey. Irina, thank you again.

GAUS: Thanks a lot for this invitation, this wonderful occasion. I'm very happy to be here.

Let's make a little trip to Switzerland and what's happening there in terms of URLs. Oh no, it's going too quick. OK. So here we are. What is in Switzerland in terms nuclear facilities. Basically, we have five nuclear power plants which are in the stage of phasing out. The Swiss people have voted in a referendum that Switzerland will phase out nuclear energy.

So basically, we have a quite clear view on the inventory, also at least we don't have a military inventory and we're quite certain about the source term, the inventory on how to dispose of. We have a legal framework which sets that we have to dispose of the high-level waste in a high-level waste repository and the low and intermediate level waste also in a deep geological repository which is slightly different from other countries.

We went through a very, site selection process with many steps and then each step we could make progress. Since the last eight years we are now in stage three ending up with three sites for the deep geological repositories in both high-level waste and low-level waste which will be hosted, and this is for certain now especially since November 2018 which will be in the Opalinus clay. So opposite to SKB we're going for a clay rock and we are going for as clay rock in Northern Switzerland. This Opalinus clay is part of the Dogger Formation, it has about 100-meter thickness, has a very low hydrologic conductivity, which is very nice in terms of transfer times for radionuclides, has excellent sorption properties, but the advantage is there in terms of long-term safety to sorption, a low transport. It's the main barrier for our multi-barrier concept.

The more difficult thing is the construction, and if you have to construct in a weak rock it becomes more difficult than constructing in granite for example. Especially if this becomes a construction at a greater depth, we are – current sites, we have three sites left, the depth varies between 600 and 900 meters, so there is an issue coming up. Around the Opalinus clay there are other layers with very favorable properties but not as favorable as the Opalinus clay.

Here we have another view of this Opalinus clay, it has been studied for the last 30 years to 40 years in the URLs. Basically, I think we have made huge progress there in understanding what happens, how these clay particles interreact with the radionuclides, how these are being sorbed, how these are being retarded. So, a huge -- a huge progress has been made in this part of science. This Opalinus clay rock has next to the Cox and several other clay rocks become an international reference. So basically, if other universities are now looking for typical clay they go to this clay rock, you know, because it's so well-known and so well described already.

Constructing a geological repository in this clay rock looks in Switzerland like that. The repository concept is a consequence of the barrier, the geological barrier which is chosen here, but also of the legal framework in Switzerland which sets out a few boundary conditions in order for this – for this repository concept that need to be met. We see here basically it goes from the surface with a ramp or shaft, it goes to a set of tunnels which are open-ended. We will put in the canister, we have a requirement in the law that we have to backfill quickly after emplacing the canisters which is different from the French concept. So, we have to put something in.

We selected bentonite as an additional barrier, so basically, we already have 100 meters of clay of ideal properties. What we add on top of that is bentonite barrier, the major advantage of the bentonite is that it has favorable properties in terms of hydrologic conductivity but also a de-swelling pressure which protects the canister surface. And this is to claim the argument of the lifetime of the canister. Because this is a weak rock, we have to do some reinforcement of the tunnel to ensure that it will be in place during in placement for operational safety but also for some while after that.

Now, how do we go about the safety case? The safety case has been first formulated in 2002 already. So basically, it's already 17 years old, it was in the document which was called Entsorgungsnachweis which is so publicly available, and which was already for the Opalanus clay. At that point, we are to follow to the international guidance from the IEAA on how to construct the safety case. So basically, it's a multi-barrier concept with multi-barriers so the waste matrix, the canister, the bentonite buffer and the host rock, it has to be placed in a stable geological environment which means it's in the northern part of Switzerland, in the southern part where you have the Alps still coming up, the erosion processes, there's also earthquake activity.

This was deemed not to be ideal, so we are going to the northern part of Switzerland and we attribute, and this provides the safety functions. So, it's confined, it can decay within the barrier system, lower listed environment, and long-term stability persists. So, this then translates, of course, into dose calculations to prove that it's safe, but also in the performance and the safety functions of the individual components of the repository concept. And this is an additional level of safety, it's defense in depth that for each of these barriers we can guarantee the performance of over time and use for that not only the performance but also performance indicators. This brings the argumentation that the repository will be safe for this very long timeframe.

These are listed here at the site, maybe you can read them in the slides. So where do URLs come in? We have – we're going for the general license now, so there are three main aspects which we are addressing now in our program, it's selecting the site, three sites left. We started to do deep bore hole drilling last week in Bülach north of Zurich. This will determine the lateral extent depend on accepting the thickness of the host rock, also next to 3D seismic.

Then we have the construction issues, the stress field rock mechanics, tunnel lining, EBS emplacement, this is where URLs can come in to a certain extent especially rock mechanics. We can do something in a generic URL but ultimately you have to measure these properties at the site and rely – adapt the layout of the repository for them. And then there's, of course, the long-term safety issues for which it's clear that the URLs can play an important role.

We have two operating URLs in Switzerland, so I think we are the only country who have two. We are lucky to have the Grimsel Test Site which is in the southern part of Switzerland, which is located in a granite host rock and is – it is there because early in the Swiss program we had a focus on granite and later then we have the Mont Terri Project which is located in the Opalinus clay but in an area where it's less deep and more tectonized.

So, both URLs are very much an international endeavor where we do multi-partner projects with over 10 to 15 international countries. The Grimsel Test Site is owned by Nagra and Mont Terri tests or Mont Terri URL is owned by the Swiss Geological Survey, the Swiss TOPO or he's managing it on behalf of the canton.

So, when did we start with these URLs? So, we have a very long development, we started – the first report came out in

1978 on deep geological disposal. We intend to – and this is very important, our timeline is very important, we intend to start operating the repository in 2060 which means that from now on we still have 40 years which is two generations. So, when choosing work in URLs or in RD&D in general, we really have to keep this timeline in mind. I mean, you only have to take the decision when it's really needed to take the decision. Decisions which can be taken in the future should not be taken now because you might actually take away flexibility or options or materials which will be developed in the future.

We can see that the Grimsel Test Site which came first or at least start in '84 in Mont Terri and the Opalinus clay start in '96. Currently we are here. 2024 is for us the next milestone where we will resubmit the safety case which dates back to 2002 after almost 20 years and with the safety case we will be updated to new data to the standards which are required now.

This is the GTS, Mick already showed the diagram, it is very much an international endeavor, it's in granite rock. Some of the experiment are being led by other countries because especially anything related to granite, our R&D program at Nagra, it's no longer on granite. So, there are some experiments which are shared with other international groups and conducted with them.

We also have this IAEA Level B/C Radiation Control Zone which allows us to do experiments with radionuclides, and this is really an asset because there are not many places in the world where you can actually inject radionuclides in a rock.

This is the Mont Terri URL, it goes basically there's a motorway here, we just dug a tunnel next to it, so it was another huge investment and it's operated by the geological survey, I already mentioned it is – here are the siting regions in Northern Switzerland where the repository will come, here is the Mont Terri.

So, what are the drivers for establishing these URLs? For both the crystal and the sedimentary rock program, the initial idea was because this was in the '90s and the fundamental understanding of how nuclides move through rock was not as developed as it is yet. It was recognized that in order to say something sensible about the safety case that we need to go look at the rock and do a lot of testing. So, this is what happened with the Grimsel Test Site. We were initially thinking to have the repository in the granite and great in-depth in Northern Switzerland. The granite at the Grimsel Pass where the rock laboratory is now was very similar, so we could characterize the rock there. So, this was in early days.

Now for the Mont Terri Lab, we see here the Mont Terri here, the siting regions, so the Opalinus clay dips towards this end, comes at 500-meter, 600-meter deep here but at the motorway or the highway tunnel, actually it comes up and it's somewhat more tectonized, but it's exactly the same layer and the same logic went there, OK if you want to understand how to construct in the clays, how these clays behave, we need to have access to them in a certain way. Although the real site was not yet known at that moment.

Both URLs and this is also important, I think, used planned infrastructure to create the URL. So, in terms – in the case of Mont Terri, it was the highway. In the case of Grimsel Test Site, there was a series of dams, hydrologic dams which allows to construct or start the URL with relatively low cost, which also allows us now to continue working over the URLs with – and maintain the GTS for example without this requiring in a huge investment.

The phases how URLs evolve, have already been introduced by Mick also, the initial phase, '80s, '90s were very much on developing fundamental understanding, characterizing the rock, find out how you can measure things, how do you measure in low permeability rock reliable transmissivity, specifically these kinds of things.

Later phases you will see really that there is a shift in understanding on how does the repository affect the rock, what are the repository uses and effects and how do they evolve over time such that you can actually claim the properties of the host rock also in the longer term and ensure that your host rock is not destroyed by what you have put in there.

For the last 15 years we're going to watch large scale demonstrators, also this THMC behavior is evolving in the lab scale, different scales and there is a need to demonstrate it also at a one-to-one scale, first you can construct it as you think you can do it but also that it performs and think you can do it. And this is what we see on several URLs but also what is very important that is because we have such a long-time scale, so we need very long-term experiments. Now if you want to put in the license, you need an experiment of 20 years of monitoring data, you need to start the experiment before, because otherwise you will not be able to use it for the license.

So, this is also why we start some of the experiments now with the aim to run into over the next license already supporting the construction license which is going to come in 2040. So, it's really trying to get these long-term results, and there's a tendency now to very long-term, maybe more simple but very long-term experiments.

Where we are with the GTS, the Grimsel Test Site in the Swiss program today? I have to watch the time. OK. It’s shifted. The research has shifted towards characterizing EBS systems. I mean, Nagra is no longer interested in the granite, we look at how the EBS performs and that’s what we can do with one-to-one scale experiments, the GAST experiment is a one-to-one scale seal, demonstrating how we think we can move gas through a sealing system in the longer term.

Next to that, of course, it's a platform for international cooperation, scientific and engineering issues but also for communication with the public. In both URLs we have approximately 3,500 visitors each year and we really see that by talking to the people, they can touch what's happening, you can gain acceptance and credibility.

Here are the main projects, what also is a tendency is to open up the URLs for other activities whether this is carbon sequestration, but also in this because it's hard rock is geothermal activities, we try to open up this because a lot of techniques and problems or scientific challenges are very similar. So, this kind of cross – yes, cross working between different research groups really helps also the tools to improve and the predictions and the process understanding to improve.

The Mont Terri URL and the Swiss program today we have done a lot of characterization there, you see a major shift now from Mont Terri towards the selected sites. Now we go to the sites, we started the deep drilling. Our regulator is now requesting that we obtain the properties at the site and no longer at Mont Terri especially for certain aspects like geomechanics. We still have experiments and we continue to do experiments at Mont Terri, one-to-one scale, very long-term to characterize these very slow long-term processes.

So here we are with a list of experiments, also U.S. DOE is involved in several of them, a new area which is developing now is related to the fracture reactivation. Probably there's a contamination or we don't want to say negatively, but the whole fracture reactivation discussion also very prominently present in the carbon sequestration domain is not going to go away. We probably have to do more work there and we have to realize that.

So now there are experiments starting there although we have to take the tradeoff that is not as deep as in the selected sites, so the stress regime and also the overburden pressure are fundamentally different.

Now, how do these URLs function in our succession of safety cases? Because we're really going through a succession of multiple safety cases. The first one in 2002, the next one 2024, construction license 2040, this is our current planning.

So now we have these two, these two URLs, we do these tests, we hope to get the license approved by 2030, and then by law we will have another URL where we will redo some of the experimental work we have been doing before. So, this is another period of testing of material demonstration also with technology development, this is a part of the program by the French who already are in technology development. We don't do this technology development at the moment because we want to profit from the next generation.

So, after 2030 we will go down at the site, construct another URL and answer all the questions there regarding the detail design, also reinforcement of the tunnels, kind of how much material you need. It's basically the technology, it's the detail design stage we try to avoid now in our research program unless it has an impact on conceptual design or on the site because with the next slides we fix site and conceptual design.

So, for example, the GAST exp – the GAST seal experiment I showed, we're doing this now because there might be – we need to demonstration feasibility because it's a unique thing. So, this is really a decision we tried to make, conceptual design site suitability is now safety case and then the next generation will then be the detailed design.

We also have a pilot facility which is not a URL, which is an additional safety measure which is also written in our law, that we have to emplace a representative share of the waste in a pilot facility which is monitored by the repository itself will not be monitored. And this will – the pilot facility will be monitored during emplacement to confirm the performance of the emplaced waste there.

So now how do we do this prioritization? And this is very much a top down approach, we have the obligation to write the five-year research and R&D report which accompanies the waste management plan, so basically everything which is not clear and clear cut in the waste management plan goes to the R&D plan and there we listed the activities we take up and gave a detail for the next five years but also a longer outlook.

This is a bit – this is open access, you can take it from the website. Internally, we have a much stricter way of dealing to actually focus what we're going to do the next five years in terms of a priority plan. This is updated every one to two years. It is a risk-based approach where we see, OK, we have to go for this next license, how is our understanding of the system, not only of long-term safety but also feasibility of construction.

Where do we think we have the biggest gaps? This goes over all the disciplines and it goes bottom up but also top down. And then we assign attributes to each research priority in terms of the importance, is it a real major argument? If it's a minor argument, we do not want to put in a lot of effort. The urgency, how much work is needed? Do we have to start it next year or can we wait three or four years?

The risk of not reaching the outcomes, so science can somehow go not wrong but have another outcome and you anticipate, how bad would it be. If it's, again, a critical thing you want to line up, parallel experiment or have a URL experiment but then have also a series of lab experiments, and the driver of the activity which is now more not only safety but also cost and this is what was also addressed. So, cost is now that programs are more and more getting towards realizing the repository, cost plays an important role. I mean, at a certain point, someone has to bring up the money and it's either the taxpayer or the energy consumer in the end.

So, these are the URL activities which are based on many drivers, this is not only arguments for safety case, it can also be training, it can also be monitoring equipment development, this is a very broad range of categories. What I would like to stress here is that recently optimization of repository components is coming in as an important aspect. So how can we maybe adjust our barriers such that it fulfills the requirements, but it is actually easier to emplace, that the argumentation becomes easier to defend or that the cost or materials also are chosen such that the cost is reduced. Within the same set of original safety requirements, optimization for safety is always an important aspect there as well.

So, this is an old diagram, I still like it. It's the URL that plays – they are really addressing this initial – this very important question in our domain which is the time space of upscaling. OK. We have somehow to predict which predict will never work but to state how the repository will look in the next million years and prove that it's safe in each of these stages, and there the URL sits in between the laboratory experiments which are always needed and which are very nicely confined, but which are generally on this type of rock bits where you look at one process and the natural analogs which are long-term, large scale but which are generally badly constrained. So, if you want to model them you're swimming in a few hundred parameters and it's difficult to constrain the models. So basically, what I want to say is we need all three in order to build up the arguments that the repository is safe and to ensure that the safety functions are fulfilled at all times.

This then goes into this logic of how do we build up the argument. It always goes through the cycle, experiments, lab experiments but also URL experiments, system analysis, synthesis. And there's this important part of upscaling space and time which is really needed, and which is the challenge and which – I think why we have in our domain these URLs, because we only have this question that we have to say, "OK, it's going to be safe for a million years." So, this is – this logic which counts for many aspects in our program, but it counts for these aspects which are safety relevant or whether it's optimization. It's not for the whole scientific development of the repository, but somehow you need measures to constrain the work that you're focusing on.

And I have a few examples here, so we're trying to capture this repository evolution, demonstrating the performance in a system of storyboards or a decision making schemes or also in modeling change and there's one here, the system was generic one, basically what we see here is a repository evolution over time until failure of canisters, we are looking probably around 10,000 to 100,000 years and to see the major chemical process has been also the mechanical processes here.

In red, you see the temperature, it goes up with canister placement and then it slowly re-saturates. So, we try to gain an understanding of all these processes in sufficient detail that are taking place, sufficiently developed such that we can assure that the safety is guaranteed. And it's based on these schemes that we actually identify the R&D priorities and the color code of the priority is the urgency or the importance.

I can give a few examples, we have this steel canister and the steel canister will fail, we have as a reference as steel canister, it will fail after more than a thousand years which was written by law that we have to guarantee that. But still you have a very strong reliance on these corrosion rates because these are being measured over long-term experiments 15, 20 years, but then you expand this over a hundred thousand years. So, if there's a small error, you kind of extrapolate this very quickly.

So, there we do multiple efforts still to measure corrosion rates, lab programs, we do this in U.K. but also URL programs. We still have bentonite with corrosion emplaced in Mont Terri as well as in Grimsel to see if our understanding of corrosion is really this general corrosion, it's not microbially induced if it becomes microbially induced under set circumstances. So, there we have our research priority.

Here's radionuclide transport, it was already mentioned. We still have it because we still at each stage we need to bring together the state of the art, so we cannot say radionuclide transport done and then in 10 years nobody knows. So, we're still having a basic activity there focusing on sorption competition for example but the activity – the role of radionuclide transport in our R&D program has gone down significantly over the last years.

Another example is this decision-making system, because we have a very tight host rock and we have a lot of metals in there, tunnel reinforcement, canisters, whatever, these start to corrode, they generate gas, hydrogen gas, they build up pressures. And you need to go, you need to prove that this pressure buildup will not affect the barriers. Now, if it would all go wrong and basically you would create a crack, there will be no impact on radionuclides, this is always to realize we want to ensure that by – and making sure that this pressure is not going too high, that the barriers remain intact.

So, it's another – it's defense in depth, no radionuclide consequence, only minor but ensuring that the barrier performance is over the whole repository evolution intact. So, there are different – and we're not looking at kind of possible repository failure here, we're looking at, do we have to take additional measures to reduce these overpressures here? We can always recondition the waste which comes at a cost, melting kind of pyrolysis of organic materials, but this is a decision framework to maintain the safety relevant area of overpressures.

And also, there, we have research priorities, the corrosion I already mentioned but especially the transports through EDZ, excavation damage zone, the enhanced gas transport in the Opalinus clay is a high research priority for us, also because Switzerland has a particular issue with gas and therefore we have to really demonstrate that we're on top of this area.

So, this is how we try to identify research priorities and some of these priorities can have a component in the URL depending on the urgency and the importance, we would rather go for URL component as well.

The third and last example I have here is this early evolution of a system. Basically when you have these very simply – not simplified but kind of schematized models of radionuclide release, this happened here when everything is back to – back home again so the thermal pulse is over, the re-saturation has ensured – has occurred, but basically you have to make sure that you end up in a stake here and you can defend the state with sufficient arguments.

So, we're looking really at how is this early evolution going, again, time, space is a problem there. So, we see this as an RD&D priority and trying to match each of the phases which goes over multiple hundred years with large scale URL experiments. So, this one is the FE experiment which started in 2014 in the Mont Terri URL, we're looking at the THM impact on the rock, also an aspect was demonstrating that you can actually build it but the main goal was the THM impact.

The next one was on the FEBEX which was taken out after 18 years, one of this very nice large-scale long-term experiments and for the final one where we didn't put in any heating, we just tried to re-saturate and see how this bentonite performs under re-saturation was already finalized 2012.

So this brings me then to the conclusion saying that how to identify RD&D in a URL, I think we have to first stress what might be a technical societal political difficult issue, but we have to acknowledge that over the last 40 years we have built up a huge knowledgebase on what happens in the repositories and, of course, there are always uncertainties which can be further reduced, but the understanding has fundamentally improved.

We go take now an approach where we claimed that we have an understanding of the evolution of the repository that is described in sufficient detail such that we don't forget major processes and that the performance can be assessed in terms of fulfilling the safety functions. We have the storyboards, model chains and decision frameworks to identify the RD&D priorities and what we also have to say that the URL activity's one experiment is not going to deliver the number which is then going to clip them to the dose calculation. It is really an integration and a knowledge-base of different elements.

We could identify quite early the need for generic underground research laboratories. If we would start a program now, we would probably not do it the same way, because 40 years later there is so much around RD&D. We use this very strict because it allows to constrain the RD&D program, or the prioritization of RD&D through priority plan, assessing the need for URL components always with an eye on the next license.

We try to collaborate as much as possible because it's cost sharing but also even more important, it’s knowledge sharing. I mean, plan now long-term experiments to get the data for – already for the next license, this is key. And I think one of the major things is international collaboration is really needed because there are very few experts in each country on each domain. So, if these don’t come together, you know, it's very difficult to build up the critical mass. And this is the Mont Terri URL the entrance. Thank you.

ZOBACK: Mary Lou Zoback, Board. Irina, thank you so much for a very confidence-inspiring presentation. Unfortunately, we did not build in time for questions after these talks, but all of those international speakers and Mick will be part of a panel that will follow. So, thank you and the questions will come later.

GAUS: I'm ready for it.

BAHR: Great. Thanks. Our next speaker is – came from Sweden, Patrik Vidstrand, he's a hydrogeologist, he's head of the research in post closure safety unit for SKB, the Swiss – the Swedish implementer.

He's had several academic postings both in Scotland and Sweden and he's also worked in the private sector. And for the last 20 years he's been working for or with SKB in conceptual and numerical groundwater flow and solute transport modeling, so he is a hydrogeologist fundamentally. And thank you, Patrik, for coming.

VIDSTRAND: Thank you Mary Lou for that nice introduction. Thank you for allowing me to come here. It's – as Irina said, it's a pleasure. A little bit nervous, I haven't been on this kind of public hearings before. I've never seen this in Sweden actually.

BAHR: We're friendly.

VIDSTRAND: Yes. Sure. I asked my predecessor Peter Vekeburg about Äspö which is our URL and he said that was – you can read them and that tells basically everything.

He's worked for SKB between '79 to last year when he retired, and now he works for international helping China. So, he's been around for long term. So, this is outline of my presentation, I will give you a little bit of a background. The Swedish waste system which we have to handle a little bit about safety assessment, the safety case, the regulators and the laws that we need to follow, data and information for the safety assessment.

The KBS-3 concept which is our design concept, the Forsmark site which is our repository site that we are suggesting, and I will not say anything about the SKB organization. I only added that to give you a fright here.

And then I will talk a little bit about the URL. So, the Swedish waste system, it's very much similar to the one that Irina showed about Nagra, we have two kind of waste streams. One for low and intermediate level waste and one for high level waste. And we will, of course, focus on the high-level waste here, but SKB is responsible for everything here. From picking it up at the nuclear power stations, handling all the transportations, interim storage and everything. And that puts a lot of demands on our entire organization on what we are doing. We raise how we set the waste accepting criteria, how the producers must hand over the waste to us. And that is also affecting all the work we are doing.

So, we have two kind of laws that govern our work, we have a nuclear act which is the one giving permission to actually store and build a repository, but to construct in the environment we also need to go for the environmental code. These are two different laws in Sweden and they are governed in a different way. The environmental code is just giving one decision and it needs a firm understanding of the site and the system and the problems and everything at one time.

While the Nuclear Act can actually give you permissions to go ahead and then to the next step and then the next step. Which is a bit easier to work with. None of these regulators is actually doing the acceptance, it's the government that decides, but as soon as they have decided it goes back to the authorities or the court to do the stipulations, and we don't really know what that will mean especially from our environmental court at the moment.

So, the safety assessment or the safety case, it should answer the question is a repository safe in the long-term? And basic international standards for doing this but I would say that every country needs to find its own dialect of doing this. We have different kinds of repository designs, we have different sites, we have different regulations, and so on. And in Sweden, the Swedish Radiation Safety

Authority, SSM which we call them, establish what society considers as safe. And safe, as of dose, is 100th of the natural background radiation in Sweden which is quite hard demand to do, if we take our low and intermediate level repositories, if we take other ways and place it on an agricultural land of a normal size in Sweden, that would be smaller doses than from natural background radiation.

So, we're handling quite tricky questions here, but important. There was a little bit of questions to me if there were any demands from URLs based from the act of nuclear activities. There aren't really in Sweden but if we're handling radioactive materials we need to have a permission for that. But we do need to have an environmental act, an environmental code decision for building in the URL. So, all that as soon as we do underground is important.

However, we are by law forced to do a research and development plan every third year. And in that, we also propose what we need to do, and URLs are included in that kind of research and development plans.

So, the latest safety assessment we did for we spent fuel is called SR Site, it's Safety Report Site, so it's the safety assessment we are using when we have found the site which we are proposing. It supports the license application and license applications we call it in Sweden is more or less a safety case I would say.

It's a final repository in Forsmark, we submitted it in 2011, it's a long time ago. In 2017 early, we got the first answers, so it took six years for the authorities and regulators to give us a continued journey here. It's based on a KBS-3 concept which I'll to – we'll talk about a little bit more and the Forsmark site which I also will talk a little bit more.

The picture here shows the main contents of the safety assessment that we are producing, and I would say most of these main references here had inputs from the URLs. The features, events and processes are internationally driven and also added features and then processes from your repository design of interest. And I would say that that is nowadays a checklist, don't forget anything, but it's not driving safety. I think Mick said that its safety functions and I totally agree with that.

The production reports are here six and they are how we are going to construct the canister, how are we going to construct the buffer materials. And how are we going to construct in the rock, and how are we going to construct in the rock is really something that comes from URL work. The canister process report is also coming from that, the backfill is more or less entirely coming from that, geosphere process report.

As a scientist, I must say I'm not really agreeing with Mick when he says that hydrogeology is not important. It's kind of of my field, so I want to have it important and it is important for being able to say that we have stable chemical or mechanical conditions down there. For the safety case, it has minor importance.

OK. So, I would say also that kind of relates a little bit to public confidence that all reports that we are producing are publicly available, and you are able to download them as PDFs. Most of them are easy to find and I would say that 90 percent of them are in English.

So, data and information from a safety assessment, the first bullet here is basic science. I would say I agree when we say that basic science is the past when we talk about putting mass into processes, but there is a fine border between applied science and basic science. We don't really understand how fracturing occurs in crystalline rocks in high temperatures for instance. So, we need to do lots of basic science still and that is more specific knowledge to apply basic science to our specific conditions.

And I attended, I think it was two years ago, a conference where Francois Cornet, one of the fathers of hydro-mechanical fracturing occurred and he said, "We don't know anything." And he was just retiring, so he wasn't looking for more jobs. But that still is a lot to learn about basic sciences and we need to do that. But as Irina said, we are getting closer and closer to construction and the money is limited. So, we have to focus, and that's a problem sometimes. And I would say that's where we need the Board to tell us what we don't understand here.

The properties of the site is very important, fractures, Mick told you that sample of Onkalo, they had kind of strict first rules of what not to include, so in future they would not have discriminated those positions, but it's true that they did that in this case, so – and we also need to engineer barrier properties at deposition and the deposition values are not – it's kind of an initial condition for the safety assessment. So, it's not the same as the safety function.

For instance, the copper thickness safety function for corrosion protection is more than zero, but initially it needs to be five centimeters. So, the numbers are not always the same. The KBS-3 concept, I think we will see these more. I would say there's primary safety function here for spent fuel and I think this is true for all countries for spent fuel is complete confinement. This is what we want to achieve. And how do we achieve that? It's only to have the copper canister tight for entire period.

It can be very long transport times, if it's diffusion-driven it could be fast, if it's fracture flow, but retardation is just a prime – secondary safety function. So, we will never have that as a complete help.

The complete containment of the canister is still having under safety functions. For instance, we need to ensure that is not corroding, so we need to have an understandable chemical environment at all the times, also understandable stress environment. And we need to understand basic science. In Sweden, they have a debate at the moment if we have corrosion of copper in oxygen-free water or gas oxygen-free water, because we have always oxygen in water, but it also in Sweden needs to withstand huge isostatic loads which we will have during a future ice age.

The maximum height of an ice age of the last period was somewhere between three kilometers and four kilometers, and that's adding quite a lot of load, both a weight load and more hydrostatic loads. So, the canister needs to withstand that and that is actually quite a complicated task for a mechanics to do, especially for a steel inlet inside of it. And it also needs to withstand shear, Sweden is very stable for earthquakes, but we can't exclude them.

Yes. And I continue with that. So, site studies, I will not say very much here. In the earliest part we did deep drilling and analyze deep drillings from a number of sites in Sweden. In the '90s we did regional studies, and what you see here in green is all the parts of Sweden that were said to be acceptable. That means that most of Sweden is actually good enough to host a repository. It also means that there are more heterogeneities between two bore holes at a site than there are between two sites. This is one reason why we need in URL to investigate larger volume because there are huge differences in the site.

The site investigation in the end focused on two municipalities Östhammar and Oskarshamn and we did choose Östhammar municipality in the Forsmark site. It was selected in 2009 after seven years of surface-based investigations and site modeling. And it is a comprehensive site description including modelings. Thermal, hydro-mechanical, chemical models we have mentioned those quite a few times now.

So, a little bit of the site is homogeneous, steep and dipping deformation zones, high stress quite uncommon in Sweden. Hydrogeology hardly transmits fractures close to the surface. This is kind of good because it kind of creates this hydrologic cage concept that we are around for a long time. Is very few transmissive fractures at depth and I would say it's very few fractures. We actually have hundred meters sometimes between fractures that flow.

And you see the guy here carrying course. We have sometimes 50 meters between natural fractures coming up. So, it's a very good rock. Groundwater composition is freshwaters only, at shallow depth and salinity increase with depth and you have a report here.

And the repository, how does it look initially? We know it from site investigations and sites and engineered components specifications, with canisters, everything is back to URLs.

So now URLs, I will not say anything about this because Mick said it and I more or less agree about the conclusions. I will not say any much more about the Stripa Project either that was also mentioned in all the three phases, but as Irina also said, lots of international participations, that is crucial.

So, the Äspö research village is not only the URL, it’s labs on the surface and it’s full scale labs but the URL is the major part. And the first steps towards Äspö was set in the research and development and demonstration plans in '86 and that was first we were forced to do by the law, and one major highlight in that program was to plan for an URL. And the main aim was to provide an opportunity for research, development, and demonstration. And I would stress those two words because that's what we have been focusing on quite a lot in undisturbed rock environment and mostly realistic.

Vital decisions here. It was to be a generic repository for all times. The use of underground laboratory is only for research purposes and will not be converted into repository in the future. It should have a suitable geology and we also focused on one of the our nuclear plants.

Phases of realizations, and I think this is really important because we were really close to starting our site investigations already at this time. So, one of the tasks was actually to try to learn about site understanding, site investigations. So, the pre-investigation phase between '86 and '90 included regional geological investigations, surface and bore hole investigations, and predictions, all of that we needed to do in the site characterization phase.

And when we started to construct, we could evaluate how good were we at these predictions. We did quite a lot modeling of groundwater flow and lots of the development of modeling techniques was done there. Operating phase from '95, and it's been focusing on testing models as described in the barrier and demonstrating technology and functions for repository systems.

And you saw this slide before and this is the ongoing experiments at 2019, I think you had a little bit more on your slides Mick, but I agree, quite a lot is focusing on chemistry, radioactive matrix diffusion, but also in demonstrating how to construct.

We do quite a lot of international work, there is an international panel with five partners and we have joint programs and joint progress for basically everything, and training courses. And I would highlight this because this is one of the important things I think of having a generic repository. Seventy five percent of the people working in my group have done PhD works at Äspö. This is where we train the staff that will do the work for us.

A couple examples and lots of these, I have six posters, so lots of these will be, again, found in the poster session this afternoon, so I will not say so much on all of them but a couple of ones. The LUT which we call this, long term test of buffer materials is one of the most publicly known experiments. It has been broken down a couple of times and we still have a couple of ones left and some environmental groups want us to take up or they say, "You don't want to pick it up because you are afraid of the results."

But we want to have it as long as possible. So, we are standing there in a political debate. That's one of the problems of doing this. Another problem with doing this is we did this to think about bentonite, but we added copper and we didn't think so much about what we added as copper. So, we didn't carefully look at all the copper before but afterwards. So, we don't really know what has happened sometimes.

LASGIT is about gas, Irina talked about that and I'm sure Daniel will talk more about gas also. It's more important for clay. Microbe, I would say this is kind of one of a few things where we did science for fun. In the early '82, I think it was, we got a PhD, Karsten Pedersen who did a PhD on microbes and he came up with the idea of why not look at microbes underground, and we thought well, it's not important but if you want to do it, do it.

This is the most important topic we have today. It affects the engineered barriers in a crucial way together with chemistry, and that's what we are focusing on today. So sometimes, doing things for fun might lead to the most important findings, and that is also one thing of our experiments, you never find in advance what you find in the end.

Radionuclide experiments, we've done a couple ones, this one will be presented by DOE in some parts later on. They are involved in modeling. The prototype is a demonstration experiment of full scale and this actually did demonstrate that we are able to do this. Three posters on that later on also.

We also have retrieved its extremely complicated and expensive, but it works. I wouldn't recommend a future generation to take it up again. But if they want, it's possible.

Mechanical rock excavation methods, things that you should be talking about in advance, we have created installation machines that need flat floors, creating flat floors in rock of very hard materials is not so easy. Maybe it's easier to create a machine that rock goes on rough rock, I don't know, but it also relates to backfilling, so. Domplu we also have a poster on, this is the second assignment I would say which is kind of important thing.

This is my kind of ending, technology readiness level. Without the URLs we would still be at level four. With the URLs I would say we are at level seven. In Sweden, we sometimes miss around level eight and that's a problem because when you start to do operations, you need to be at the top. And finding that last bit is probably what we need to do in the site-specific repository. It's probably not possible to do it in the URLs.

And I will end with this, it's a Swedish artist, he calls himself "The Photographer" but it's more a Photoshopper but I always use this because I love it, it's – we are laying the roads for the future generations and it must be a good road. Thank you.

ZOBACK: Mary Lou Zoback, Board. Patrik, thank you for a very information-filled talk and, again, a confidence-inspiring one and, again, unfortunately we did not build in time for questions for the speakers at this point. But I believe we have a 15-minute break now?

BAHR: We have a 10-minute break.

And there should be coffee and tea in the back of the room. So please help yourselves. The restrooms are just out the door, pretty close and we will start again at 10:10. Thank you.

BREAK

BAHR: We're going to get started again. The coffee was a little late but perhaps people can, sort of, cycle through that but just because we do have a very tight schedule, we're going to keep going. And Mary Lou is going to introduce our next speaker.

ZOBACK: So, our next speaker is Daniel Delort. He is from France. He's the Deputy Head of the International Relations Department of Andra, the French National Radioactive Waste Management Agency.

He has master's degree in geology and geophysics. And prior to coming to Andra, he was a project manager for geologic storage in the oil and gas industry. He came to Andra in 2004 to complete the design of the underground disposal for high-level radioactive waste in granite.

However, he showed his flexibility and soon became a clay expert and he is now involved, of course, in that project.

Thank you, Daniel.

DELORT: Thanks a lot for inviting me here. And I have a special thanks to address to Leslie Bret, which is a member of your Board.

And he was very supportive to prepare this presentation for you. And as you can imagine explain simple things to French usually takes time. So, my presentation will be in three-part. The first one will be a presentation of Cigeo project, which is our roadmap and where we are currently.

And the second part will be on the URL, our URL in Bure in clay layer and then a few examples of that experience. After that in the afternoon, I have a poster, so I can – and I will be there to answer any questions.

And I have brought few but a limited amount of brochures about our project, about reversibility, which is a very French topic, and about our laboratory. So, who are we? So in France, we are the – we are a national agency for everybody.

We were created in 1991 in the – with the law – by law and our mission is governed by law and we got three laws to – concerning radioactive waste management. We are in charge of the design, all the R&D, the licensing, construction, operation of the – and closure of all radioactive waste disposal in France. And we have two repositories in operation – surface repositories.

We are independent from radioactive waste producers by law. And, well, however our agency is quite significant and we just up in a few weeks ago our website in English. So, all are invited to visit.

Just in a nutshell, our Cigeo project, so it's a geological repository. It will be developed in a clay layer at about 500 meters depth. And the clay layer is about 140 meters thickness and it will accommodate entirely our nuclear waste long-lived, and our high-level waste.

In France, due to reprocessing our reference inventory concern liquefied waste only, for the moment. We have two separate zones for intermediate-level waste and high-level waste. The access will be done through shafts. And for the waste packages, we will be using a ramp.

So Cigeo project was quite a long program in France, about one generation meaning that the people who started Cigeo, they are now quite ready to leave Andra. So, this gives you the significance of what we are doing.

Twenty years program, it was a very legal process in France with three acts. The first one was on the beginning of our program. Three R&D options were compared, long-term storages, partitioning and transmutation and the geological repository.

And with a rendezvous in 2005 for France – for the Parliament to decide which will be the reference solution for France. A part of that in that law, there was a commitment to open URLs, generic URLs and the story after that showed that our generic URLs in Bure became specific, but this is, it comes later.

In part of that there was a public debate in France which is quite a large mess and discussions with the public and we are preparing – we just launched the first one here one week ago.

Our site is located in the eastern border of the Parisian Basin. And at such a location we have at about 500 meters of clay layer. So, the 500 meters in France came from – well, we have a requirement for it to isolate the deep geological repository from the biosphere and future generations.

But the 500 meters came from the depth of this layer at this location. It could have been 400 meters. It would have been OK. So, the geology in this area is quite well known because there was some oil and gas investigations, water.

The geology is quite simple. It is a very stable basin, well, quite well-documented and, well, stable space for more than 2 million – 20 million years. The Callovo-Oxfordian so as the name indicates you can find it also in U.K.

Well, it's a quite very simple geology. It was mentioned by Irina, our R&D program is linked to the function we are distributing into the system to the different components of the repository system and where there are main uncertainties we are developing R&D to try to reduce the consequence of these uncertainties and to understand.

Some of those researches were performing in surface laboratory. Other ones were solved by engineering activities and most of them were done in our laboratory in Bure, and specifically for a certain scale of experiment that we would need to have a direct access to rock mass at repository conditions.

So, Bure URL, so it was a long process to develop this laboratory, so the siting phase started in 1992 with mainly a call for volunteers, so there was a large program of consultation in France.

And this was led by – it was led by a deputy of the French Parliament. So, it was a political issue to find the sites since the beginning more than a geological issue. So, the geological surveillance has provided maps but finding a site was a political issue.

So, well, after that we – when we all, we went to site for performing site investigation works and we applied three licenses for three URLs in three parts of France, so one in Bure, the other one in the east of France in granite and another one in south of France in clay as well.

Due to instruction only one site was agreed. It was allowed for receiving a laboratory. And so, we started construction of the Bure Laboratory in 2000 where it was two shafts and one experimental gallery on top of the clay layer.

So, we drilled the shaft, we drilled the gallery and from this gallery, we drilled bore holes to try to understand the impact of the construction of the laboratory at the right layer, right level. What would be the impact on the clay mass?

And we launched the first set of experiments, which were strictly linked to the performance we were expecting from the clay. The interesting properties of the clay, on sorption and aggregate properties of the clay and also what will be the impact of the clay of constructing galleries in this medium.

So, we come up with our first file of feasibility safety case, let's say, in 2005 and then it was decided to continue with the program on Bure – at Bure. After that we – during that time, we also prepared a new R&D program with additional experiments and tried to investigate new field of R&D that are missing.

So, we went through a large extension program to develop our laboratory to have enough places and enough galleries to perform all the experiments we were planning to do. So, we continue the story. And this subset of experiments were launched in 2010 and we got also the extension of the operation license of the laboratory to 2030.

And now, we are launching a new phase of construction of the extension of the laboratory to perform the last experiments we will need to support our license application.

So, the initial concept for the first R&D program, well, it was a very basic concept and we tried to define exactly what we would need for the 2005 milestone of the program.

So, very simple – very basic concept. And with this concept and what we knew from the existing – from the site, we defined the first program focusing on the characterization of the containment properties of the rock mass, the analysis of the mechanical damage of the review to the construction and verify the possibility to seal the drifts.

So, and this is the first phase of the laboratory. So, the two shafts, this preliminary gallery on the top of the clay layer and just a few galleries to launch the first experiment focusing on geological surveying, on pore water composition and fuel retention and geomechanical behavior of the rock mass.

The second stage of the development of the laboratory was performed in 2006, so we develop reconstructing new set of galleries and closed the first loop of – the link the shafts and we developed new set of galleries. And here we start to introduce our program, THMC processes and related experiments.

The first one was we are ready to try characterize the interesting properties of the clay and now we were looking for what will be the impact on the constructing and using this clay for disposal of radioactive waste, high-level waste.

The third phase of the program started in 2011 and this started to integrate a new development in our programs. It was more technological development advancing some cells, some gallery, wider gallery.

So, it was more implementation of a technological program in our laboratory, especially for the high-level waste disposal cells and we started construction of 100 percent scale cells in our laboratory.

So today, we – so as I told you, we are launching the fourth phase of the construction of the laboratory with the very large gallery, which are really looking like the disposal cells for intermediate-level waste, so it's intermediate-level waste, so it's large galleries.

And also, we are continuing where we continue drilling our high-level waste cells. So today, well, we have two shafts. We have more than 1.7 kilometers of gallery. We have tested already three excavation methods from traditional and TBMs.

We have developed lining and support for the clay because the clay has various strength of different behavior – mechanical behavior. Well, we have constructed 13 high-level cells. And we are continuing to implement technologies in our repository.

Today, for the R&D, we have more than 70 experiments ongoing at Bure laboratory and, well, many bore holes and a lot of examples and sensors.

So, the topic of this part of my presentation was to show you that the program of the laboratory was developed by phase and those phases were linked to the development of the program itself.

The first stage was we are really to consolidate that this clay layer can be a host formation for a high-level waste repository. The second one was how can we understand what will be the disturbance of the repository in that clay and this disturbance, what will be the disturbance on these favorable properties of the clay, and then after that we now

– we are more focusing on technologies. How will we construct and operate this facility in the future?

So five examples of experiments, well, I got to make a choice. Well, this is one of the first experiments which was in link with our program. It was this tracer diffusion experiment, which was launched – sorry, which was first initially launched in this little gallery to measure the diffusion.

And then we – in 2006, we launched a new set of experiments to compare between those two. And these experiments were launched very early in our program for mainly two reasons. The first one, we would need some information for the 2005 milestone and also it is long-term experiments.

So, we need to implement them for as early as possible and the reasons were very important for our safety case.

As I show you in 2011, we started construction of these high-level waste cells, which are micro channels, originally for micro channel with steel lining.

And sorry, yes, so it was – the first trials were feasibility tests and then after that we got to work on the connection of the sleeves and the thing like this to develop a quite robust technology here, to develop these high-level waste cells. And today, we are using these cells to perform sample test.

With the behavior of the clay, we were in front of a dilemma as we needed to be reversible and that we need to keep the drift as safe and secure as long as we can – well, at least for a century, so meaning that we need to have a very stable lining.

And with the conventional techniques we were looking for segments of one-meter thickness and so we got to develop special elements to try to absorb the first convergence of the clay and to reduce at the end the thickness of the segments.

We have launched seal core experiments. So, it, well, it is in the downward gallery, we have constructed a seal to study the implantation of the bentonite and we are also using an artificial hydrating device to limit the time.

Well, as we are disposing vitrified waste, we also launched experiments to steady the behavior of the glass in the repository situation to verify that the investigations, the lixiviation of the glass is very low in our conditions.

So, we launched several tests and there are active tests and there are also passive tests where we are collecting samples dormant tests. I was very fast. So, just to – well, in fact, it was very difficult, I mean, a 20 years program to make a summary in 20 minutes, it was quite challenging and, well, so, OK.

So, this is clearly linked with the introduction of Irina, well, there is one thing really in our program. We didn't develop URL for academic research and the URL was – since in the beginning included in the program, in the disposal program, meaning that we were able to implement in our R&D program milestone of the projects and meaning that we were expecting results at already defined point of time.

So, what was very important for us is – was to go to this functional analysis and try to distribute the function in the system and try to allocate to the expected performance for each component and from this link to the, on the real uncertainties and performance we have developed our R&D program.

And this safety – this functional analysis approach was really developed since the beginning of the program because we were in some sense, we knew it is a system engineering problematic and with the formal definition of the NEA where the system is defined, the main functions are defined, the environments of the system are defined and also the lifecycle of the system was defined.

It was clear for us since the beginning that it is a system engineering approach that we have to apply to this, even if it concerned R&D activities. So, well, with all this, we went to a disposal performance specification, identifying where we need to make additional research. Is it academic research and laboratory in a URL, or those kind of uncertainties can be managed by engineering activities.

Then we got all this – after this period of work linked to the milestones of the project, we made this consolidation of all the result from the different source of work, of our R&D work. We performed a safety assessment or safety analysis and then we got to project reviews.

And this is something that has – that was mentioned also by Patrik, our regulation allows this iteration and stimulates this iteration. For the safety authority in French, this project is also new, and we are building this project with them, so they are involved many times.

And it was a very progressive approach in France since, since 1991 while with a progressive siting process, as I told you the initial intention of Bure laboratory was a generic laboratory.

It was just to study clay, let's say few hundred meters. It became after the 2010 a site-specific laboratory, but it cannot be used in the repository. It is similar to Äspö. It was a commitment at the beginning, but this laboratory will never be included in a repository.

It was a gradual development, so from 2005 to the current stage, we've got many engineering developments and try to assess the cost and also operational safety became more and more significant in our design and in our progress.

Step by step assessment process. We've got all this iteration and with most of the time the safety authority are watching this. We got to develop mature governance processes and if you look into detail you will find a board very similar to your Board in our system.

And we really developed a system engineering approach starting from the need, the functions and then we developed our we program according to that.

So, Bure URL plays a major role in the completion of the license application of Cigeo and we are expecting to apply for the license next year in 2020.

With the discussion we have today with the safety authority, we are expecting at least, well, between three to five years construction because it will be the first of a kind. It's quite a complex issue.

So, well, so this is for the timing, but anyhow, the laboratory plays a major role in several rooms of our program. To justify the design choices and all we dispatch this function in the system and how we characterize uncertainties to try to improve our safety assessment.

To demonstrate the technology readiness of Cigeo and this was also a point of Patrik while we – if we want to start we have to be at the highest level of this TRL scale and meaning that we have to be sure that we can construct, operate, and close the facility.

To consolidate our phenomenological analysis, understanding the behavior of the repository in the future, developing models, testing models, calibrating models and sometimes finding things that we are not expecting.

I mean, for example, in our clay, we have pyrite and due to the drilling of the high-level drifts, we are oxidizing the pyrite at the time we are disaggregating the clay and wonder what have come back. We have this reaction and the pH is increasing a lot and changing all the assumptions we were having on the corrosion rate of the steel.

So, we've got to adapt our program to adjust our program with this. But now, what? Certainly, it was a major input of the URL in our program, the understanding of the phenomenological processes that were involved in the facility.

Civilians and monitoring program, yes, because when you are able to characterize all these different relation and process you can start to develop monitoring activities and monitoring techniques to try to investigate before – to continue the understanding of the things and also we have developed and we are also registering probes, special probes for our special use.

Very important to gain of the stakeholders' trust, well, we are now in Bure since 2000. So, we are neighbors. We are living there. We are able to explain to the people they can visit our facility, so they'll understand our program.

And it was not the case at the beginning when just – we were intruders there. But now we are living there. They are our neighbors. And now today it's more important than ever before because now we are working on the implementation of this facility in this specific region.

And we developed a lot of consultation and we are working with the communities to try to see with them, well, we need a railway, so we have to discuss about infrastructure, roads, railway, where to put them, how to arrange this.

We are also, we will have an impact of the consumption of energy locally, consumption of water, so how we do that. So, because we have this facility and the people knows already our program, they are able to discuss with us of the real impact of the repository for their living conditions there and, OK, and this is it. Thank you very much.

I'm sorry for my English, sometimes it is rough.

ZOBACK: No. Thank you so much, Daniel. And you were exactly on time. Really appreciate that, so, unfortunately, no questions now, but for the panel discussion. And now, I'm honored to introduce our final international speaker, Dr. Simon Norris. He is a geophysicist.

He's a senior manager, research manager at the Radioactive Waste Management Limited, which is the U.K.'s government organization to deliver a repository. He has a Ph.D. in geophysics from Liverpool.

He is responsible for Rad Waste Management geosphere and waste-derived gas research activities. And the activities led by Dr. Norris consider the range of rock types they might use for a repository, how the different rock types within a repository might evolve and the impact of long-term geologic and climate processes on the geologic environment.

So, thank you, Dr. Norris.

NORRIS: Thank you very much for the introduction and also, I thank you for the Board for the invitation.

So, talk to you a little bit about what we do in the U.K. for geological disposal of radioactive waste and how our work in underground research laboratories contributes to R&D. I just state the outset that the U.K. program is maybe not so far advanced as the other programs you've been listening to today.

So, we do not have a site and we have not chosen a particular geology, so that many are covering quite a broad basis in our research work. But I hope to explain that despite – well, we are where are, that's just a fact. We can still undertake the significant meaningful research, international collaboration, international cooperation and make some progress as our program advances.

So RWM, Radioactive Waste Management, it's a – we're a government organization, so I’m a public servant and we've got a mission to deliver the repository also known as the

GDF, Geological Disposal Facility and to provide radioactive waste management solutions.

So that's a map of Great Britain with sites that have radioactive waste or will have radioactive wastes arising. We have a lot of nuclear power stations. We have military waste. This needs to be managed in the longer term, obviously.

We have low level waste, it is currently disposed to the low-level waste repository as with the – in the Sellafield in Cumbria, has been operational since the 1950s. So, we won't be talking about low-level waste today. What we're talking about is higher activity waste.

And in higher activity waste, we kind of categorize it into two types. We have low-heat generating waste, which is broadly equivalent to intermediate-level waste, so it's kind of sobriquet. So intermediate-level waste is being produced and packaged now.

It goes to interim storage, but the long-term plan is that it will go for disposal in a repository. So, it's just an example of intermediate-level waste. It's in a steel container. The waste has been encapsulated in cement.

The waste arises due to the decommissioning of power stations and also a resolution of other processes. That canister itself is about 1.2 meters high by about 80 centimeters diameter. And there are quite a few of those already in existence.

So, we want to come up with a strategy that allows us to deal with the waste we have now and to manage it. For today, so we can decommission power stations, for example. But we also want to ensure that in the longer term, the waste is packaged in a manner such that it is disposable.

The other category of waste is sort of high-heat generating waste. It's more of the spent fuel, that type of thing, that side of things. For example, there are some vit flasks. In terms of our inventory, when you total it all up we've got about – when packaged about 650,000 cubic meters.

It is a large, large inventory. So, we have a lot to deal with.

Government strategy, it was kind of captured initially in 2014 in a whitepaper *Implementing Radiological Disposal* in which the U.K. government commits to geological disposal of higher activity wastes and to the development and implementation of a geological disposal facility.

What will this look like? You've seen various versions of this today. So, this is one of our versions, key principles. Isolate radioactivity from the surface, contain until most of the hazard is decayed. And you are looking for passive safety, so not requiring human action in the longer term.

In the U.K. context, you'll have a fairly small surface footprint that allows operations to proceed. But at depth we are going to – we're planning to co-dispose of the waste both intermediate-level waste and the spent fuel in the same facility, so access via shaft or drift, you'll have an intermediate-level module there. And you also have a higher activity spent fuel, higher activity waste spent fuel module.

They’ll be separated by our spec distance say, for example, 500 meters. In terms of footprint, this is large given our inventory. And the size varies by the properties of host rocks that are chosen, but this could be of order at 10 to 15 square kilometers footprint.

So, it's quite a large facility if you place it in a single tier. There are also options of potentially of stacking it. It really depends on site properties. The majority of the area is needed for the spent fuel and that's managing the thermal load which was alluded to earlier as an issue.

So, we need to separate it. We need to separate the packages a certain amount at the minute if you want to maintain a temperature of no more than 100 degrees for example. That has a knock-on effect on the size of the footprint you need.

Just something to note, it's a consent-based repository siting program. So, we're looking for a suitable site with a willing host community.

So, from 2014, work has been started on three initial actions, geological screening, land use planning and working with communities.

Geological screening was really collating all the information we had from various databases about U.K. geology. So, it's looking at rock type, structure, groundwater flow what was known as rock groundwater flow resources, such matters like that.

And the purpose of it was really not really to screen in but really to exclude areas that we knew wouldn't be suitable to host repository based on, for example, previous resource exploitation.

And within this document, there’s commitment for community investment funding, at sort of, not in any substantial level.

And again, the policy is based on community consent, so we go to somewhere where we’re wanted. Just to say, this is a U.K. government document but in the U.K. waste is also, involved administration level, say for example the Welsh government is doing something very similar to what the U.K. government is.

But the Scottish government has a different position. So, the Scottish government does not favor geological disposal, so their policy at the moment is that waste should be managed near site, near surface – so sorry, near surface, near the site of the rising.

So, that's just something to bear in mind that really talking about this going forward in this talk. I'll be looking – speak mainly about how this policy plays out for England and Wales and when we come to –a place, locate a geological disposal facility, Scotland is not playing at the minute.

So, progress since 2014, legislation makes the repository GDF a nationally significant infrastructure project. We've undertaken consultations on working with communities and national policy statements. And we've updated the GDF siting policy framework this document have which you can download at the web and it replaces the 2014 whitepaper, so this is the policy that we are taking forward.

And within that, a bit of a complicated figure, again, this is what the process for implementing geological disposal. Things to take away from it, we're talking about a project to last hundreds plus, so significant multi-generational project.

Protecting the environment and people is key. There are a number of activities we want to undertake, investment, you may end up – we may start with a number of communities. And each community will receive some investment for being part of the process, as we move along and down select to a chosen site, the level of investment increases for that particular chosen site.

So just want to be upfront about the process we intend forward, intend following, working with committees is obviously a key issue.

And so just focusing on the shorter-term side of, it will go out to 15 years. We're currently off to the left, we're about sort of embark on the first stage here, so some investment and we'll be inviting, shortly inviting communities to indicate that they wish to sort of participate in what we want to do.

I think you've seen various versions of this, but it's just looking at sort of – because we have a higher activity waste separated into low-heat generating waste and high-heat generating waste, we basically have two disposal concepts.

So, for the low-heat generating waste, we have the cementitious encapsulated in capsule. In normally, something like a stainless-steel waste container, which will be in placed in the underground with a cementitious buffer and interact with a host rock.

Whereas for the high-heat generating waste, more of a sort of concept that depends on the engineered barrier system. So, you have a thick container, a clay buffer, bentonite buffer typically and then a function of the rock.

So, just to bear in mind the concepts look different, although we have one facility. We basically have two modules and we're running with two different disposal concepts essentially. And in for far distant future these are sort of things we need to think about when we're trying to evaluate how a site will perform. Also helps us think about what sort of processes we need to think about when we're questioning how waste as it evolves underground, how will it interact with the rock mass.

So how does the rock affect radionuclide movement? What is groundwater movement and rock matrix diffusion and sorption – diffusion and dispersion? And when we think about whether or not they are short circuit mechanisms.

Need to think about waste derived gas, future is also assuming interactions and also in a very long time, natural processes, tectonic and climatic events. So, this gives you a sort of a FEP list, however you want to call it a checklist of processes you need to think about and how your waste will interact with the – in our case a range of geologies on a very long-term scope.

So, in the U.K., we haven't got a site. As I just explained, we're about to embark on a site selection program. So, at the minute we make an assumption of a generic – of a number of generic geological disposal facilities and we are considering a range of potential host rocks.

So, we're considering a higher strength rock, for example, granite. A lower-strength sedimentary rock, for example, a clay and also an evaporate, salt. Now, these are just the host rocks.

You may well build your facility within the host rock, we also need to think about what's on top of the host rock, the surrounding geology and the role of the surrounding geology.

So, in terms of what you need to investigate when you're planning for a repository such as this.

Yes, you need to investigate the host rock and how it responds to the presence of waste and the waste as it evolves. We also need to think about the overlying geology and how that influences the site processes.

So, we developed illustrative disposal concepts. Get them right to you in a minute. We’re cognizant of international precedents that you've heard already this morning, so will take a lot of knowledge from Swiss, the French, the Swedish program, the Finnish programs.

That allows us to develop our range of safety cases. We also need to think about is there anything special about our waste that isn't covered off already, because of some of the – we have some of our intermediate-level waste is fairly unusual, fairly unique, so we need to think about how that would evolve and how that would interact with some of the rock mass that may require us to do individual bespoke experiments.

And also, what are the options in the U.K. that we could use, the geology of the U.K. is very varied. We do have a nice suite of a range of higher-strength rocks, a range of clays and some evaporites.

But we don't cover off everything, so for example, sort of the more plastic clays that you see at HADES and Belgium and Mol. We don't really have those – what you would have at repository depths.

So, we need to sort of be careful that we study international precedents that are of relevance to the U.K. context. And we develop generic safety cases. We can do this on the basis of idealized geology – U.K. geology and cross-sections – various cross-sections and how the waste when emplaced would actually respond and behave on the longer term.

So, this really sort of starts to interact with or brings on board where the role of the URL based R&D comes within our program. You've seen various versions of this before we develop the safety cases and the overview, really sits on top of a structure.

So, safety cases underpinned by assessment studies, underpinned by how you – what you require of your disposal system, what you're required to do. What it might look like, its design and also the underpinning knowledge based you have and also the supporting references.

Some information from R&D that we undertake both in URL based R&D but also other scales, laboratory-based for example, does provide us, does provide us with the sort of information here that allows us to feed up into the safety case.

And the safety case itself in our context for each one particular design – for each one particular geology, sorry. We look at transport. We look at operations. We look at environmental safety case.

Transport is really how you get waste from A to B sites of rising to the site of the GDF, operational safety cases, the construction and operation of the repository on a very long-time scale. Environmental safety case, other people call it post-closure safety cases, the very long-term one. The bars here really explain or try to illustrate the various strands of our research activities.

So, we need to understand how the waste packages that we are planning to use or indeed are using will behave, how the engineered barrier system could behave, the geology, behavior of radionuclides and also we're worried about what else is in the waste apart from radionuclides, so non-radiological species, role of biosphere, issues with gas, criticality, and also waste package accident performance.

So, it’s quite a broad-based research program in the context of a number of different potential geologies. Irina had a version of this and hers look nicer. So, it's the relationship between the laboratory studies, in situ experiments in URLs and natural analogs.

I think natural analogs play a role. But we also undertake experiments in conventional laboratory settings. And we also learn from natural analogs.

So, given where we are, we don't have our own URL. We don't have a chosen site. We don't have a chosen geology. We are actually participating in a lot of international studies in URLs to upskill ourselves, those of the company, but also to make sure that our supply chain is upskilled, so our supply chain gets to work on exciting detail-rich, information-rich work, problems and I think this helps both RWM in the longer term, making sure that ourselves we are able to fill the intelligent customer role, but also make sure that our supply chain is able to actively work and to make sure that we are able to compete – not compete, compete is the wrong word, but to input our international work as a sort of sensible partner.

So, the ones in red are the ones that are just highlighted, and we got work ongoing, international collaborative work at Äspö. At Bure as Daniel said is the Callovo-Oxfordian clay that is the subject of interest, where the unit repeats in the U.K.

So, it's actually entirely sensible for us to undertake some work or use data from that – from going from experience at Bure because we have the same clay basically, so. I think we need to think about – I know we call this generic, GDF, but it's kind of – it's not geology generic often.

It's often that we use information from the geologies of relevance in the U.K. in our own work and we gain that experience from outputs from international work. Onkalo has been mentioned before, Mont Terri we recently joined and also Grimsel we've been a member for quite a while.

So, we have a set of portfolios of URLs that we are engaged with actively undertaking research that provides input to our safety case via addition to the knowledge base. Given that I said earlier on, we're looking at three types of host rock, high-strength rock, clays and evaporites. There's a glaring omission here.

And I think it’s something we need to think about as a company. We don't do enough work within halide-based systems. Although, we claim it on an equal path in our own programs with higher-strength rock and clays, so we need to take measures ourselves to some sort of help ourselves.

So I think that’s just something that we need to be aware of but it's also something that our regulators are aware of, given our program that we do have to make sure that we could genuinely go in with a – if a community sets forward that is a halide based geology beneath it then we are genuinely in a position to go in and have an active sensible conversation with them.

I think trying to tie that sort of loop together. Just an example of the rocks, some of the projects we have involved with at Grimsel. Many is the answer. So, over the years, it's sort of a well-run project and has many interesting projects that we can contribute to.

We don't just join them for the sake of it. We joint them on the basis of structured thinking about how all this information help enhance the robustness of our safety case and also build our confidence that we understand sort of the key phenomena, key processes.

So just an example of one of those projects I was involved with – it was called the Long-Term Cement Studies Project. It's now finished, but the project – this is envisaged, so this is one of the main tunnels at Grimsel, project envisaged the emplacement of cement tubes in an emplacement bore hole.

I wanted to see how those tubes would evolve over time themselves and also how leachates from the tube would move in the sort of groundwater flow pattern predicted at Grimsel and what you'd see in the monitoring bore holes.

So, this allowed us to do some detailed hydro-chemical modeling, which I think is good for us because I think the C angle is typically under resourced. THM in terms of coupled process modeling is quite well-resourced, which I think the C angle and particularly the gas angle get left behind sometimes, well, at least they have been historically.

So, I think this allowed us to do some predictive modeling. So, we tried to undertake some modeling blind, because we didn’t know what the answer was, publish it and then we came back to see how well we'd done once the results had been recovered.

So, this is some of the tubes, cement tubes that were recovered from this emplacement bore hole and we had a go at sort of modeling the evolution of cement, how that behaved over time.

So, we looked at some porosity evolution and see how that changed within the tubes. But also, we had a go at doing some transport modeling. This is always fun. It's always much more complicated than you think, doing – releasing a particle here and you'll expect it to get there at a certain rate and it often does something completely unpredictable.

So, we had to go at it. It's a very interesting issue in highlighting what you still need to do more of, I think. And it also emphasizes that perhaps it's not possible to characterize a site as thoroughly as you might need to, to undertake this sort of very detailed modeling.

So, there's always going to be an element of what is an acceptable result. I don't think expecting A, B, C transport over a very, you need to be able to predict it accurately up front is a particularly realistic thing always to have a go at. So, again, it's still uncertainties.

This is about the third time this has been shown but we are actively involved with some projects at LASGIT. And we have also recently joined sort of the Mont Terri project and looking at clays.

This is a subset of the projects being run at Mont Terri. So, it's not everything. We haven't joined everything. We've been through sort of systematic sift and joined the projects that we think will give us some added benefit to our safety case, but also perhaps to take us in a new direction, to maybe open us up to things we haven't really started yet in our program.

So, now we're looking at a shafts experiment for example, but we are long way of leading a shaft experiment or needing to seal a shaft. There's no harm now being involved in a project is being run by people who need it sooner than you need it and also taking some benefit from it.

That's just part of the sandwich, it's called the Sandwich Project, the seal. That's just an example. And you can tell by the logos. It's a large multi-partner project.

Just coming towards the end, you can undertake the experiments in URLs yourself. You can join projects – international collaborative projects that undertake experiments in URLs. You can also make use of data sets that come out of URLs. And so, this is our project that I'm involved with.

That's my organization, again, there's a quite a few of us in the room who are also involved in various tranches of DECOVALEX, so it's the development of coupled models and their validation against experiments. It's a very long-term project that runs in three and a half year tranches.

And it's just about, up to 27 years now. It's a very successful project. But it does give you the – just a very different task positive, sort of gives you the ability to join various tasks and this is really sort of quite cutting-edge research.

So, it's looking at do you understand those quite fundamental processes. Do you need to sort of enhance where you thought, so task A is a project looking at gas migration through bentonite, for example, which has undertaken some of its lab work but some of it will based next time around on work from LASGIT and Task E is based on an experiment at Bure.

So, our involvement in this gives us the example – it gives us a heads up about the performance of Callovo-Oxfordian clay out at Bure, but we would extrapolate that to how Callovo-Oxfordian would behave in the U.K.

So just to finish, we have a position on U.K. underground investigations. So, this paper is 2009, it is still current.

We haven't superseded it. So, it's been described as somewhat long in the tooth. So, it is still current though. So as our program advances, when we become site-specific, we can integrate underground investigation activities and disposal facility construction, that’s not dissimilar to other programs you've seen today, and knowledge gained from surface- based investigations will be used to inform requirements from the ground works, so common sense.

But now, present day, given where we are, given that we don't have a site, given that we are carrying a number of geologies forward, we're going to maintain our links and cooperation with the network of underground research facilities located in rock types of relevance.

And it provides access to techniques and results of relevant features and processes in underground openings. And we'll be able – that will enable us to inform a judgment on the need to conduct equivalent research under the specific site, conditions of a preferred site.

So, this presentation hasn't been as detailed as some of the previous ones, but I think it's a kind of reflection of where are. We don't – our program is where it is. It's advancing, but it's just not as advanced as the three – those of the three previous speakers.

But what I'm trying to emphasize is that irrespective of where we are, URLs still play a role. We haven't got one, but because we are able to work collaborative and cooperatively with international peers, it allows us to learn a lot from what's going on, upskill ourselves, make sure we maintain our upskills, help our supply chain, and also make sure that the safety cases that we develop even though they are generic are underpinned by a rich knowledge base and that helps us to boost, to build confidence in the studies that we are undertaking. Thank you.

ZOBACK: Thank you, Simon, and you finished a few minutes early, so there is time for questions.

BAHR: No, there is not.

ZOBACK: Oh, there is not time for questions. OK. We are right on time. Thank you for finishing two minutes early.

BAHR: Sorry. No, we're not…

ZOBACK: Right. OK. So now we're going to transition to the panel. I'll invite the international speakers to go up front. Just get up there.

Thanks. Okay. That was a relatively quick transition to this new format. Again, I want to thank all the speakers. We gave them a long list of questions, and you did an outstanding job of addressing the questions and bringing a lot of extremely valuable information, and by my calculations, a hundred years of experience among the groups here working underground.

APTED: I don’t like to say a hundred years.

ZOBACK: So just in general about the format here, we have 45 minutes allocated to this discussion. We are going to leave time for questions from the audience, but to begin with, Tissa and I were hoping to have a bit of discussion among the panelists. I know after Irina and Patrik spoke, they were meeting in the back talking about some commonalities already.

And I think we saw in our first speaker, Mick likes to be provocative. So, in order to stimulate the discussion, we've asked Mick to make a few comments. And Mick brought up the term filibuster. I think that this is probably common to most people. It's, I think, a distinctly U.S. term. I don't know, maybe it's British and I'm – I'm sorry, it's British. A British term. The...

NORRIS: You have to hear MPs doing it…

ZOBACK: Long-winded is basically – anyway. So, Mick, you were admonishing that – us on that, so let's hear your thoughts.

APTED: I think I was admonishing myself more than anyone.

ZOBACK: Okay. Well, we'll work on that.

APTED: Just to start it off, as a question among the rest of the panel, in one of my slides, and the question came up from the Board about generic versus site-specific URLs. And my comment at the end as question was, is it worth going to a generic URL if eventually a site is selected, you're going to do a site-specific URL.

So, I was going to just start with Irina and go down the panel, briefly sort of what is your organization and your – sort of your personal view on that issue of sort of generic versus site-specific URLs.

GAUS: Thank you. If you have a generic program and going for a – this is personal view. Going for a generic URL, it's putting a lot of eggs in one basket. Of course, a generic URL can bring a lot of insights but also if it's supporting one major program, one implementer, it also needs resources. So teaming up there and trying to feed as Simon also nicely illustrated, trying to feed your generic program with insights from different URLs, which are already thriving and which also represent a research community in a series of experiments at the edge of science, at the state-of-the-art might in a lot of cases bring more benefit to a generic program than going – selecting a generic geology -- generic URL which might, in the site selection process, be not so illustrative in the end because the geology might be completely different.

VIDSTRAND: Okay. Thanks. It’s a very hard and expensive question. I would say that, as I said, when you plan on experiments, you had expectations and the outcome is rarely what you see. And when you construct a repository, you can't really do experiments down there, and also the training of people. I acknowledge the cost for a company to have a generic repository. I would say rather site-specific very similar to your repository. I think you’d need something where you can train people, where you can actually set up experiments if something happens that you’re not expecting.

DELORT: Okay. Well, as I told you, our URL becomes site-specific during the process, during Cigeo program but at the beginning it was generic URL so it’s quite difficult for me to argue on this difference you are making. But I'm sure that today if France was willing to – if we had to restart the program and saying to the people that we are looking for a site-specific meaning that at the beginning of the discussion with the public and the stakeholders, we are already saying that you will have a repository in that area. It would have been a major difficulty. It will be a major difficulty for us and because you are stressing the, your R&D program with its conclusions, maybe it’s too early.

The other thing is I don’t know if the timing is over for a generic laboratory despite trainings, things needs. There is also a maybe new program, a little bit limited. I mean it’s not – it’s not bad wording, meaning that while you have time, as you see our program took several decades and we have started from scratch from the basic concept and in fact, we didn’t move too much from the origin of the concept.

So Sweden working on copper for many years and bentonite for many years. We are working on steel – carbon steel. We are – but if there is new materials, ceramics, I don’t know, other alloys, we may need to improve to increase our R&D and to make sure that we want to measure something, maybe a generic laboratory is better because if you want to measure the impact of the water flow, you need – you need water flow in your – in your URL.

So, you don’t – you – the program, the R&D program with a generic laboratory is not the same for the site-specific – I'm sorry for that, that’s my feeling. Site-specific, you looking for ideal condition you would like to have in your repository. For generic, you want to measure something. You want to calibrate models, you want to still do something. So maybe you will be happy to have a generic URL in your fort. That’s – you will try to exclude from a site-specific laboratory, but in a site-specific laboratory if you want to measure something, it takes much more time because you are in ideal situation for a repository. So, it will depend on where you are in your program.

APTED: I thought the word depends would show up in everybody’s comment. All right. Simon, how about you?

NORRIS: Yes. Given what we’ve – given the state of the U.K. program we need access to underground facilities. I think it really depends on what you – the definition you put on the word generic. For example, Grimsel Test Site is a good example of facility hosted in a high-strength rock. It is not specific for the Swiss program anymore. It might have been when it was first constructed. I wouldn’t want to lose that as a facility that we can use, and whether or not you would describe that a generic, I find it a bit of – a bit of an unclear situation because again, things do evolve. You said that you didn’t want to become – you know, I'm sorry for paraphrasing you badly, but you want to move away from a sort of generic URL because you understand the hydrogeology, groundwater flow models.

There were many other things we also need to think about, so groundwater is one thing, but I am going to come on through coupled transport processes. And I think those is – and seeing how they interact with a rock mass is a difficult question that we still need to work on. It may not have a massive impact on post-closure risk, for example, but I'm sure the regulator is going to want to know that you understand the processes and understand how you've come to the conclusion that you don't think it's a massive impact in terms of where it may affect long-term post closure study. And I think we all do evolve.

Patrik brought forward this – the issue on microbes. That wasn't an issue at one point and then we look at it further and so it becomes quite a significant issue or has a potential to become a significant issue. I think we just need to be open to the fact that we know a lot. And we do have an extremely large knowledge base to draw from, but we may still need to act with.

Just one final thing. With coming at this primarily from the point of view of an environmental safety case, long-term safety case, if you want to understand how to drill and blast, tunnel construction, operate underground, I think perhaps another role generic URL could have. There's the Swiss facility, Hagenbach, which has nothing to do with rad waste management. It's a – it's a facility run by the tunneling industry, for the tunneling and mining industry but they're not – they're un-amenable to people going in there and testing their kit that they may wish to use to deploy the – to sort of use them in a GDF in due course. So, I think it's just – that is – that is generally a generic GDF, generic URL. You won't undertake any experiments in there to look at rock mass properties in terms of how radionuclides or contaminants could move, it's really kind of, you know, or do you actually need to understand to physically construct the facility in the first place. And also, then to keep the facility open over the sort of prolonged timescale that you need in the post-closure and in the operational period. I'll shut up.

APTED: Let me just – my own question response, in the part two, that little slide of the organizational boxes, I think, again, an early – a country and a program just starting has opportunities and we see it Simon in your talks, of going to all these laboratories and looking at what's going on in clay and granite, and salt, and so on to learn from that, and rather than having to build, just putting a shaft down the ramp is a big cost versus using that money to go overseas or some other country to go. So, I'm not adverse to a generic if we call those – if you're in a generic stage of your project those – you know, there are a lot of opportunities. And that’s what we see. This – 40 years in, 50 years into this business, there’s a lot of URLs, you know, that snake diagram, there are real opportunities out there to collaborate, so. But over to Tissa and Mary Lou, I mean, why don’t you take it over from here.

ZOBACK: Thank you. And you all have noticed that I’ve done all the talking so far and I'm known for that, but my co-organizer, Tisa, developed pneumonia last week and is recovering and is saving his voice for the crucial questions he would like to ask and we’re going to have him start out now.

ILLANGASEKARE: Yes. Thank you. Again, I'm saving my voice. It’s really interesting from the different – all the speakers have different styles to explain something very important in my – my own work and this has – many people are looking at this issue of space and temporal scales and upscaling. I thought these are – this is not a trivial problem because when you do it, a special scaling issue of hydrogeology came up and hydrogeology is actually not only driven by physical but by chemical hydrogeology, too, which evolves as time goes.

So, my question is – your input is that looking at some of the figures, we are trying to connect lab-scale to URL-scale to the field-scale, I can see some light at the end of tunnel if you look at spatial scaling but what – I want to know your thoughts on the time scaling.

ZOBACK: Why don't we start – so we don't always just go the same way, we'll start with Simon if you have something you'd like to say?

NORRIS: I think it's a good – it's a very good question. I think we work – well, in our program, we're trying to do a lot of work on – more of an analog-based approach. We've done a lot of work recently to try and make sure that we have a toolkit available to deploy at a specific site such that we can understand or have an attempt at understanding how the hydrogeology of the system has evolved from way back in the past through to the present day so, you know, paleo-hydrogeological study, how the site or how a site – it was a

– it was a site we looked at in the past, how the site has responded over a very long time scale to the imposition of ice-sheet loading to permafrost, how that's affected the groundwater chemistry at depth, what we can say about how the system is, today, is almost certainly not in steady state in transience still. And how the system moving forward – once you place a repository in it, how it could then evolve in a – in a much longer time scale.

You need to understand how the system got to where it is first before you can have any idea about how – you can understand how it will evolve in the future. This was just a site we looked at a long time ago but we're just doing a little bit of work in the background as – we have a data set, we have very large data set that is available to use because that's an interesting study for us to look at. And we also undertaking some work, for example, on rock-matrix diffusion at the minute. So we want to understand – well, we want to sort of question ourselves, do we fully understand the processes of rock-matrix diffusion and how it works in a very long time scale.

We’re looking at some samples. We’ve – we’ve got some samples from Grimsel and also some complementing efforts in laboratory-based work. So, we want to understand, again, how the rock we’ve looked at – we looked at in Grimsel has evolved to where it is now and then how it could evolve in the future when you impose your repository in it. The problem comes with the imposition of the repository because it’s a massive blip in terms of mechanics, hydro – you know, hydrogeological framework, chemistry, and you need to take, you know, a lot of careful thought about how – how you change the repository – how you change the host rock environment could manifest itself given what you know about the site already.

ZOBACK: Daniel.

DELORT: Thank you. Yes, well, managing time-scale work, I would say that something – I think it’s quite obvious. This is an obsession. I mean – all we are doing – most of what we are doing at the laboratory is to consolidate our models to investigate the future and the – and the realm of all the facility and trying to assess the long-term performance of the facility.

So – but this – maybe doesn’t answer the question so meaning that – as I tried to show that there are difficult experiments where a long time is needed to collect a sufficient amount of data. So those are – those are – those topic has to be identified as soon as possible to be – to implement the relative experiments as soon as you can in your laboratory. There is one thing I didn’t talk about that – and this is a link maybe with a site-specific and generic, at Bure we have also developed on surface, an observatory of the environment because in fact, the most of the time, we are making an assumption that the biosphere doesn’t change too much.

And in fact, we – so we realized in 2010 that we also need to have a clear baseline of the environment, so we have a very important monitoring program, we are collecting seed samples of the environment, we are making a lot of analysis to this so yes, time-scale, it is an obsession, you know, in our program.

VIDSTRAND: Thank you, Tissa, for asking that question. I can probably filibuster for two days now. I will not do that. First, I would say – a little bit like Simon was saying, I think it’s very important that the site investigation create a history, a conceptual picture how the site has evolved in time and how that has led up to present day conditions and if possible also some kind of prediction about the future that is needed for the safety assessment but, of course, it’s much more complicated to do that.

About numerical modeling, I think that the models have developed quite a lot. We can nowadays do quite a lot of things with mixing scales – both mixing time scales and mixing spatial scales, but at the same time we are also always trying to extend it, so especially like when we coupled in chemistry with other things. Chemistry acts on different time scales and on different support volumes and other things. And we are presently, I would say, daring to do coupled chemistry models that are probably wrong, because we are just importing wrong boundary conditions or moving things too fast.

And finally, I would also like to stress what Daniel was into here where with the monitoring program, not only the surface because we also have a monitoring issue about monitoring long-term safety. And how will we do that in a passive system where we are not supposed to interfere with things. So, we need to do some kind of monitoring on the short term and then do a prediction on that monitoring into the future. So, time-scales are tricky in many parts, and – but I think most groups is thinking of that quite a lot, so. Yes.

GAUS: And I can acknowledge what has been said already, but I think we're probably in an industry where we have to claim this million years, time-scale to cover this. And therefore, we also have the possibility to do this through a set of arguments. We don't have to bring the mathematical proof. It is impossible anyhow. So, this set of arguments then relies, too, on models and assumptions, and covering time-scale I think the THM part, the thermo-hydro-mechanical part is probably – lends itself easier to covering larger parts of the time-scale because the mathematics behind it, the physical laws behind it are easily amenable to longer-term predictions.

However, the chemistry – and I think we have to acknowledge that making predictions over longer time regarding certain – not all, but certain chemical evolutions is more difficult, because what plays a bigger role in those is the reaction kinetics. And you might have a reaction which is so slow, you’re not even to measure it in 30 years experiment for a THM problem, you probably might – might be able to capture this better in a – in a longer-term experiment. So, then the only thing you can do in order to get the arguments together is either to open the bandwidths for ensuring the safety case or avoiding the issue, and that’s why we tried to choose materials which have a very low chemical contrast with the materials which are already there.

So, putting bentonite and clay is clay and clay, so you don’t expect a lot of chemical reactivity or you have – can show that the – whatever happens in the worst case for the chemistry, it’s not affecting the safety. So, they’re also stepping in to fully coupled THMC models on a 3D scale over a million years and probably not going to get there soon. So, we have to realize that in trying to bound the issues especially from a chemical point of view which might affect the evolution of your repository.

APTED: Good to hear after 40 years of URLs, we’re just coming to chemistry, okay. No, I take Daniel’s point about the word obsession. I think when you really look at what can be monitored even over the several decades or 80 years in a repository, I think you can probably do a good job of confirming your thermal conduction models, but probably not your buffer saturation models now, it's turning out with a gap between the rock and the buffer, that the buffer is not saturating for thousands of years and so on.

So, I think we have to a little careful what our ambition levels will be about the time-scale and what we’re selling about the time-scale aspect of it. On other hand, going to higher temperature does couple strongly with flow and chemistry. I think that’s – that’s the kind of thing that often could be done first at the surface and sort of develop some understanding before you go underground, but I think the spatial scale I think is a real useful aspect and scale up. I'm not so convinced that the time-scale of the 40 to hundred-year development is really going to allow confirmation of many models that – anticipating for the long-term safety that Irina is talking about.

ILLANGASEKARE: Yes. So, these are really good answers. So, this is just to, more for comment. So, it seems like the – when you look at upscaling – I don’t think we should look at upscaling in the context of just models. You’d have to understand scaling in the context of processes, too, because if you understand processes and scale, you brought insight process in larger scale, in that way, you can bring this idea of monitoring, correct monitoring system to decide how the upscale system behaves. So, I think – I think your answers are good in that context that it’s an obsession but at the same time, you should not do everything thinking that we can upscale these problems in – especially in the – in the time-scale.

ZOBACK: Good. I'm going to shift gears a little bit and just say as I listened to the various talks this morning, I heard so many common threads and such thoughtful approaches. This – the solution that we're seeking is a multi-generational solution. It doesn't happen in 12 years, 10 years. All of these programs have evolved already over a very long period of time and I think as Irina pointed out, there's been a real evolution of knowledge. And I think one of the most striking things I heard was also from Irina where she said you should never take a decision until you absolutely have to.

And what I see in all of these programs are a step-wise approach but also a very iterative one. There's information gained, knowledge gained, and that feeds back in always with a focus on what matters to the safety case. And to that point and what I'd like to have any comments on having worked in the real earth myself, there's always surprises, and I think we've heard Patrik mention the microbial experiment was just to satisfy some flaky Ph.D. student and now, it turns out to perhaps be one of the most important processes in terms of the engineered barrier system.

The whole issue of copper corrosion has thrown, let's say, a monkey wrench -- that's a colloquial expression – into a process that seemed to have been moving along pretty steadily in a straightforward way and then, Daniel, you mentioned about pyrite in the clay and the impact on chemistry. So, I guess I'd like to hear more about the kinds of knowledge going forward and getting to this point about how we project into these extremely long time periods, what other surprises are there you anticipate. Anybody want to venture a guess?

APTED: Start with Daniel.

ZOBACK: Daniel.

APTED: The tough ones go to you.

DELORT: Yes. Well, today, we have – we are – but it is – it is technological difficulties. We have to construct these very big gallery, big tunnels, for the – for the disposal of the – of the intermediate-level waste. So, we never built such kind of section in our URL. So, in the new program, we have to – we have to study this, and we may find some difficulties. Another thing is for the seals, in our concept, we want to remove the lining to have a direct contact between bentonite and the clay. And we – it is not usual, I mean, to this – to this construct, still aligning for doing this kind of job.

And the last point is what I mentioned for the – for the corrosion processes, we – the design of the – of the disposal cell is becoming more and more complex so we may face some feasibility – construction feasibility difficulties and so we – we are working hard on this and that – today, we have reached a certain level that the main difficulties we identified in front of us are mainly technological difficulties.

ZOBACK: Thank you. Patrik.

VIDSTRAND: I've – I think I mentioned before that Forsmark is highly stressed. It's not high in the sense of a really high stress around the world but from Swedish point of view, it's high. And the concepts – the sort of concepts we have is kind of optimized around the position holes. And if some locations in the repository will not be round, then we would have problems. And if we don't have a solution for that upfront, then that would be a stop in the process and that's one issue that could happen.

Another issue could that we do have an expectation of extremely few fractures, but we only have surface investigations so far and by physics we could miss some horizontal structure. So, what if we find a horizontal structure at exactly at the deposition level and how we would treat that. So, there's lots of technical I would say, but they all also relate to safety case issues.

ZOBACK: And could – you know, as you mentioned, the thermal effects on fracturing, if you have a problem, it could get worse as time goes on.

VIDSTRAND: It could. Definitely could. And the thermal effect is also something that we can't monitor because it happens when it's deposited, so.

ZOBACK: Right. Yes.

VIDSTRAND: Yes.

ZOBACK: Okay. Thank you. Irina.

GAUS: I can probably bring a few – two issues related to gas. It’s always when you change an idea where – as in Switzerland who went from this granite-based host rock to a clay-based host rock. And while we saw immediately the benefit of the clay in terms of sorption and transport, we didn’t – at the beginning in the early 2000s, we didn’t really thought that the fact that you close something in becomes then an issue on the other end, because we have a quite important gas generation and it becomes like a closed box with a pressure buildup.

So gradually, we acknowledged that and build up the knowledge and the engineering measures to take away that there might be any damage to the host rock and have a whole model change around them. This was like you change -- optimize the system for one aspect but for the other aspect you also have to look at it, and some of the basic process understanding on how gas moves through clay was not yet available at the time.

And then another example was when we tried to predict the chemical evolution of the repository we had in our – and this is long-term safety, but it’s early evolution. We had in our nobles and thoughts that we would have a period of a couple of hundred years of conditions where there would be oxygen available because we had placed the waste in the bentonite.

And when we’re actually doing this one-to-one experiment, we were too late with our machine to actually measure the oxygen because already when you placed the bentonite, the oxygen was being consumed, and this has an important follow-on effect for corrosion allowances. But somehow when you actually do it one-to-one and you start to monitor it, this is – the need to actually to do this one to one experiments actually see if what you think is going to happen is actually happening also in this early evolution.

APTED: I'll make two quick points. One, I think surprises will always be with us, so we have to – we can't plan on those surprises if I only them, you know, crystal ball. But every repository program has seen these come up and so on. So, you see, for example, the Canadian program, they've looked at the word adaptive in their – in an optimization. Irina talked about optimization. And I think oh, it's because it's multi-decades, there's going to be addressing, as surprises are revealed, some sort of then countermeasure or a modification of design.

Patrik was sort of referring to stress problems and so on. But I'm a big fan of engineering and I think the engineers are – it isn't always going to be science that gets us out of these surprises and so on type of thing. So, I'm confident that over this time-scale as we learn and do the science underground and the measurements, that the engineering countermeasures can be brought into play to adapt.

The other part I'd just quickly mention is – I think the idea of surprises again come back to a topic that I find very important and that is sort of the safety function approach, because we've been in situations we're dealing with stakeholders and they ask, "Well, what about this and what about that?"

I think that's one of the advantages of the safety function approach is you can say, well, haven't thought about exactly that what if, but the impacts are going to be exactly like this that we will have already considered and so on. So, I think it gives us much better than sort of the bottom up FEP stamp collecting approach, sort of the top down safety functions will give us some more confidence in dealing with surprises as they arise.

ZOBACK: Thank you. We're going to let Simon weigh in and then we're going to open the discussion up to the Board and staff and that's all there's time for.

NORRIS: So, I think depending on the geology you have, you may wish to put the waste in and backfill very quickly just for the mechanical reasons if nothing else. But in certain other scenarios, it may be that you want to keep the repository open for a period of time and this may be a requirement of the host community that it is open, and you do some confirmatory testing once it is open and prior to sealing as a pre-condition of you moving to a sealing process or a sealing time.

I think it’s just – it’s a big uncertainty. You can make predictions about what you think will happen over that operational period of maybe a hundred years. But what comes to pass may be quite -- may be totally different, maybe a lot different. And whatever happens you need to make sure that the new information is input into your safety case and that you redevelop your safety case to make sure that, if you’re looking at evolved host rock that’s been open in an oxygenating atmosphere, de-saturated for a hundred years, that is reflected in your safety case and you make sure that your safety case is founded on good information at a time when you’re making decisions. So, I think it’s just that if you start interacting with what stakeholders need with what scientists and technicians may prefer to do could end up opening up a bit of a – another uncertainty period.

ZOBACK: Great. Okay. I think we have about 10 minutes left if anyone on the Board would like to ask a question. Lee Petticord.

PETTICORD: Lee Petticord from the Board. I’ve got kind of two connected questions. I think they’re connected. Let’s try it and see. But the first part of this is one – this is building on Dr. Zoback’s observation of kind of the commonalities. And one of the things that came up almost universally across all your presentations with the value of these facilities of training. And I think that’s really key.

Now, another part I’d like to connect to this – well, so as part of that, is there an opportunity here maybe that has not quite been fully utilized is to develop a training concept that spans across your collective facilities. So, countries your own, but more importantly perhaps like our own that haven’t been able to take advantage of your facilities in training but maybe there would be an overall approach in that. And I was particularly struck by Patrik’s comment that this is one of the values of a generic facility as well, too.

But the other thing that I wanted to link to this is when we had an opportunity to visit Äspö and Bure in – sorry about that – that you link these very closely – we didn’t ask you this question, but surface facilities as well, too, where you’re demonstrating technologies that you’re eventually going to take underground.

And, again, that was extraordinarily impressive as you had really these large-scale technology endeavors that will eventually be implemented. So, I'm talking about training or asking about training is kind of cross-cutting opportunity. The same thing with this technology demonstration, you know, everybody’s going to be doing a little different but again are there some generic issues in which your service facilities, which are superb in your countries, could be utilized more to better advantages by the international community. Thank you.

ZOBACK: Anyone – Patrik? Someone would like to take that question?

VIDSTRAND: Yes, I could start. So, I think that we already do quite a lot of international exchange. We go abroad, and we have people coming to us, and especially Asian countries is basically placing employees SKB or Äspö for a year or half year to participate in our work so not doing their own research but actually participating in what we are doing. So indeed, I think that’s a helpful...So please repeat.

PETTICORD: Surface facilities technology development but let – let me throw another one. Is the organization like NEA kind of the right entity to start pulling such things together? But your response was very encouraging.

ZOBACK: Is there anyone else – I – can I ask the Board members and staff and consultants, if you want to ask a question, put up your cards so we know how many questions there are? Zero questions? Wow. Okay. Then talk on. Right. Now, we have...

APTED: I think Irina wanted to address that.

DELORT: Can I...

ZOBACK: Yes. No, let’s stay on this question for now, but...

DELORT: A few words about training. Well, I think in a decade there will be three underground disposal in function, so training could be more – may be more interesting. And also, we our mission will move. I mean today we are – we are implementing with R&D our program, it is our program, but one day we will be an operator of the repository, meaning that while we will continue R&D but that we need to question, do we still need our laboratory to perform this research?

So, meaning that -- I'm always a little bit cautious when I hear this kind of wait-and-see strategy on R&D. I mean if you’re really believing that Äspö will remain open after the reopening of the repository, our laboratory will remain open, ONKALO part of the repository, so it will be much more difficult to conduct experiments in the facility, so I would be cautious on this, but we will – we would propose additional training on operation of repositories for sure.

The other – the other thing about the technological center, this came up in 2007, we were having this laboratory where we are speaking of science with highly educated people with Ph.D. and post-PhD, post-doctorate, et cetera, but our people didn’t understand those people. So, it was clear that we got to develop something to explain them with what we are doing. And so, we are matching these two needs, the need to develop new technologies because there is nothing on the market for our purpose and to show it, to explain what is a repository, what is a waste package, what is a disposal package, what are the equipment we would like to use in our facility. And it was really an improvement with our – the discussion with our public throughout this facility, this technological center.

ZOBACK: Thank you. We have about two minutes. So, David, would you like to ask your question?

BISH: Sure.

ZOBACK: Say your name.

BISH: David Bish, Board consultant. I have more of a comment than a question, but I enjoyed everything this morning very much and quite heartened to hear a lot of different points of view. I – my – I wanted to make the point about, kind of taking off from what Mick said about the generic versus site-specific URLs. And I've read a lot over the years and even heard some today about, for example, a generic granite or a generic argillite or I believe Irina talked about a – I think you used the term typical clay. And – but I think we've seen excellent evidence that there is no such thing as a generic granite or a generic argillite.

So, this reinforces the idea that it's difficult to use a generic URL, for example, in granite and extend those results in a very convincing way to another granite site without knowing a tremendous amount about the other granite site. So, I think it lends support to the idea that –

Irina’s idea – let’s put off our URLs until we know where we’re going.

But in the end, I think what I’ve seen in – at our meetings and all of the things I’ve read is that the biggest contribution the generic URLs make is to give us a better understanding of the effects of emplacement of a – of a bore hole, emplacement of a backfill, and looking at, for example, in that case a FEBEX, at the longer-term effects so we get some experience, not necessarily directly applicable, but it allows us to learn to gain – sorry, Mick, but to gain fundamental information that we don’t have. I stop.

ZOBACK: Thanks. That’s a great comment. Bret, did you have a question? There are no other questions? Okay. We’re strictly right on time, but I feel like I ought to give those of you up here if there’s something pressing that you feel hasn’t come out, I – you don’t have to say anything, but if you have something you’ve been waiting to say, please do. Mick, I’m joking. Does anybody?

GAUS: I think what we experienced – one thing. What we experienced in Nagra is when you go to process of finding research priorities, it’s extremely important next to top-down safety case approach to involve the scientists at the level and have this combined bottom-up, top-down approach because at the top level, you never have the insight and the detail and also the expert scientists have to defend the arguments in the end when it comes to a discussion point between expert and expert. So, at that point when defining a research program, it is very important that experts but also generalists agree on what needs to be done in order to make argument.

ZOBACK: Excellent point. Anyone else like to...

BAHR: Mary Lou, I'm going to have to exert my leadership in keeping us on time I think because we do have a long day and we have a number of other talks.

ZOBACK: Well, you still have another chance at the second panel.

BAHR: Yes. So, thanks to all of the panelists and to Mary Lou and Tissa for organizing portion. The next speaker is going to be Bill Boyle. He’s going to give us a short of overview of DOE’s Collaborations and Underground Research Program and that will be our final talk before lunch. We’ll have about 15 minutes for questions after Bill’s talk and then we’ll have a one-hour lunch break, which is going to be kind of tight, but then we will hear after lunch a continuation from Jens Birkholzer of more specific discussion of how DOE’s programs are related to these international activities in URLs. So, Bill, take it away.

BOYLE: Let’s make sure it works. So, let me make sure it works. Okay. All right. Thank you for the introduction and thank you for this opportunity. I am here to talk about the U.S. Department of Energy Collaboration and Underground Research Program, the Overall Program and Approach. Looking at the agenda, which I think everybody has access to, the questions to be addressed included: what are the main objectives and missions of this group within the Office of Nuclear Energy? what are the main components of the program?

what are the priorities? and how do these priorities relate to the key uncertainties?

Now, this presentation was to be made by Tim Gunther, but he had a conflict and wasn’t able to come so I'm making the presentation but I'm using the slides he prepared. Now, as Chairman Bahr just noted, I will be followed after lunch by Jens Birkholzer of LBL with more details and I’ll submit all the rest of today is more details on what DOE is doing and almost all of tomorrow. So, this talk was set up to provide an overview of what it is the Department of Energy is doing. And so, this slide is a representation of a generic nuclear fuel cycle all the way from let’s-mine-the-uranium all the way to let’s-dispose-of-the-waste.

The group that I'm in in the Office of Nuclear Energy is more interested in these backend activities. A lot of countries around the world have worked on this and are working on it and Finland’s probably the farthest along but no country yet has an operating repository for the disposal of spent fuel or high level waste. Some countries have never implemented some aspects of the fuel cycle, other countries have implemented them all. Like for example, in the U.S. we currently do not recycle or reprocess. We have done limited amounts in the past. France in contrast has for a long time, Japan as well. U.K. continue to do so.

Okay. So most of the talk today – all the talk through the – today and tomorrow is related to that last part of the fuel cycle. Okay. So, the DOE's efforts are managed by the Office of Nuclear Energy and the Office of Spent Fuel and Waste Science and Technology, SFWST. This used to be the used fuel disposition campaign, UFD. Chairman Bahr called me Bill and the slide says William, the name can change, I'm the same person.

That is what we have here. And this – these activities, they are for storage transportation and disposal. And this slide is focused on the national labs that participate and they work on all three aspects of that problem; storage, transportation, and disposal. We also have private companies that do – for those who were at the last Board meeting in Albuquerque that was focused more on storage, there were representatives from private companies that we used to talk about the storage activities.

But when it comes to disposal all the way back to Yucca Mountain, the bulk of the activities were done by the national laboratories as represented here. Okay. The campaign mission and this has been ever since back when used fuel disposition was set up 2009 and ’10 is to identify alternatives and conduct scientific research and technology in the development to enable storage, transportation, and disposal. Storage, transportation, disposal. Illustrations of them both for waste generated by existing fuel cycles, what we have in our possession today and are generating today, but also potentially future nuclear fuel cycles that might produce different waste streams.

This is how we’re organized in terms of project management and bookkeeping for the campaign. This is what was discussed at the last Board meeting if you will, the storage side of the chart, but this is what we’re talking about for today and tomorrow in particular, that aspect right there.

Okay. What is the current focus of the disposal research and development? And these first three bullets actually go back to the creation of the used fuel disposition campaign. They were there at the beginning and they're still here today, provide a sound technical basis for multiple disposal options in the U.S., increase confidence in these concepts, and develop the tools to support implementation.

These last two bullets weren't there at the start. This fourth bullet – conduct R&D on the direct disposal of existing dual-purpose storage and transportation canisters is a result of a NWTRB meeting like this. It was the one that was held in Pentagon City whatever and it was as a result of questions from a Board member, Andy Kadac. It was a – the presentation we were making – we were looking at standardized canisters, if you will, and I'll focus on the pressurized water reactor fuel assemblies.

We were looking at canisters that could take four or 12 or whatever and his question was, "Well, nobody uses those. Why don't look at what people use today," which are, again, for pressurized water reactor assemblies or 32 or 37 assemblies per canister. So ever since, we’ve actually – we added that work effort as a result of that exchange at that Board meeting.

And leverage international collaboration, which is the subject of today and tomorrow’s meeting. That, I associate most with Dr. Pete Lyons when he was the Assistant Secretary for Nuclear Energy. He had a very active interest across all of Nuclear Energy’s activities being interactive with other countries. And so that’s when we really started to focus on our international collaborations.

Okay. I wasn’t even here for these meetings. It was – I was still working on shutting down Yucca Mountain. But people at the very beginning decided to look at – to use a systematic process to identify the research priorities that ended up getting documented in a report in 2012 and this indicates it is recently – just a couple months ago, there was yet another meeting on the same topic and I don’t want to imply that there were no discussions between 2010 and 2019.

Every year when we go through our planning process, we look at what have we been doing, what we have learned, what should we be doing. And so, we've continued to refine our topics and here's what they are for the natural system, the effects of a disturbed zone in shale, flow and transport pathways, and in granitic crystalline rocks, chemical processes for shale, thermal for shale, hydrologic for salt, that's for the natural system.

This slide is the same as the prior one except that it focuses on the engineered barrier system instead of the natural system. And here are the priority topics there, buffer and backfill materials including chemical, mechanical, thermal processes, and also, chemical processes related to the EBS components.

All right. So here is a summary of the cross-cutting priority R&D topics today, put forward in the form questions, divided into four different key topics, near-field disturbances perturbation, engineered barrier integrity, flow and transport, and how does the whole system behave. And these are the questions we're asking ourselves and trying to get answers to. And now this color-coding will come back in a later slide that I'll present and then Jens will present later as well.

It's just tied to these four key topics, the color-coding. So, we – all the way back even in 2010, had an idea of – these are the things we're interested in and then we ask ourselves when we decided to get involved with other countries, well, what are others already doing. What – is there anything we could participate in and then after identifying what others were doing, we then ask do any of them flange up to what we want to do and we went through that process and identified efforts that we could participate in that would be beneficial to us join others. And this next slide – oh, no. Did I miss a slide? No, here it is, okay. Let me back up.

So, all along is, we've wanted to – well, what activities would we be interested in? We're looking at things that will, you know, benefit ourselves and our partners. As others have discussed today, we're – by participating in this, we're developing the capabilities of our staff. I believe as others have mentioned. If you join with others, you can do so on a cost-effective manner or in a short period of time. If you don't have to excavate the tunnel, you've just saved yourself a lot of time.

And here's where it ends up in. And this is a slide that Jens will also show after lunch, he will go into more details. This is – by these key topic areas, here are the international URL experiments we have or are participating in, the U.S. Department of Energy.

So, the rest of today after lunch and most of tomorrow, we'll go into details for some of these experiments and analyses we have participated in. Yes. So, all the remaining presentations for the next day and a half for the most part will provide further discussion on DOE's collaboration and international programs and initiatives and how it helps us, our pursuit of avenues for international collaboration and focus on partnership that allow for active R&D collaboration and as – we're always trying to maintain a balanced portfolio.

It was Simon I think who mentioned that in the U.K. he believes that perhaps are a bit shy on the evaporative work, right? So, I think that countries that haven't yet chosen a specific geology or worse by nature were given no choice, right, you know, but if you have a choice, it’s a good idea to try to remain balanced if you haven't made up your mind yet. So those were my prepared slides.

BAHR: Okay.

BOYLE: And as a general ground rule, for the next day and a half, if you have detailed scientific questions like what’s the solubility under partial pressure of CO_2 or something, ask the presenters. I won’t get up and answer. If somehow or another a question comes up about DOE policy, I will probably get up and answer it. And that's a heads up to any of the presenters. You don't need to field any DOE policy questions if you don't want.

BAHR: OK. Well, thank you for a succinct presentation, Bill. One of the questions we ask and maybe you can go back and reflect a little bit, you said there was a new priority exercise just recently. And so, you know, we asked what are the priorities -- you've laid out sort of general priority R&D areas. But how are these relate -- what are the key remaining uncertainties that have been identified with respect to the host environments?

Have those involved or are the same things that were uncertain and that were driving the research program in 2010, are those the same today, have we made any progress?

BOYLE: My guess would be, they must have evolved some. That's a guess because as I said I wasn't there at the beginning. And although it was certainly that 2012 was prepared while I was there, I didn't attend the January, 2019 meeting. And I didn't have the foresight to ask Tim.

Now Peter Swift is here. Were you at the 2019 meeting?

SWIFT: Yes, I was.

BOYLE: Yes, yes. Has there been -- I will put it this way, has there been a substantive change in the priorities from

2010 to 2019, or in contrast to substantive, more on the margin?

SWIFT: Peter Swift, Sandia National Labs. The substantive changes, no. The largest uncertainties are associated with site-specific questions we can’t address in a generic world. And we will hopefully someday get to them.

In the generic sense we have confirmed largely that the topics we have picked on seven years ago or eight years ago were the right ones. We've made progress on a lot of them. For example, the behavior of bentonite buffers at elevated temperatures, we were realizing as Mick pointed out earlier that a 100-degree limit was sort of self-imposed by the community. We think we can do better than that. We think that at those pressures and depths that in fact bentonite will probably perform reasonably well at somewhat higher temperatures. We don't know how high we can go yet.

What else? The results of the recent review of our prioritization are being documented in reports and review now. Bret Leslie he was present at the meeting in late January, Bret? Yes.

We had a presentation on it at the High-Level Waste Conference just last week in Knoxville. And we can get that material to the Board as soon as it has completed its internal review.

Anything else, Bill, or?

BOYLE: No, other than to say thank you.

SWIFT: Yes.

BOYLE: I see Jens has his hand up.

BIRKHOLZER: I think one thing to point out is that in 2010 early on, let's say we were asking kind of three questions. One is what are the relevant topics for safety cases in each of the alternative host rock options that we were starting to look at. The second was where does the international community stand in that respect. And the third is what do we need to learn and whether we need to develop our tools.

And I think what happened in between is that tool development really evolved within the U.S. And we settled some of these works that we had conducted, but there are also some other questions now were sort of coming to the fore where, I think the entire international end and our community is interested, new topics that have to do perhaps with either high temperature exposures to bentonites, DBC-related questions, the issues related to gas transport, that wasn't there in 2010.

So, you know, it's sort of a shift in what we needed to pick up our capabilities and test them, and against data to working with the international communities and remain on remaining topics that need to be addressed.

BOYLE: Yes, that's a good thing. Thank you, Jens. And it's a good point he brings up. Back in 2010, I would say the U.S. had the most expertise with respect to repositories that were in the unsaturated zone. And all our tools and expertise were related to that.

Not all of that expertise or the tools were instantly transferable to the other rock-types. So, we were starting way back then, it wasn't as level a playing field but in the intervening years, particularly with respect to our development and tools have advanced for the other rock types, salt, granite, clay shale.

BAHR: If there are questions from other Board members, Mary Lou?

ZOBACK: Yes, this is probably more a comment, but we listened to descriptions of other countries and programs this morning and the thread that ran through all of them was safe, safety case. Bill, you didn't say safe once in your presentation; Jens you mentioned safety once. But somehow, I see these other countries begin with the idea of a safety case and making sure things are safe, yet we go through this, a long list of things and safety is never mentioned.

BOYLE: All day, I am glad I was here for Patrik's presentation and I don't want to put any words in his mouth. I will just tell you what I heard. I thought I heard him say that in many respects their license application submitted represented their safety case, or was their safety case, or words to that effect.

U.S. law, U.S. regulations never mention the word safety case, they certainly probably do mention safety. So myself personally I've always viewed it as using, looking backwards at the one example we have at Yucca Mountain. The safety case is represented by the license application. And I was heartened to hear Patrik say something similar to that.

Back to my example of myself William and Bill and the name may change, but I'm the same person. Whether you call it a safety case or call it whatever you want, a license application to be successful has got to convince people that it's safe.

ZOBACK: I thought I heard a broader application of safety case. I thought it guided research priorities every step of the way.

So, this is a comment. You are talking to the public, I think they want to hear safe. I don't think license application does it for them.

BOYLE: Yes, OK. Now one thing I will bring up, I agree, I was glad that I was here for Mick Apted's remarks that your priorities and the work you should do shouldn't be guided by your top-down assessment of is this whole system safe and what causes that safety needle to move one way or the other, that's what you should look at. And I would say that was the intent for many years on the Yucca Mountain project when it was up and running, and it's still the intent today that we try to do when we get back to our priorities is to the best of our knowledge what is moving the safety needle for the disposal concepts for those other rock types and spend money there.

BAHR: Are there other questions from Board members? Are there questions from staff? Bret Leslie?

LESLIE: Bret Leslie, Board staff. Having worked for the regulator and knowing what's required by the regulation, one of the things that we've tried to ask our international folks to get a better understanding is as they develop their URLs and their safety case is it driven solely by what's required in the license application? Or is it that as an organization you need to know that it works, not just the post closure safety assessment, which is all of those things up there, but as we heard earlier today the operations, the concepts, can you get those DPCs underground?

So, in terms of prioritizing DOE’s program, so far it looks like you are prioritizing just post closure safety assessment, can you comment on the larger picture of what other people look at what the safety case is?

BOYLE: Yes, and again, I will go back to Yucca Mountain and its license application. There was a huge section on operations that in our terminology was pre-closure. We don't do that much in any right now. We really are more focused on disposal, the million-year part of it.

We do as I have shown on the slides, we do look at storage which is operational but it's not operational at a repository. Some of the operations would be similar between an interim storage facility and a repository under operations would be different. But I will concede that in the years that the campaign has been up and running operations at a repository have not been a focus of our research. Storage and transportation have been, but not necessarily.

I would say the closest we got to that was when we were working on bore-hole disposal. And we had to look at what would it take to actually handle things at a drill rig, you know, radioactive spent fuel on that. That was the closest we probably got to it.

BAHR: Are there questions from the staff consultants, Board members? OK. Well, we are a little bit ahead of time, but I think in the interest of allowing people the maximum time for lunch we should probably break now, and we will reconvene at 1:30, so we have just a little bit more than an hour.

Thanks again for all the morning speakers.

LUNCH BREAK

BAHR: OK. Well, welcome back for the afternoon session of our first day of the workshop. And we heard a little bit before lunch from Bill Boyle about the overall DOE R&D program related to disposal. And now we are going to hear more specifics from Jens Birkholzer from Lawrence Berkeley National Laboratory who has been, I think, the leader in the international collaboration program for some years now.

So, thanks, Jen.

BIRKHOLZER: All right, well, good afternoon. I wouldn't say leader, I would say coordinator. We'll get to that later.

So, what I want to do is give some more specifics of the international program that we established within the disposal research for the last seven or eight years or so and particularly with the activities related to underground research labs or facilities and I will talk about it.

So, what I want to do is first set the stage a little bit to illustrate why we should, selected to, really reengage with the international communities, when Yucca Mountain got suspended or went away as an option. And then go a little deeper in where we set our priorities and also some of the principles, and then we forward look to the next two days of more details, specific activities and research work that will be presented. And then I will wrap it up with some of the experience that we had over the past years.

So just to reiterate where we are currently in the overall disposal research program in the U.S. With Yucca Mountain off the table we are interested in multiple alternative disposal options, different host rock, different designs. We are interested in developing the tools to be what I would call repository ready when at some time we are allowed to do site-specific research in the U.S. And currently we are not allowed to do that.

We are specifically interested in the DPC canisters which for what you'll see today is partially related to being able to raise the temperature limits on certain repositories and of course in all of that I want to explain how we'd leverage international collaboration.

Going back in time I just want to illustrate how different the relevant processes and the characteristics of Yucca Mountain are when you compare it to some alternative options, disposal options that are considered elsewhere in the world. So, this is Yucca Mountain in a sketch. It is a fairly fractured permeable volcanic tuff environment that's unsaturated, so it's above the water table and water really trickles down in the unsaturated zone, always oxidizing because the air is present and it's an open tunnel in placement which means there is no backfill material. Heat is basically radiating outward.

And then of course if we look at most other disposal options we strive for low permeability host rock which is mostly saturated, under the water table, because that's fairly typical as you see in a near field environment. You start out at least with reducing condition until you have some sort of backfill that provides mechanical support and also has some retention capacity, right?

So, we really have to, 10 years ago, reorient our research program to be looking at the specific processes relevant for alternative disposal options and designs.

So, these are the three sort of host rocks that we are primarily looking at these days. The very hard competent crystalline environments, and then sort of less strength clays or argillites or sediments, and then also evaporites here. And as I mentioned it before we also of course have to start learning a lot about bentonite backfill as one material that is brought in, perhaps pelletized or is a powder. And then hydrates and swells and develops strength and also certain sorption retention capacities. And then in salt we also talk about salt backfill.

And then of course if you look at and we've seen four presentations in the morning, if you look at the international community these host rocks and the expected backfill, it has been researched for quite a while.

This is the roster of countries looking at crystalline environment and then we had Patrik talk about the Swedish program. In France, and in Switzerland and some other rocks we are looking at sedimentary environments. And also salt, it's currently in Germany and the United States. So a lot of work done in the international communities, which essentially 10 years ago really for us it was a no-brainer to decide at that point as we are going towards better understanding, developing a knowledge base, developing tools that we really wanted to be part of that international community in terms of gaining knowledge fast and cost effectively, at the same time also giving back.

We felt that the National Lab scientists and their capabilities could, going forward, be part of international science that tackles the remaining issues related to, say, salt disposal, clay, host rocks or granitic environments. So that's when we saw a lot of benefit tapping into the information and knowledge that was available, gaining access to data sets and experiments and concepts, and in that basically improving our science base and becoming sort of repository ready.

We wanted to develop specific tools to analyze safety relevant processes, both in terms of modeling and monitoring, and of course share costs.

So, we did lay out some, we felt we should lay out some ground rules. And one was that we wanted this collaborative work to be active in the sense that we wanted to have our scientists to directly work on projects with the international scientists. We didn't want this to be sort of a paper exercise, go to a clay club meeting once a year and then come back a year later, we really wanted this to be process-based, a project-based, I'm sorry.

And we felt that for various reasons that we already pointed out that particularly research done in our research labs would be beneficial to us in terms of the data sets, provided the research at scale that can be conducted in the geologic units that we are interested in. But also, because at least to my experience, scientists and programs, they rally around large and complex and well-designed experiments and we felt that if we tap into work there, that we could most easily and in the best way connect with the international community.

And then of course we had to decide where we put our priorities, and part of that of course has to do with, you know, what is the technical merit of a certain experiment or a certain program, how relevant is what we are looking at for the safety case, or safety relevant features. And if you think about the safety case, or reference case, cost benefit, and we wanted to balance them in some ways. We didn't want to put all our eggs into a, say, crystalline rock environment basket and not look at clays or other host rock options.

So, what happened then in this early planning process is that we did some sort of, in the campaign we did some gap analysis of overall what we should focus on, defining R&D priorities. In that of course we looked at what the state of the art internationally was.

At the same time as we did that we also, we tried to find pathways for engaging with some of the international programs and we made some decisions, we established formal and partially informal cooperations and then started activities that we'll talk about in a little bit.

Before going there, I did want to reiterate some of the high-level priorities that we set out as a campaign. It doesn't mean that all of them were tackled by an international work. And I want to start that out by looking on this timeline of repository phases and relevant processes. And the example here is from a bentonite back-wood repository and a clay. This a paper from Paul Bossart from a Mont Terri project.

Irina had a similar slide which kind of shows the early perturbation and here it's sort of exemplified by the temperature profile which goes up early. It could be somewhere around 100 degrees. Or if we were able to do the respective research we might be able to raise it. And then of course that temperature perturbation decays and then will get to a point that is initially perturbed from bringing a repository in and having repository impacts to a phase where have back to equilibrium.

And if you think about the research that's done and in this early phase where we have stresses and gradients and changes in chemical and mechanical, and hydrological, and what did I forget? Thermal behaviors.

In this space we are really trying to understand how these processes could affect properties, materials that would be, you know, from permeabilities, fracturing that would, at later stages when canisters fail, affect the release and migration of radionuclides, I tend of this early perturbation to be helping us to have a later better assessment of how long-term transport could work.

And now if we look at some of the research topics and the things that you need to understand in terms of features, events and processes in that space you see that a lot of them are very different from what we have to understand in the old Yucca Mountain days.

Let's say a damage zone that forms from mechanical changes are opening a tunnel that is not so relevant at Yucca because it is fractured and permeable to begin with. It is very relevant for clay-based repository, for changes from reducing to oxidizing conditions back to reducing, Yucca is always oxidizing. And then the behavior of bentonite, how it hydrates up or homogenizes, how it provides back pressure, the sealing or healing of the damage zone, not relevant at Yucca.

And then also it relates to the later transport processes where unsaturated flow and migration of radionuclides is very, very different from what happens with diffusive transport in clays or maybe saturated fractured transport in crystalline repository.

So, Bill showed this before and what I've tried to do here is bin some of our high-level research questions that we wanted to tackle. In these key topics the two first of those would be related to early perturbations, so I wanted to understand how the near-field rocks change. We want to understand the engineered barrier integrity. And in that space, you would be interested in thermo-mechanical and perturbations and how they affect long-term properties.

The same with filling and sealing, can all of that be predicted? And these predictions have to include coupled thermal, hydrology, mechanical, and in some cases chemical and biological behavior.

For EBS the question is about stability of these materials. There is a specific question and I think the SKB program has been looking at it for a while. Can bentonites be eroded by flowing fractures?

Other interactions between engineered and natural materials that could change parameters and properties.

And then the question that Irina was talking about, the corrosion by-products which could be gas build-up. If that cannot easily release because we have very low permeability bentonite and host rocks, and can that potentially induce damage, right?

So, flow and radionuclide transports going on, are there effects of high temperature on the diffusion and characteristics of clay-based materials, so that's specific to the question. Can we raise the allowable temperature at perhaps at 200 degrees? Colloid transport, the question of predictability.

And then the final set of key area that has to do with maybe the question of building a repository, being able to construct, being able to demonstrate it in full scale, having monitoring methods that's suitable for performance confirmation. So that's sort of the entire campaign, if you wish. Not all of that, again, is suitable for international work necessarily.

OK, so when we have been doing this sort of survey of where we wanted to put our research focus and also what type of programs would be good to interact with, we build this portfolio and it's partially a portfolio that is based on joining multi-national initiatives, partially it's bilaterals. And we decided on these in terms of the multi-national initiatives that we were joining, sort of based on a partnership fee.

The first three up here are what you might call multi-purpose. So, you become a member and there's a lot of experiments or tasks that one can select. And you will certainly not select all of them because there's a lot going on and the three of them down here, very sort of focused, and single purposed if you wish.

So, Simon was talking all about DECOVALEX which is in some sense a modeling comparison project, but it always will bring in and look into experimental work, most of it experiments in underground research labs.

Partners in that project, some partners in that project will propose tasks and then bring them into a certain DECOVALEX project space, and then other partners will essentially form modeling teams and will analyze the data, will compare, will try to sort of learn lessons and improve their respective set of prediction tools. And depending on what is brought in you have multiple host rocks on multiple underground research labs, that you cover it with their project.

We joined Mont Terri which is a, as we heard earlier an underground research lab run by Swisstopo in an argillite rock in Switzerland. And there is some multitude of experiments that a partner can either just access data from or participate in a monitoring, modeling function or you can also run your own experiments. It's almost like a community lab in which you can propose research which was important for us because we don't have an underground research lab in an argillite in this country.

And then we also joined, Patrik will appreciate that the SKB Task Forces which in some ways are also analyzing modeling tasks often related to experiments, not always, and often related to the Äspö lab. So, the prototype for example was a task in these task forces.

And then going down the list, all of these sort of single purpose projects are at Grimsel Test Site. We decided on joining the Colloid Formation Migration Project. The question here is if clay-based colloids can enhance transport in fractured media.

FEBEX, FEBX stands for full-scale engineered barrier experiment, this was very important to us because we used it to understand long-term thermal, hydrologic, mechanical and chemical alterations in a bentonite that had been heated for 18 years, and then was dismantled it basically gave us a beautiful three-dimensional data set of the postmortem. And you will see later some talks showing what we did with those data.

And then another one HotBENT is in fact, work that we'll be starting soon. It's an experiment similar to this full-scale heater test but we are going to ramp it up to 200 degrees. So that's tapping our interest in higher temperature repositories.

I got to move on. I just want to show that the world is really connected in these initiatives. And part of us joining was not just joining into a particular experiment but it was joining into the collective knowledge of multiple countries, some of them that are fairly far ahead in terms of their repository programs close to license applications. Some of them they are kind of starting early, and you'll see all of these reflected here in the various countries and organizations.

We did have some bilaterals. I don't want to dwell on that too much, but they opened other opportunities in terms of experimental in the underground research lab work, we are exploring the landscape as we go. Someone mentioned China with URL maybe in 2025 or so.

So overall, we ended up essentially having access to these three clay or sediment-based underground research labs and these four crystalline-based, most of them we've heard about before, Mont Terri, Bure in France, or Horonobe in Japan, it's a mud-rock. There is some interactions there. Mizunami is in Japan. It's a crystalline environment.

We've heard of what Äspö and Grimsel, and KURT is the Korean Underground Research Tunnel. The site of that is in Korea. It's also a crystalline environment.

Now what did we do there? And this is of course a very long table and I don't want you to read any of that. What I wanted to show is that we have done quite a bit of work in each of these areas, near field, engineered barrier integrity, flow and radionuclide transport, tackling some of the research questions that we laid out before.

And I will go into some of these sorts of bolded experiments in a little bit because they are the ones that you will see example presentations about today and tomorrow. And keep in mind in some cases we just looked at a portion of a data set and some limited engagement. And in other cases, we are full-blown partners in doing years and years of work analyzing data that may come in from a full-scale heater test. So, there is a variability in how deep we engage at times.

This is sort of my attempt to show where we have, how we have set up our individual activities in terms of balance or in terms of focus, if you wish. So, what you see here is three pies that show host rocks, so this is crystalline and this argillite down here. And this is salt. The size doesn't really mean anything it doesn't mean a level of effort.

And then you see in the center the EBS and then there would be near field surrounding it and the far field would be out here. And then we placed each sort of activity as an arrow, kind of showing scale, if you wish, into that pie chart, and it's labeled by color. So, it's a lot to digest and I don't want you to digest it all, but I think there's a few observations.

One is that we are fairly balanced. We did quite a bit of work in crystalline and argillite environments internationally, a little less on salt. That has two reasons. We have our own WIPP facility to conduct research, and there is simply not as many international countries that are currently looking at salt, right?

Another observation may be interesting is that if you look at far field behavior and flow and radionuclide transport there is more work in crystalline environments in part because I still think that prediction, understanding of migration and fracture rock it's complicated, so we wanted to spend some time here.

If you think about argillites we see more work in terms of near field perturbation just because there we are starting out with low permeability diffusive environment. If we have excavation damage, if we have something that changes that we really want to be able to understand how healing and sealing could convert these rocks back into diffusive environments.

Now what you see here enlarged now are specific activities that will be brought out in the talks that follow. I will give a little preview here. Starting with near field perturbations, so that's the first topic here.

There is a talk just after myself by Jonny who will essentially explain our work on simulating thermal-hydro-mechanical processes related to some heater test at Mont Terri and also some heater tests at Bure.

These first ones here mostly to establish that the processes can be predicted, that we understand the fundamentals. And then at Bure there is some interest in understanding up-scaling because there is a series of different sized experiments, different scale experiments that can be used for that purpose.

And then Kris will tomorrow talk about some similar work but in a salt environment with a planned heater test that we are conducting, starting this year, at WIPP facility.

This is about engineered barrier system, and particularly about coupled processes and potential alterations of bentonites as a function of stresses from temperature. We are concerned about stability, retention capability and also interactions, and high temperature that Liange Zheng will later talk about the two large-scale experiments. I already explained the FEBEX DP, 18-year old heater test. And then he will also talk about our plans for HotBENT.

And then there is also some lab work in conjunction with these experiments and some nice micro-x-ray work that will help us understand how on a small scale, potential retention capability changes.

There is a topic of gas transport which we have picked up as a priority. There is currently international work as part of DECOVALEX happening. It is lab based so far, lab experiments that are well designed. But we may go in a few years into a field experiment that Patrik mentioned really briefly. It's a large-scale gas injection test and it provides beautiful data, which may be available in DECOVALEX.

We will move into flow and transport and here is a talk tomorrow about colloid formation migration, both in terms of erosion of bentonites and also the potential for enhanced transport and there is beautiful data generated at Grimsel Test Site. And then finally there is Hari from LANL talking about method development for discrete fracture modeling of flow and transport and testing against two experiments.

One is flow and transport. And that's the bentonite rock interaction experiment, and then also a diffusion experiment. And you will know about that later, both of these are at Äspö.

If you go back to that timeline and as the repository is evolving, we could place these six or seven presentations onto that timeline. You will see there are some that really tackle this early system perturbation behavior. There are some that may lay somewhere in between, the bentonite rock interaction. If you think about the erosion component that would probably be a longer-term effect. If you think about gas migration or gas pressure buildup from corrosion that would be a longer-term effect.

And then at the very end with we are starting, you know, looking at these experiments with long-term flow and transport, so just to put that into sort of a timeline perspective here.

All right, I did want to talk a little bit about how we organize ourselves. Now this is just to show a timeline of planning and in some sense it's priority planning for the entire campaign which we did in 2010 looking at features, events and processes and their relevance to safety mechanisms, and where did we really need to engage. And then we had a follow-up workshop where we discussed how international calibration could work.

And then we have since then, essentially, we always revisit that portfolio. So, we are looking at new opportunities, new experiments and new trends.

Gas pressure buildup, I don't think was a big topic 10, 15 years ago. We may have changing priorities, the idea about dual-purpose canisters and higher temperature environments really came about maybe five years ago.

And as mentioned earlier we just had a workshop where we kind of asked ourselves overall in that campaign, we did something in 2010, what did we learn, what are our changing priorities and that will be documented pretty soon for folks to look up. And that will have some implication for what we choose to do in an international program.

Just how we organize, Bill showed that figure before. So, these are work packages, and we have specific work packages for each sort of main host rock unit. There is also one for engineered barrier. In these we have both generic and international research. So supposedly to have it integrated.

And what's here in the center that's really just a coordination. It's sort of a conduit, me essentially, connecting our researchers with international opportunities and basically a two-way flow of information, and obviously when we are planning activities we are doing that together in a leadership team.

I think there was some question earlier on whether this campaign is doing, what we are doing in terms of generic safety assessments. We have reference test cases that will be talked tomorrow by Emily Stein. And I think she will lay out at this international component and the improved process models nicely feed into what she is doing and what her team is doing in this space. And of course, the results of safety assessments for different reference cases will also inform to some degree what type of research question we need to tackle, so that's a two-way process too.

I did want to say that when we tackle a research question, let's say in this case what is the effect of going to 200 degrees in a bentonite clay repository, we tried to develop plans to tackle that among the different sort of work packages and sort of engineered barrier with the international folks but also with performance assessments.

So, you see here, for example, we started with fairly simple lab experiments to, let's say you heat bentonite up to 200 degrees. You just see what kind of chemistry changes, mineralogical alterations, you get a different conditions, but then we really need to get to the point that the entire system is analyzed, so you have a heater, you have strong gradients, you have bentonite saturating at the same time as heat is being put into a system, and then there is also host rock that provides the hydration fluid. So that can only be tested with more complex experiments in the lab or in situ, and that's where potentially an experiment at, Grimsel test site comes in.

And of course, then if we have, you know, results in terms of a predicted potential change of bentonite retention capability then that feeds into performances that's been started. And you see how impactful that is.

So out of this exercise came our desire to really have a large-scale experiment and we interacted with the international community, with Nagra and others, and now there's field experiment on HotBENT it's actually going to happen very soon.

OK, time to wrap up. One thing I did want to say is that the way we have been working in terms of identifying what we wanted to do in the international space has changed over time. When we started in 2012 or so, we basically had to see what are the opportunities, what are the countries doing, what experiments might we jump onto?

We hadn't been involved in planning what was happening. So since then it has changed. I think we've been much more active in sort of forward-looking, you know, what is next, what needs to be done, what would we as a community have to tackle. And an example is HotBENT, we'll hear about that a little later.

It's also that DOE scientists, me as a chair in the DECOVALEX project which is nice for us because we can -- so we can certainly make sure there are interesting tasks relevant to DOE. We will actually as DOE proposes two new tasks into the next phase of DECOVALEX. One is related to performance assessment and bench-marking of that. And one is the mostly likely will be the planned salt heater test that we, which we'll hear about tomorrow.

And there are constraints of course. Not everything is easy. Sometimes what we are interested in doesn't always align timing-wise, or effort-wise with where international efforts are at that time, so that needs to be managed. Sometimes we just need to pick what is out there.

We are just like Simon was explaining where you have to be very broad. So, we have to be selective, funding is relatively modest. And then there is one concern as we might be interested in actually conducting are being part of long-term activities like field experiments, if our funding levels go up and down every year it's a little hard to plan for that for multi-year commitments essentially.

Overall, I think it's been, I think it's been a success story. We have made international work the central element of the disposal program. And I think we have in a really short time built up a knowledge base and we have done that pretty cost effectively, and that includes new tools that were being developed, having a science base now that is state-of-the-art I think. And now we are essentially more and more, as I mentioned earlier working with our international colleagues to really tackle specific questions that are still worth tackling.

And again, I think we are fairly balanced in terms that we have managed to relatively balance the portfolio. We didn't pick any early winners.

And then there is some, in addition to sort of just the technical benefits there are some indirect benefits. I think it is important that we are now back in terms of international efforts, during the Yucca Mountain times, it wasn't always beneficial because the relevant processes that cut the risk of the host rock was so different, there wasn't a lot of overlap, now it is.

It's important to share knowledge and experience. We can stay abreast with new science advances that if gas pressure buildup or now biology perhaps it's a real issue. We learn about it, we can pick it up. And I think it's also important to work towards a common set of best practices and lessons learned. And if there is a failure in some country, in some program internationally that failure will also be our failure and vice versa because if you have an accident and something goes wrong it's going to affect the entire world.

Finally, and someone mentioned earlier that there isn't, I think it was Irina, there aren't so many experts around in the world working on waste disposal. That's certainly true for the United States. Over the last years we really had trouble I think attracting and building a new generation of what's called waste disposal scientists, that folks that understand the underlying mechanisms and modeling and monitoring whatnot.

And I think at least in my lab I've seen that being able to work on super exciting data sets, experiments, going to Mont Terri, getting beautiful, you know, examples from FEBEX DP has really helped our folks to not work on oil and gas related issues but rather work in the nuclear waste program and I think that is important.

Just finalizing there is a big report that we write every year. If anyone is interested I think it's downloadable, should be at least. I can certainly share it. And then finally I just wanted to say there are some posters today where we have four that are sort of deeper dives of results. So, you will see that Liange will have some more info on his presentation. I don't want to go through it. At least I will leave it up.

There are also two that explain additional work, field experiments and the national efforts that we are not presenting today and tomorrow. One of which is actually related to something Irina brought up in terms of thermal, potentially thermal damage and shearing, integrating flow paths.

And then there is one that has nothing to with underground research labs but it is an important international coloration, that is the Thermodynamics Database Project which is an effort run by NEA, and DOE has quite some work in that project.

And I think that's all I have. Yes. OK.

BAHR: Thank, Jens. That was a nice overview showing us where these various projects fit into some sort of parts of the repository system, and the different types of host rocks.

One other way of thinking about categorizing these research projects is which are addressing questions where there's really an opportunity to learn something new and fundamental and fill real knowledge gaps. And which are, might be considered more sort of in confirmatory performance. You know, you do a long-term test, you are pretty sure that you have some good models and you do predictions and your data are confirming the model.

Where on the spectrum do these activities, and I am thinking back to Mick's early statements that we are sort of done with the fundamental science and a lot of it is technological and operational at this point.

BIRKHOLZER: Yes. That could be a long answer. I think part of it depends on how you define fundamental versus applied.

BAHR: Well, I am thinking more, you know, where are the holes or things that we really don't think we understand, and which experiments are being done to improve parameterization of models where we think we have a good model of the process? We just don't know the appropriate parameters to put into it.

BIRKHOLZER: So, I would say that I think there are maybe three examples where I personally and that others might have different ideas, feel that we are scratching still at the basic phenomenon. And one of which is a gas transport in these clay-based materials, bentonites or host rocks.

These lab experiments that Jonny will tomorrow talk a little more about, have shown that the pathways are the way gases migrate is erratic, and it's not fully understand -- if that's -- because it's a complicated bubble transport of its dilating pathways or some folks are actually thinking it might be damage that is occurring but others don't think so. So, I think we're really starting with the fundamentals in that space.

At the same time there is no, you know, some field experiments that could demonstrate that at the end of the day fully understanding the fundamentals isn't as important as perhaps others are understanding what the bulk behavior of the system is. But anyways, in fundamental space that's still a big question and folks that are work in oil and gas know it is still something that we don't fully understand.

I think the sort of higher temperature behavior is something that clearly, we would need to tackle as a new research theme, what chemical changes they go to, 175 or 200 degrees, could you have transformations from, you know, a swelling clay to a non-swelling clay which would be detrimental. How is that dependent on water chemistry? And also, what of the other stresses if you have this essentially doubling in temperature change?

And another one is thermal damage. I think some questions about pressures could perhaps result in discontinuities, slipping, shearing off, does that create permeability? To what degree does it create permeability and how long does it last?

I think other things, maybe our thermal-hydrological mechanic modeling of bentonite behavior and how it hydrates as a function of time, we know a lot. And I think it was a lot of tool development that we did initially which we are now testing against long-term data sets.

Someone mentioned that processes are slow. The FEBEX DP, the dismantling project, those data became available a year or two ago, but they have been produced over an 18-year time period. But now we have the data set where we can nicely test our data against. So that I think is more advanced, but it allows an opportunity to test against beautiful data sets and make sure that our confidence is there.

BAHR: Thank you. Are there other questions from, Tissa?

ILLANGASEKARE: Yes, I would sort of get your thoughts on the integrated modeling. So, my understanding is that your integrating models which are processes, understood that you try to put them together. My question is that when you integrate the model it's going to be site specific because you are not going to do an integrated generic site. So how do you benefit from this international collaboration in the context of that particular strategy of integrated modeling?

And also, you had a bullet that says that validation of integrated models, can you elaborate on that a little bit?

BIRKHOLZER: Well I think anything we do, any tools that we develop, any scientific understanding, lessons learned that we have now from being part of experiments conducted somewhere would have to be taken back to any site that we are doing our research in but at least we have a basic fundamental understanding of what's relevant and how it pans out, and how you might model it and what kind of constitutive relationships you might want to put into a thermal-hydrologic and mechanical bentonite model, right. So, we have the tools, we have the basic understanding, but we will have to bring it back to the individual besides that we ultimately, hopefully will, you know, tackle in the United States. What was the second part?

ILLANGASEKARE: Validation?

BIRKHOLZER: Well, I mean, again you may validate or test your model for specific conditions, but then you will have to take it back and test it for other site-specific conditions. And yet there may be surprises. But at least we would be at a point where we almost immediately could take what the knowledge, and the models and the simulation experiments and could apply it to, and that's the idea we could apply it almost immediately to any crystalline or salt, or any, you know, clay sedimentary site that we could potentially look at in the United States.

We have a lot of real estate. We have pretty much any of these host rock options available.

BAHR: Are there questions from the Board? Mary Lou Zoback?

ZOBACK: Mary Lou Zoback, Board. Thank you, Jens. A really nice overview.

My question is really reflecting one of the questions we gave you and it builds a bit on what Tissa asked and Jean.

And one of the questions we were curious about, you've been collaborating now for a number of years. I was just trying to find how many years in these experiments, when did they begin?

BIRKHOLZER: Well, I mean the list that I've showed some of the early activities might have started around 2013, 2014. That list does not mean that we were doing each activity for, you know….

ZOBACK: No, understood, understood. The question that we had asked is how have the results that you've obtained in any of these experiments to date informed and challenged the assumptions of any of your models. Have you learned new things that – you build a model with a large set of assumptions and initial conditions and have the data changed any of those assumptions or is it more to confirm your assumptions?

BIRKHOLZER: Well, I think it goes back to what I said earlier. I don't think – there are some topics where I don't think we even had assumptions, right? I mean, gas migration is one of the topics and...

ZOBACK: So, more multiple working hypothesis.

BIRKHOLZER: Yes. Yes. And in fact, DECOVALEX, I mean I expect you'll hear about it tomorrow. We have about 10 modeling or research tools participating and each of them have almost their own conceptual understanding which they try to fit to the data and it is really interesting because we see that the train is going somewhere, but I don't think we have fully established that yet.

I think there are – there were clearly some surprises in details when it came to some of these dismantling projects. There's one that was done at isothermal, the EB experiment and folks in that experiment did try to saturate so that could speed up hydration. It turned out that that may have resulted in sort of heterogeneities that would otherwise not have happened. In the FEBX, we actually saw that was kind of like expected behavior which is a good thing.

Let's see what else. I think there is some interesting work in the fracture and faults lab experiments at Mont Terri where we have currently not a very good idea what type of permeability, shear, dilation relationships we need to pop into but we got some really nice data right now.

Maybe my answer would be, again, going back to the early days, I think we started building capacity. And now, we're at the space where we're really working with the community to tackle whatever is left to understand. Surprises will come when we go back to the United States.

ZOBACK: Right. Thank you.

BIRKHOLZER: I'm not sure that was a very good answer.

ZOBACK: No. No. That was good.

BAHR: I think I saw a question from Sue Bradley.

BRANTLEY: Sue Brantley, Board. I'm just curious if there's opportunities with the international URLs that are focused on microbiological experiments and I'm wondering whether DOE is interested in those.

BIRKHOLZER: So, there are certainly. I'm not so sure what's happening in Sweden. I should probably ask Patrik. But I do know at Mont Terri, there's a few experiments and in fact, there is almost like a clean room if you wish, which was established right there. So, some of the water or samples could be directly brought without any contamination into that clean space that is in the underground tunnels.

And that's about understanding what microbial communities are there and how would they be affected or not by some of the early perturbations. There's also some research done I believe currently trying to understand how these microbes could eat up some of the corrosion gases that are being produced at later stages and could that actually be a safety mechanism. Of course, there's also the question about canister corrosion, things like that.

So, there is work. We've been looking – I actually asked one my colleagues to look into that and they will get me a little work package to see what should we potentially engage in, but not much has happened yet. Something that we would have to discuss as a campaign, I mean, you might argue that

– but maybe that's a bad argument, but we might argue that some of the microbial communities that are so site specific, but I don't know what we learned there, is somewhat transferable.

BRANTLEY: So, I think you just had a 2019 prioritization workshop. Is that right? That's already happened?

BIRKHOLZER: Yes.

BRANTLEY: Was that discussed? Was the microbiology as a possible research target discussed because apparently, it's a gap?

BIRKHOLZER: I can't answer that right now. There were various parallel sessions. I would have to look it up for you, but I can do that, sure. I'm sorry.

BRANTLEY: I'm not really sure how to ask this question, but does DOE have microbiologists that would be available to work on this topic?

BIRKHOLZER: Yes, including in my lab.

BRANTLEY: And would they have been invited to that workshop? Would have they been invited to the prioritization workshop?

BIRKHOLZER: Yes. Yes. I mean, maybe not the ones directly working in the weeds but some that do know what the capabilities and the issues are.

BRANTLEY: OK.

BAHR: Other questions from the Board, from staff or consultants?

Bret Leslie?

LESLIE: Bret Leslie, staff. I've got maybe four questions. Well, you invited me...

BAHR: We have six minutes.

LESLIE: Yes. I know. But, Simon talked about knowing your inventory and how diverse the inventory they have. Most of your generic repository work has really been focused on commercial spent fuel. How is DOE is integrating the knowledge experts of the DOE spent fuel to ensure that one of those processes that isn't important for commercial spent fuel but would be for DOE spent fuel that you're focused on?

BIRKHOLZER: So, we do have a pretty good idea about our inventory. As a geoscientist in the space that I'm working in, I think a lot of the broad research we're doing right now is fairly independent. We obviously look at inventory in terms of when we do long term radionuclide transport predictions. We look at the potential temperature curves that we need to put into predictive models.

I'm not sure that we have a very prominent process right now to look at each of our waste categories in all gory detail. Emily might talk tomorrow a little bit about how they treat their waste inventory in terms of the generic disposal safety analysis modeling that is being conducted. I'm not sure if you do, but it's possible. If someone else has something to add...

LESLIE: I would like to ask my subsequent questions.

BIRKHOLZER: OK.

LESLIE: And we'll follow up with Emily.

BIRKHOLZER: Good.

LESLIE: Bret Leslie, Board staff. So, Bill talked about how DOE is responsible for storage disposal – or storage transportation and disposal. And we heard recently at one of the Board meetings how DOE has done a gap analysis in 2012 which was pretty much a top-down look at what the holes are and then updated again in 2017.

I looked at your 2012 prioritization that was based upon FEPS as a bottom-up approach. I attended the 2019 reprioritization. It was still focused on kind of "Are these FEPS still important" and I want to know – and the reason why I asked the DOE spent fuel is if you don't look at the big picture, you don't know what your gaps are. So, I guess is there a comparable process on the disposal side to do kind of from a big picture, "Here's our entire system and what are the gaps we really need to focus on" rather than just focusing on necessarily the post-closure.

BIRKHOLZER: Bill, do you want to talk about that?

BOYLE: William Boyle, Department of Energy. Disposal as far as I'm concerned largely is you can measure it by time or whatever else. It's the post-closure. And in terms of the challenges, pre- and post-closure, has anybody done disposal on spent fuel anywhere in the world?

No, not for a year, not for 1,000, not for a million – the people handle spent fuel of all types worldwide and have for decades. Yes. The challenge is going back to Yucca Mountain pre-closure. It was – sure, there were some mainly related to the sheer amount that was going to have to be handled in the timeframe allotted. But in terms of moving spent fuel and things like that, there's a due diligence aspect but honestly, I believe they – the technical challenge was more on the post-closure than the pre-closure site.

I'm not aware of any country that's there is a due diligence aspect where countries do try out equipment and techniques and that sort of thing, France, Germany, many of them, but the more the technical challenge is because of the unprecedented nature I think have been on the post-closure. And I think that shows in the National Academy of Sciences Studies through the years. If we were to go back and look at them, they're all predominantly disposal focused, not pre-closure operation.

BAHR: We have time for one more question, Bret, if you have one. Is there one more question from anyone else.

OK. Then, I think we will move on to the next speaker. There also were supposed some drinks coming in and they have come in. So, if you want to help yourself to lemonade or iced tea, that's in the back of the room. And as people are doing that, we'll get our next speaker up and I think Paul Turinsky is going to lead....

BRANTLEY: OK. Instead of Paul, it's going to be – I'm going to introduce our next speaker, Dr. Jonny Rutqvist, from Lawrence Berkeley National Laboratory. Dr. Rutqvist is a Senior Scientist in the Energy Sciences Davison in Lawrence Berkeley lab.

His background is Rock Mechanics with a PhD in Engineering Geology from the Royal Institute of Technology of Sweden in 1995 and he's been working for 25 years in a coupled processes and geologic medium. So, welcome.

RUTQVIST: Well, I'm going to present a little bit more details about the thermo-hydro mechanical perturbation of the near field system in bentonite and argillite repositories.

And first, our team at the Lawrence Berkeley Lab on working on coupled modelings is including myself and Hao Xiu who became our post-docs working with us. Liange Zheng is staff scientist. So, he will have a presentation – next presentation, including also chemical processes and then Jens.

Also, we have a strong international collaboration. These are the task leads from Nagra and Swiss Topo on the Mont Terri experiments and also the task leads from Andra on the heater test experiments at the Bure Underground Research Laboratory and as seen in Cox clay stone. And then, we have a number of international research teams, so in the DECOVALEX projects, maybe over 10 international research teams which are on the work we will present there.

OK. So, first, argillite repository, so in the United States, this shows the inventory or the clay-shale provinces in the United States reviewed by Gonzalez and Johnson in 1984 for potential clay and shale sites. And then, here I show the Swiss concept of a multi-barrier system again which you've seen before, where you have the repository located in the argillite at about – a depth of about 400 to 900 meters in an argillite layer and you still have these multiple barriers including the waste canister, bentonite and the surrounding rock.

So, a coupled processes, THM processes in this system can be quite complex. And these are thermal driven, relatively short term. And I start there with the – so you have heating because of the heat release from the waste canister. So, you are heating up both the bentonite and the surrounding rock and you create the thermal gradient from the waste canister out into the rock.

So, this increased temperature here will induce in the bentonite that is emplaced around the waste canister, will induce some drying due to evaporation and we create also vapor flow in the gas phase out from the waste canister along the thermal gradient towards the cooler regions. At the same time, you have infiltration of water from the rock into the bentonite here – as you can see here. And this will induce both a wetting and swelling of the bentonite starting from the boundary.

The temperature increases in the rock will induce several processes such as thermal stress and also thermal pressurization. This is due to thermal expansion of the trapped fluid in the medium. And you can have a large stress changes that then will also induce changes maybe in the permeability, especially in this zone near the tunnel which is the excavation disturbed zone. So, these are quite complex processes which will occur as long as you have an elevated temperature around this repository.

And – but these processes also may affect the – it gives some long-term impacts. So, if you see at the long term when the temperature is back close to ambient, you may have restored fluid pressure to more or less hydrostatic. And you may have the bentonite is fully saturated. So, that means that the swelling pressure has developed – fully developed. It might be for some system around 5 Megapascal. And this swelling then assures that you have a tight system. So, you will seal the interface between the rock and the bentonite buffer and you may seal fractures – any open fractures.

However, you still may have an excavation disturbed zone from this initial phase of the excavation and also the thermal perturbation and then there's a question, how is the properties of this excavation – how have they changed, did the permeability increase permanently so you have an increased permeability for a radionuclide transport along the tunnels. And also, if this does not go as expected, if you don't get the – if this re-saturation is more slowly than expected, you may not develop the swelling pressure as you intended, and this may have bigger consequences on the excavation disturbed zone.

OK. So, the experiment we're going to study to study this is the heater test at the Mont Terri and Bure. So, it's the HE-E heater test. There's a half scale heater test at Mont Terri. The FE heater test is the largest scale demonstration experiment. And at Bure, we have the TD and ACL test which are more on the – looking at the disturbance in the rock a little bit outside of the emplacement tunnels. And as we said – so, this is happening for these experiments during this early thermal perturbation period here.

OK. So, to study this phenomena, we developed some framework – modeling framework for studying this and we have developed something based on our TOUGH2 which is multi-phased flow simulator developed at our lab. And then to do the coupled THM phenomena, we linked it to a mechanical simulator which is shown here. So, these are two established stimulators that have thousands of users worldwide and both are continuously developed and applied in their wide range of fields in geoscience for multi-phased flow and geomechanics.

So, we have a bit of a large numbers of fluid, the mechanical and constitute the models in these systems. So, these are the advantages of this one. Actually, this linking of these two was developed first and applied in the Yucca Mountain project, and when we really need to study high temperature, multi-phased flow effects and also include geomechanics into the system.

So, for the – where we then started to go over to look at alternative host mediums, we had to add some additional capabilities to this initial framework. For example, for modeling of bentonite and clay rocks and also for modeling host – the salt host rock and backfill. So, this has been done through this program.

There is also – this TOUGH-FLAC simulator is also used in many other application areas such as carbon sequestration worldwide. And also, in nuclear waste, there are several international groups working on it in Germany, for example, in the United Kingdom, Switzerland, and South Korea.

OK. This is an example of the capabilities we added to the code. This is for bentonite, to be able to model bentonite more rigorously. So, we implemented the Barcelona basic model. So, this is a constituted model for unsaturated clay. And as we can see here on this figure, that the clay can be very different, the bentonite clay, depending on the – whether it's dry or wet. So, this is one sample stored. It's a compacted bentonite stored at 55 percent relative humidity. And if you change the relative humidity to 99 percent, you can see this sample has swelled, considerably expanded, free expansion here and this also becomes more soft and less stiff, so, very, very dependent on the suction or the relative humidity.

So, this kind of model can simulate this kind of behavior, mechanical behavior. Another model which is more advanced is the Barcelona expansive model. This one considers the model of the micro and macro porosity as you see in here and it's more advanced, but all parameters are not really available for various types of bentonite. We have used it for like for FEBEX bentonites, so in that case, the Barcelona group has actually developed all the parameters for this model or for like MX-80 bentonite also whereas for other ones, they are not readily available.

So, I'm going to present first the experiment is the half scale experiment at the Mont Terri for Opalinus clay. So, this was conducted as part of the DECOVALEX 2015 project – international project called Comparison Project. And this involves heating up to three years, up to 140 degrees C where we simulated the first three years of the test.

And this is the model. So, the model includes all the components of these elements. So, the heater, the bentonite buffer – so, that used two different kinds of bentonites here. And then, the heaters are resting on a pedestal of bentonite blocks. And then, we have also these concrete plugs in order. So, the bentonite parameters for this modeling is derived from lab experiments, small scale lab experiments. Mostly available in the literature or at the Mont Terri project.

For the Opalinus clay, the host rock we also have – using lab experiment data and also some in situ data for our determining the THM properties for this material. So, having these properties, we then performed a blind prediction of this half scale experiment, the heating experiment over three years and compared our simulated results to the measurements. And then, after this comparison we tried to understand the field data and update the model if necessary.

So, I want to go through a little bit more detail, some of the important processes here. So, this is for the coupled thermal-hydrological changes in the buffer during the early heating phase. So, what you see here is a section from the heater out to their host rock here and these are the thermal hydrologic processes going on here. So, when you start the heater, you create the thermal gradient like this here. And what happens then is the – so, the bentonite was emplaced at about 65 or 50 or 65-degree saturation.

And what happens here then – evaporation of liquid to vapor, and then you have the vapor diffusion along the thermal gradient out to cooler regions. And here, the vapor – water vapor is again condensed into liquid. Because you have this drying here, you also create the gradient in the capillary pressure in the buffer. So, that means that you get the liquid flow from the outside towards the inside here.

So, this is a circulation of moisture going on continuously, and you get this slow drying of the buffer here from the inside. At the same time, you have inflow from the host rock which is fully saturated and this kind of host inflow from host will at some point overcome this dry part of the buffer and the buffer will become fully saturated and develop the swelling pressure. So, this is something we have to model in our simulations to do this.

So, this one shows the model prediction and measurements of temperature and relative humidity for several points within the buffer. And if we first look at the temperature here, so the temperature near the heater is ramped up to about 140 degrees, so much over 100 degrees here. 140 degrees and then they kept it constant like this. You can see that the temperature at the rock surface increases to about 45 degrees here after three years.

If you look at the relative humidity, so, this is relative humidity, so starting at about 40 percent, they emplaced the buffer first then we start the simulation. Then, they emplaced the buffer fewer months before they start the heating. So, you already start to have wetting of the buffer here. And then, the wetting continues, and you get almost fully saturated conditions here close to the rock boundary.

If you look at the point close to the heater, you’ve got this drying I talked about before. So, you dry down here to about to 10 percent relative humidity. If you look at the comparison between the modeling, the model predictions are in the dashed lines and the measurements are in the solid lines. So, you can see that the temperature is quite well predicted, and this is typical when you model these kinds of systems because it's actually dominated by thermal conduction.

The only difficult – maybe the difficulty is that actually the thermal conductivity of the buffer depends on the relative – or the saturation of the buffer. So, we have some changes in the thermal conductivity. If you look at the relative humidity, so, it's quite good, but it's not perfect here in the middle we tend to actually overestimate the re-saturation there. Re-saturation in the experiment actually that goes slower than what we did in the model predictions.

These are comparisons between all the teams that participated in this DECOVALEX project from different countries and these are for two points. So, the symbols are for the field data. These are the two points that are located the same distance from the heater, but in two different bentonite material, one in the granular bentonite here and one in the bentonite blocks down here.

So, you can see that the – it's quite – I mean, all the teams can model the basic process of the temperature and the drying near the heater here, but there are some – there are of course differences in the results for the different modeling teams. All of them are using different models and maybe some different conceptualizations of the experiments.

Next one is the modeling of the full-scale demonstration experiment at the Mont Terri. So, this is a larger scale experiment. You have – experiment is we have a tunnel here 50 meters long and 2.5 meters in diameter and there are three heaters in here to simulate the Swiss concept of emplacement in Opalinus clay. And here, actually the heating may go on for 15 to 20 years with monitoring, and there are monitoring of several thousands of monitoring points both in the rock and also in the bentonite measuring thermal THMC changes in the system.

And here, we can see the work with the emplacement of the bentonite. You have the heaters here resting on the pedestal of the bentonite blocks and you can also see the instrumentation they put into the tunnel here. So, this is kind of also a demonstration on how to emplace the waste and the bentonite into the system.

So, we have done the modeling of this also together with other modeling teams in the Mont Terri FE heater experiment project. And our model is shown here. So, you include of course the surrounding rock and also the access tunnel, the concrete plug, the heaters, and the bentonite. Here is a more detailed models view. So, you have the bentonite blocks on the floor here and then you have the bentonite pellets on top here and there is also shotcrete here.

So, the THM properties we used here is all based on the previous HE-E heater scale model simulation, so, all exact same, similar properties. And comparison of the – these are the comparison of the simulated and the modeling results for up to 1,000 or it's more than three years. And you can see that the temperature is very good agreement and again, the temperature is usually quite straightforward to predict. And is also easy to measure because it's basically a thermal conduction but you also have changes in thermal conductivity due to the wetting.

Here, you can see the relative humidity. Also, for these points, a good agreement – general agreement; however, I should say that in this case we actually had to reduce the effective vapor diffusion coefficient for the bentonite, otherwise, we will get like too much drying. So, this is something that was not entirely consistent with our previous modeling, and this is something we continuously try to understand why it's not only our modeling team that achieved this, it's also other modeling teams.

So, this is now running for about three years – more than three years, but it will be important to follow the long-term – more than 10 years evolution to confirm also the swelling stress evolution in the buffer, because still the buffer is quite dry and there is not a lot of the swelling stress I think developed from the measurements so far. So, it will be important to follow this further on so we can see how the swelling stress develops over the longer term.

The third experiment I'm going to present is the – one in the Cox clay at the Andra. This is also part of a current DECOVALEX task and this is led by Andra in France. So, this is really also about up-scaling. So, we go from samples, small scale through intermediate heater experiments, larger scale heater experiment and then we are going to do full scale repository scale simulations. So, it's how to go from sample scale to repository scale.

And, yes, the heater test, I'm going to present results from one of the heater tests, this one. And the host rock in this case is the Callovo-Oxfordian clay stone, so Cox clay stone. And one of the main issue studies in this is actually the thermally induced pore pressure changes in the – or pore pressure buildup due to the temperature increase and how the stress changes around the repository when you have this huge or big temperature changes and pressure buildup.

So, I'm going to show some simulation results, and this is the model, again, the same simulator. And in this case, we digitized some of the important like tunnels and then you have the – this is the micro tunnel with the heaters. So, this should simulate this kind of emplacement tunnel according the French' concept of nuclear waste disposal in horizontal tunnels or micro tunnels. So, the heaters there should simulate this.

And here also in the model, we had to do quite detailed modeling of – there was a gap between the host rock and the steel casing here. To simulate this, we had a quite detailed digitization in this area.

So, I'm going to show a movie how this changes with time. And you can also follow what's happening in two points here. So, you're going to start soon the heating here and you're going to see heat here and you're going to see how the temperature evolves here. And then, you're going to see how the pressure, thermally induced thermal pressurization evolves in this one. So, this is a plain view.

So, if you can start the movie – yes, so, you can see in our excavation here, you got the pressure change. And then, you see heating starts here. You got the thermal pressurization of the fluid surrounding this heat source. And if you follow in one point, so, in this point here, you can see that the temperature increases here up to about 45 degrees, 50 degrees, the maximum, and during this initial phase of a strong thermal rate of increasing temperature, we get the thermal pressurization. So, this is caused by the fluid inside this medium. We just have low permeabilities that want to expand and the fluid thermal expansion much higher than the thermal expansion of the clay.

So, this causes an overpressure in the clay. And you can then see that it actually goes down here later, and this is because fluid can actually diffuse into this tunnel here which is at atmospheric pressure. So, maybe we can try play it again to see – if you want to see. On this excavation and then the heating starts here. So, you can see the pressure develops like this. So, these are now simulated results, but you can actually see results in the measurements. We can see in the next slide – or next – OK, this one.

So, here, you can see the comparison of the temperature and pore pressure as a function of time. So, the dashed lines are here, the experiments, and the solid lines are the numerical modeling. So, again, for the temperature, we have an excellent agreement, whereas for the pressure, we're OK to predict the average pressure increase here. So, the pressure increases from initial, about 4.5 Megapascal up to about 7 Megapascal or 8 Megapascal.

You can see there's a good agreement in some points like this point which is actually located on the side of the heat source. We have the not so good agreement on the longer term of this point which is located about here, and that this also happens for all the simulation teams in the DECOVALEX project. They cannot get the good agreement.

Then, one way to actually get the better agreement of the pressure changes or keep the pressure high here was to actually lower the rock permeability by at least one order of magnitude. But then, the people from Andra say that this is not a realistic probability. It's actually too low than they think is in there. And also, if you do that, if you reduce the probability for that one, then, you will not get good agreement for this point. So, it's not so easy. But, we tried different options. One is to actually assume a big disturbed zone at the same time as lower permeability.

So, this is an example – I mean, there might be some process which is relevant that is not included in the model, for example, creep, deformation or something that's going on. For the output for the GDSA and the performance assessment from this kind of model, so, we are not able to actually model this for detailed process – for the whole repository system.

So, one way is actually simulate these kind of detailed processes for the tunnel at different places in the repository and then output changes, relevant changes, for example, changes in flow properties that goes into the PA model. So, the PA would include all the tunnels and drifts in the model and they simulate everything and you just could give the changes in flow properties to inform the PA modeling.

I'm also going to show a long-term simulation. So, having simulated this experiment, we have kind of validated the model and we want to try to predict how this occurs on the longer term. So, in this case, we simulate the case where you have considered horizontal tunnels like this. So, by symmetry for this tunnel – emplacement tunnel in the middle of the repository, we can use this model. And the 50 meters here is the distance between two emplacement tunnels.

So, this is a 2D model. So, we apply a 2D line heat source which is derived from the heat decay functions for spent nuclear fuel. So, in this case, you have – and these are the – the power here depends on the number of waste packages and the distance between the waste packages along the tunnel.

So, if you first look at the temperature, you can see that the peak temperature at the waste canister peaks at about, in this case, 91 degrees after about 30 years, or 50 years. And then, you look at the point away from the heat source in the rock. You can see that in that point, the temperature peaks at about 1,000 years. It's a lower temperature. But if you want to look at the – actually the thermal impact on the repository, the highest thermal impact actually will be when the temperature peaks in the rock, because then you heat up the whole rock region here when you increase the stresses very much around this area. Then, you also create a big thermal pressurization around this area.

Here, we can see the evolution of a liquid saturation. So, you can see you have full saturation after about 25 years and that this is important for development of the swelling stress in the buffer. So, when it's fully saturated, you have fully development of the swelling stress. So, that kind of swelling stress then can provide support for the excavation walls and it's good if that can happen before you have the thermal peak or the thermal stress peak.

Also, I put here the three-year limiter. So, this is about how much we have simulated in the field experiments at Mont Terri, about three years for these cases. You have the drying, but it will be good to actually follow how it goes continuous for the next 10 years and develop into all the swelling stress in the buffer.

Here, we can see the evolution of the pore pressure. So, this is caused by this thermal pressurization. So, here, you get the high pressure after about 2,000 years. So, 2,000 years after emplacement, it will have the highest thermal pressurization according to this simulation. Here, we got up to 8 Megapascal. So, that's still less than the lithostatic load on this – at this level. But if you changed the properties – some of the properties like reducing the permeability, we can actually get higher thermal pressurization that could go up to – when you have, actually could get the fracturing maybe due to the hydrologic fracturing. So, it is important for the design of the repository to actually look at this.

Here, you see the evolution of stress in the buffer. So, the stress – the total stress here depends on the thermal stress and the important too, the thermal pressurization. So, we increase the fluid pressure in this whole region, we will increase the horizontal stresses due to pore elastic response.

If you look here, you have the effective stress. So, this is actually representing the swelling stress in the buffer which peaks here at about 5 Megapascal and due to the swelling of the buffer. And then, you can see that actually the effective stress goes down here. So, this is kind of a little bit unexpected when we did these simulations, but what happens is that when you compact the bentonite and you give a swelling stress, it becomes stiff. And then, here, the temperature starts to decline. So, we have a stiff buffer and you decline the temperature, you get shrinkage of the bentonite buffer. So, that's why you see this reduction in the stress in the buffer here.

OK. And then, if you look at the evolution of the disturbed zones, so, it's important to develop the swelling stress to support the tunnels. But these are maybe site-specific conditions, the evolution of the EDZ. For example, they are maybe different at the Mont Terri and Bure, although both are argillite rocks. And also, it depends on the direction relative to the bedding and the stress field.

So, here's one example from the Bure and they excavate is very complete fracturing with shear fractures and tensile fractures around the tunnel. However, when you look at what is important for the permeability, they can deduce this kind of zones here around the tunnel which is depending mostly on the open tensile fractures which have permeability of about 10^{-17} square meter which would be about three to four orders higher than the intact rock permeability.

And then, there have been observed sealing and healing both in laboratories test and in situ. But I think the underlying mechanism maybe not fully understood, whether these are due to just mechanical or chemical processes or combination of those. So, this is not really fully understood at the moment. But, we have observed this kind of a sealing and healing in both at Mont Terri and at Bure or at least the – so, sealing is related to the reduction in permeability and healing would be some kind of mechanical healing for all the fractures.

For the state of the art of our modeling and research needs, so, I think we have developed this modeling framework. We have implemented constitutive models. Some of the constitutive behavior on the longer-term earth buffer re-saturation may be not fully understood because there are cases where they actually see surprisingly slow re-saturation of the buffer. I think Liange will talk about that a little bit in the next talk. And we also saw it in one of the HE experiments. We kind of overestimated the re-saturation of the buffer and that may be related to some micro structural changes in the buffer when there's swelling of the buffer.

For the constitutive models of the argillite rock, we have the models for anisotropic THM behavior of those and it has been validated by looking at the field scale testing in Mont Terri. And of course, this one will be site specific. So, any site, you will have different – will be different degree of anisotropy and fracturing as well and how ductile or brittle they are.

Models for the EDZ argillite, so we are using some like continuum models which has been calibrated where you look at the field data and try to mimic what's happening in the field, or we have done some discrete fracture modeling to study this fracturing around the tunnels. However, we don't have any really established model for the damaged sealing and healing of the long term. And these are also, would be site-specific properties, so, which are like at Mont Terri and Bure.

However, this is a very active research area in the European programs, especially in Switzerland, France, and Belgium, and so on. And so, we have actually a great benefit of international collaboration in this case to actually learn how to model this, although some of it site specific, but still we are developing modeling tools and learn how to model this.

So, in the future, we are continuously looking for experiments to actually validate our models or – and this is a potential one for DECOVALEX 2023 about thermal pressurization and see how fracturing can perhaps develop and we will be able to model this kind of behavior.

So, to summarize, so I think that much progress has been accomplished in understanding THM processes in bentonite and argillite through these international collaborations. So, it has been really beneficial for us because we have just experience from Yucca Mountain before. And we have developed some numerical tools. An underground experiment like this, they provide actually a very good data for testing and validation of these models to make sure that we actually can model these processes at a relevant scale.

And this has potential typically that, as I said, you can – the thermal processes, we can predict with confidence whereas hydraulics and mechanics are – there are some uncertainties. Modeling parameters for argillite can be upscaled from laboratory data and for bentonite. So, you do those bentonite experiments, small scale experiment, for example, for swelling stress or for infiltration to look at the water retention curve and so on, and those can then be used in the field scale.

But certain parameters such as those for the excavation-disturbed zone are probably best characterized in situ because in the lab, although you can learn from lab scale tests, but you cannot model all the big fractures developed in the field. So, that's my presentation.

BRANTLEY: Sue Brantley, Board, thank you. That was great. That was really good. I'm going to ask a couple of questions and then we'll have some more.

First, can you just tell me – you said you made blind predictions. Can you just tell me explicitly what that means?

RUTQVIST: So, that means that the field data is not given to the research teams ahead. So, they don't know what's the real temperature evolution in the field. So, we just try to use our models and we develop the properties from laboratory scale experiments and from modeling of some previous experiment heater tests.

And then, we set up the model for the heater experiment, put in the properties and we model. And then, the secretariat of DECOVALEX, they do the comparison to the field data and then we see the results.

BRANTLEY: But I mean you know the geometry of the experiment.

RUTQVIST: Sure.

BRANTLEY: You know what the different phases are.

RUTQVIST: Yes. We know the geometry, but we don't know the results of the temperature changes or the changes in relative humidity during these three years of heating.

BRANTLEY: But you know the starting conditions or something like that?

RUTQVIST: Starting, yes. Yes. So, we know what the starting...

BRANTLEY: And then you have to look up for...

RUTQVIST: ...and we know the – they may give us the heat power output from the heaters or they may give us the temperature evolution at the heater surface.

BRANTLEY: And then, do you have to look up properties of bentonite or are they giving you the properties of the bentonite they used or something?

RUTQVIST: So, I mean, bentonite properties are based on previous studies. I mean, like for some certain bentonites, they do a lot of laboratory scale studies of bentonite properties. So, we then use those properties and put it into our model, for example, the swelling stress or for the evolution or for the thermal conductivity of the buffer they’ve done experiments, how it changes with saturation. So, these properties we then put into our large-scale model.

BRANTLEY: And then, the same would be for the host rock. They've already done experiments on the host rock...

RUTQVIST: I mean, yes, for the host rock for Mont Terri, of course, there is a lot of previous experiments on the – done on the Mont Terri – on the Opalinus clay both in the laboratory and in the field. So, we have access to those data to actually populate our models. And then, we put that into the model for this heater test and see the results. So, that's the line prediction.

BRANTLEY: So, can you also educate me? To me, bentonite is a mineral. I mean, it's smectite, but it's also a rock that's mined like in the Dakotas or Wyoming or something, maybe in Europe somewhere. Is all bentonite the same?

RUTQVIST: No. No. They could be very different. So, like – so, I've been doing some modeling also for example in the Japan, certain bentonite and the swelling test is very much, much smaller like 1 Megapascal or something.

BRANTLEY: For some bentonites?

RUTQVIST: For some bentonites, yes. So, it depends on the mineralogical contents. Yes.

BRANTLEY: And so, I mean, how is that going to play out then when we have a repository or something. Do bentonites vary in very small amounts or do they vary like in huge amounts? Is that a worry or...

RUTQVIST: No. I mean, different bentonites can have different properties. So, a lot of people, a lot of international programs, they use the one bentonite from Wyoming, MX-80 right, and so, that one, you have a lot of properties available that you can use in our models.

BRANTLEY: And repositories it will be all the same, right?

RUTQVIST: Yes. Yes. Yes, sure. Yes. So, they will use the same – they will buy the bentonite from somewhere and it will be put into the repository. So, it will be all the same what they…

BRANTLEY: And there's no heterogeneities in the bentonite. There 's no...

RUTQVIST: I guess some – and they – then you emplace the bentonite. That's a big research topic, I guess. So, that's what they demonstrated in this and the FE heater test, they actually – they use some special things to actually shoot the bentonite pellets into the tunnel and emplace it. So, I guess, there could be some differences in there in the density along the tunnel...

BRANTLEY: You mean to put heterogeneities in.

RUTQVIST: I think – no, I think it will be quite homogenous, but there could be some differences. Yes.

BRANTLEY: And then what about heterogeneities in the rock? How do you incorporate that into your models?

RUTQVIST: So, for the Opalinus clay I think is quite homogenous, but you have a strong anisotropy in the rock and then we can – of course, if there is – we can also put in heterogeneities by – if they have some data on how heterogeneous the rock is for the bentonite – for the shale.

But if it's such – for example, for the DECOVALEX now, for these up-scaling experiment, up-scaling case, we actually put in heterogeneities in this repository model based on the data they had from Andra. And in that case, for this shale material, it didn't impact very much our results for – when we're looking at temperature and thermal pressurization actually. This is not like granite or something, where you have fractures, very permeable fractures, very high hydrogeology.

BRANTLEY: But there's bedding.

RUTQVIST: Yes. Yes, sure. Yes, bedding. Yes. Bedding, we put in.

BRANTLEY: And then, what about the disturbance zone? Is that – like, what are you going to do about that? How are you going to model that or what's your thinking because that's...

RUTQVIST: So, as I said, the disturbed zone, we can model it in a simplified way and it will also be site specific, very site specific I think to how this develop. So, we can model it like – we can make a continuum model of how permeability changes as a function of stress for example in this zone. And then, you put that into the model and simulate it.

But then, the – and then, you have to put in like the sealing and healing. That would be – you have to base it on the field experiments to learn how this evolves over time. So, that can be put in to the model and then it is impacted by the stress evolution that you calculate from this model on the boundary of this tunnel.

BRANTLEY: And when you say site-specific, you mean one repository specific or one tunnel specific?

RUTQVIST: I think it's mostly, you see in Mont Terri and the Bure, there's the evolution of excavation-disturbed zone may be a little bit different and that means it's site specific. And then, it also depends on the direction whether you go – whether your tunnel goes along the minimum principal stress direction or along the maximum principal stress direction, you get the different pattern of the disturbed zone. So, this is best studied in situ, site specific.

BRANTLEY: So, you're imagining a model for Bure, let's say, that would be specific to the direction of the tunnel and maybe the depth of the tunnel.

RUTQVIST: Yes. Yes.

BRANTLEY: And all those different things would go into the model.

RUTQVIST: It will be – yes, it will depend on the specific rock properties at that site. We did a similar thing like at Yucca Mountain. We did the studies of the disturbed zone around the tunnels using field measurements and that kind of model was put into the – actually to the simulation model, THM model to estimate how the permeability changes over time.

BRANTLEY: So, Paul?

TURINSKY: I'll follow up I think where Sue was going. How do you handle uncertainties in this model? I mean, you not only have the modeling uncertainties, you have the initial condition uncertainties. You have the description of the disturbed zone.

RUTQVIST: Yes.

TURINSKY: In an operating repository, you're not going to have field data like you do when you're doing your experiments. So, how do you put a bound on the uncertainties?

RUTQVIST: We are not going to have field – I think we'll have field data at the repository but different.

TURINSKY: I doubt it'll be at the level of your experiments, though.

RUTQVIST: I'm not sure. So, of course, we do a lot of sensitivity studies, for example, about the re-saturation of the buffer which you can see that is really the main thing is the permeability of the rock. The permeability of the rock will determine how long a time it takes to go to full saturation. So, we can vary the permeability of another rock within this uncertainty range and the other rock.

TURINSKY: OK. And so, starting from the beginning because you've said that I didn't get, why should we care? From the safety case, what is this finally influencing?

RUTQVIST: So, if you the swelling stress does not develop in time or if the re-saturation goes much slower than expected, if you don't develop the swelling stress then you get thermally impact from the surrounding heating, you may damage the tunnels and damage permanently and that could impact the flow and transport properties along the tunnel, which could be important for their performance I think. So, that's one where the disturbed zone is important.

TURINSKY: OK.

BRANTLEY: So, it could make hydrology important then.

RUTQVIST: Yes. If everything works perfectly and the disturbed zone is completely sealed, and you have only diffusion so, yes, so I think mechanics is…

BRANTLEY: I thought let's just ask John McCartney if he had any questions first. Do you have any, John?

MCCARTNEY: Yes.

BRANTLEY: Please.

MCCARTNEY: It's John McCartney, consultant to the Board. Thank you for the nice presentation. I can definitely appreciate it's very complicated to study this very coupled process. I had a few questions and maybe we can follow-up with some more details at the poster session.

One question I had when you showed the – sorry – all the different coupled processes, you didn't really mention volume change as part of that, and as part of the FEBEX you did see a gradient in density of almost 20 percent across the engineered barrier.

RUTQVIST: Yes. You are right. So, actually, in my model simulation of the long term behavior, I didn't show it here, but at the end I simulated the density and at the end actually I got the density variation from the inside of the buffer to the outside of the buffer. So, less dense on the outside of the buffer and more dense inside.

And I was kind of surprised because it’s mostly a non-linear elastic model but somehow there's no linear elastic behavior overtime and your temperature changes and everything happens. So, at the end, I actually got density variation from the inner part to the outer part. but still its density overall is higher than the criteria for the safety function of the buffer overall, so yes.

MCCARTNEY: Did you consider the coupling of the density and your thermal and hydraulic properties?

RUTQVIST: There is a relationship between the dry density and the saturated water conductivity. For the thermal properties, it's mostly depending on the – could be some on – it's mostly depending on the water saturation and the bulk thermal conductivity.

MCCARTNEY: Yes. So, I think you mentioned that your model is thermoelastic. Several other studies have looked into thermo-plasticity.

RUTQVIST: Actually, it's plastic also. It's a thermal but our model is thermo-elastoplastic. But it's mostly in this case mostly thermoelastic processes, because you have the compacted bentonite and it's compacted, so you mostly have – the most important is maybe thermoelastic properties, and then you may have some internal in the micro structure that could be inducing other processes.

MCCARTNEY: Maybe once you go to higher temperatures we start to see thermal contraction.

RUTQVIST: Yes, that's one thing if you could develop thermal drying and cracking near the heater in the early time, but as later as it gets saturated you will be swelling and they will close hopefully.

MCCARTNEY: Did people, have you observed they're trying to model like the possibility of thermal desiccation?

RUTQVIST: We have, I mean, there is a tensile – you can tensile failure here if you got negative, I mean, if stress you will get – the model will simulate tensile of failure, yes.

MCCARTNEY: I suppose another question I had maybe following up on one of Sue's questions was the calibration of the model. So, I counted in some of your papers, that could be 25 to 30 parameters, is that...

RUTQVIST: Yes. That's one of the – but this is more – for the bentonite models, the one, the more advanced model, there is a lot of parameters.

MCCARTNEY: Yes.

RUTQVIST: And that happens, I mean, you can use the simplest model, just do the basic, the simplest one is just swelling strain as a function of saturation. Then you can simulate the final swelling stress. It's more like you don't simulate the real underlying mechanism, but it's a rational way to do it.

And if you want to include more processes such as plasticity and things, you need more parameters. Or if you want to include how this microstructure affects the permeability is you have a micro, those microstructures invading the or micro porosity, invading the macro porosity, you got another parameters and these are – some of these parameters are not easy to determine and readily available.

And we have done some simulation. So, for example, the re-saturation process having that Barcelona expansion model and if we can then simulate very much, the delayed re-saturation, but it depends on the – these parameters are really not easy to ready have available.

MCCARTNEY: Is it part of maybe your future scope to maybe include some more experimental programs here in the U.S.?

RUTQVIST: Yes.

MCCARTNEY: Or is the plan actually…

RUTQVIST: I mean, this is something going on international also. And we, I mean, I don't know if we might try to do this kind of infiltration test studying – also, you can do some imaging on the nano-scale or looking at what's really happening at the very micro scale during this kind of process structure, learn what are the real underlying processes.

And I think that's maybe important. When you do the long-term predictions actually model the underlying processes correctly, not just do calibration in the short term and then try to predict. You should model the real underlying process and I think that's important.

MCCARTNEY: Can I ask one more question?

BRANTLEY: Yes, one more, Mary Lou has a question too.

MCCARTNEY: Very quick. The thermal pressurization that you saw for the bentonite, I found that those pressures are pretty high compared to other thermal pressurization tests on lower activity clays, and I haven't been able to find any validation studies on bentonite, those pressures.

RUTQVIST: So, the reason why the pressure goes up in a bentonite here is because the pressure goes up in the host rock and then the flow moves into the bentonite. This is a simulation of both the host rock and the bentonite at the same time. So, this is, always need to include both the host rock and the bentonite in the model because there are strong interactions between these. So, this is entirely done, caused by the pressurization in the host rock.

MCCARTNEY: Thanks.

BRANTLEY: Mary Lou?

ZOBACK: Mary Lou Zoback, Board. First of all, I want to thank you, Jonny, that cartoons at the beginning were exactly what we were hoping to get from people and you took a whole bunch of processes and spelled it out, so thanks so much for that.

My question is related to the in situ stresses, and you alluded to this on slide 25 where you showed Arman et. al.'s work where they were looking at the disturbed – excavation-disturbed zone and they took in consideration the orientation of the horizontal tunnel with respect to the principal stress directions which are well-known for all of the sites that we've discussing from completely separate data.

So, you're talking about pressurization of a horizontal borehole. That sounds a lot like how we do shale gas extraction, right? So, are the in situ stress orientations and magnitudes part of your boundary conditions for your modeling?

RUTQVIST: Yes. Of course, we put in a three-dimensional stress field in the model.

ZOBACK: You have never showed any stress orientations on any of your models.

RUTQVIST: I didn't know but they are in there. They have in both generic model and also the site-specific models about the HE-E heater test. And at the thermal pressurization experiment in Bure, so they are the stresses goes approximately 15 Megapascals and the in situ stresses, I mean…

ZOBACK: Well, it's the differential stress that you care about for the stress concentration around the borehole, but I'm just wondering on slide 21 where you showed large discrepancies in your modeling between the observations. You have observations roughly at 90 degrees to one another. You have the red and blue and then you have – oops.

RUTQVIST: Which one? Which one?

ZOBACK: No. No, you were right before, there.

RUTQVIST: Yes.

ZOBACK: OK, 21, right. So, you've got roughly 90 degrees between red and blue which are hugely mismatched.

RUTQVIST: Yes.

ZOBACK: And surprisingly, green and yellow, green predicted exactly, and you must move a few centimeters away and you get yellow which – anyway, I'm just wondering if there’s some sort of radial effect around the borehole that if you properly included the 3D stress field that you might be able to explain.

RUTQVIST: So, one thing, one way to actually to match – so, one way to actually to match this part here, up here and at the same time match some of these points here was actually to lower the permeability, lower the rock permeability, so then you can match the pressure change here.

And for these points, you have to include – it includes a large excavation-disturbed zone around the tunnel with an increased permeability, then that point will become closer to here, you could actually somehow match the two data points. And this is, I mean, the pressure changes here is entirely caused by, mostly caused by expansion of the fluid that is trapped and we are still in – there is still no change. There is just elastic – pressure changes are much less than the minimum principal stress.

ZOBACK: But still I imagine with a model with so many parameters, yes, you could change a parameter and get things to match.

RUTQVIST: Yes.

ZOBACK: But the question is, are there processes that are missing themselves.

RUTQVIST: No. That's what I said, maybe there are some processes here missing. And maybe there is some long term, I mean, for example, you could get creep deformation and you heat up the rock, you may, I don't know, could be some processes here were missing actually which is not included in the model because – yes.

ZOBACK: Well, the excavation process alone created a perturbed stress field around the borehole.

RUTQVIST: I mean, that's included in the model. So, the perturbed stress around this borehole I think will be very close to the borehole, the excavation – the stress disturbance around this borehole maybe extending one diameter from the borehole, I would think not more, I mean, significant changes.

BAHR: I think we're at time. So, we're scheduled right now for a 15-minute break. So, maybe some discussions can continue over that. I think there should some lemonade and iced tea remaining in the back of the room if people didn't drink it all. Please drink, yes, we can't take it with us. And we'll reconvene at 3:45. Thank you.

BREAK

BAHR: OK. So, Sue Brantley is going to get us started for the next speaker.

BRANTLEY: OK. I'd like to introduce the speaker Dr. Liange Zheng. He's a staff scientist – you're not supposed to laugh at my pronunciation – at Lawrence Berkeley National Lab. And his research focuses on numerical modeling of non-isothermal multiphase flow and multi-component reactive transport in porous media. And he's interested in coupled modeling of thermal hydrodynamic, mechanical, and chemical processes. And his PhD was at the University of La Coruña, Spain.

So, welcome.

ZHENG: OK. Thank you. You are totally forgiven for not saying my name right.

Yes. I'm here to present the DOE's activity on engineered barrier integrity focusing on the understanding of EBS coupled processes and those of mineral alterations at high temperatures using international collaborations the full large scale experiment, the FEBEX DP and HotBENT, I think it was already mentioned these two tests.

So, let me start with the acknowledgment of the collaborators of this from national labs in U.S. Lawrence Berkeley Lab, my colleagues there, also from Sandia National Lab, also the international collaborators. One is from Spain, the CIEMAT. If you translate it to English it is Environmental Energy and Technology and Education center and, of course, Nagra who is the leading organization of the two large scale tests I'm going to talk about.

So, we have seen this from previous presentations, EBS is one important component of a multi-barrier system for a repository. The space between canister and rock wall are filled with bentonite.   The reason and the bentonite initially is partially saturated, the reason we choose bentonite because it has a couple of beneficial features including it swells, it has a low permeability and also it has high retardation capability.

The major safety function for EBS bentonite barrier include limiting flow and the transport in the near field, also provide a mechanical support including dampening the rock shear movement, preventing canister from sinking and also limiting pressure on canister.

Another function is to reduce the microbial activity which as we know is related to the corrosion of canister, also causing the retardation or migration of radionuclides. While we know there are a lot of processes during the life span of a repository bentonite evolves, there are a lot of processes involved during this process, we assure verifiable with EBS in the long term understanding and modeling the early times thermal, hydrological, mechanical and the chemical. But the measure is critical because some of this change will have permanent impact on the barrier.

For example, here, the thermal processes, of course, we know this heat, the waste that generate the heat and the heat will be transported through EBS into the host rock, in the same time the water infiltrates from host rock into bentonite barrier, so hydrologically bentonite initially is unsaturated and then it will become fully saturated after go through some transient desaturation and re-saturation processes.

Of course, I know Jonny mentioned in his talk that these are mechanical changes and also there’s chemical changes including the solute transport in bentonite and also the radionuclide migration and also other changes.

So, also we have to keep in mind that all those processes are coupled with each other. As Jonny mentioned that the THM processes are coupled, the relatively well-known ones including for example the change of thermal conductivity as function of your saturation degree, also change your porosity and permeability as a result of the mechanical behavior here, for example swelling. A little less well-known is the change in mechanical property as a result of chemical change.

For example, if you saturate, if you do a simple swelling test, you take a dry bentonite and you saturate that with water with a different solution, different concentration, for example potassium, like a calcium chloride with different concentration you could get a different swelling pressure, these are very typical mechanical chemical handling processes.

Also, bentonite swells because it contains smectite, or montmorillonite. So if a bentonite has different content montmorillonite it swells at different swelling pressure because that's why for example well, Wyoming bentonite has much higher swelling pressure than Kunigel Japanese bentonite because it contains much more smectite. The Wyoming bentonite, it contains much more smectite than the Kunigel bentonite.

So, also this process, another thing to keep in mind, all these processes evolves with time. Taking 100,000 years as an example here, the heat emission decays, initially pretty hot and then gradually decrease. The temperature in the EBS initially increase and gradually it decreases until eventually we reach the ambient temperature.

And hydrologically, the bentonite will become first go through desaturation, and the re-saturation, eventually becomes fully saturated. And as Jonny showed in the initial stress we go up, then it will go down, eventually stress stabilize. And in terms of the mineral alterations, initially we will see alteration for those minerals with higher solubility, for example, sulfur minerals, carbonate minerals and for clay minerals actually because it has very slow reaction rate, clay minerals tends to – the alteration with clay minerals tends to happen in a much later time. So, let's keep in mind all those processes are coupled with each other and it also evolves with time and space.

So, what are the key unknowns and uncertainties in understanding and modeling the EBS evolutions, because this is essentially for long term disposal safety evaluation. So, to build such model, I think we need to know first what are the key processes that have to be included in the model?

Do we consider all the THMC processes? Or, can we simply find a model that's considered well done if we decided we did not need to consider all those processes. Do we have a reliable constitutive relationship to describe those processes and do we have parameters to describe those processes? For example, in the porosity and permeability change, you can derive those relationships using, and empirical relationships, based on fundamental understanding, you can do it in various ways.

And if people come out with different relationships, which one is appropriate for this scenario, we need to study it and also the stress evolution, and also do we have reliable chemical models and the parameters to describe the chemical processes, for example, evolution of pore geochemistry in bentonite.

And actually when I first I looked into the business of bentonite actually, I found out actually to learn, to manage the pore chemistry is extremely difficult just because especially for the initial condition with such lowered content. To manage the concentration of pore water is not easy. And also, the mineral change in bentonite with all the chemical reaction networks and with the different chemical conditions to have the right conceptual model to describe those mineral phase change is not an easy job.

And also, the retardation capability is changed with time and also as a result of heating or mineralogic phase change. And also, another challenge is at interface area, for example, the canister bentonite and the canister host rock.

While we learned that – we have been studying bentonite for quite a long time, more than a couple of decades and then we learned a lot. We found out that the laboratory experiment certainly is very helpful, but the larger scale for answers unknowns and reducing uncertainties because it allows us to explore processes and parameters at the full scale of emplacement tunnel, so the scale with the same as a real repository.

Also, lets us test the system with all the coupled processes incorporated at the scale of a repository. And also, the ability that we can model the in situ test is a demonstration of model capability I know will greatly enhance our confidence.

So, sorry you have seen this figure now several times, just to give you an idea the test I'm going to talk about why it stands in terms of DOE URL portfolio, so here I'm going to talk about FEBEX and HotBENT. FEBEX – oops – so FEBEX and HotBENT essentially deal with engineered barrier integrity. The FEBEX experiment was conducted at 100 degrees Celsius and the HotBENT is a planned experiment and it will be conducted at 150 to 200 degrees Celsius.

So, let me just quickly go through the FEBEX in situ test, as we've heard from Irina and also Jens. So, it’s a full-scale test located in Grimsel, the test site is south of Zurich. FEBEX actually is a larger project that is composed of lab study, in situ test, mock-up test and a lot of modeling work. And the centerpiece, of course, is the in situ test conducted at Grimsel.

In this test, two heaters were emplaced in the center of a granite tunnel and the bentonite barrier was installed by bentonite blocks, the pre-fabricated bentonite blocks were different shapes. I brought one piece, if you're interested you can check it out on the table.

A lot of sensors were embedded in the bentonite bricks so that we can measure some variables in situ, for example, the stress, pore pressure, relative humidity, of course temperature, so to measure the in situ real time. Another heating study in 1997, so one difficulty is to measure it is geochemical change, so to measure geochemical change, you have to take samples from the field, so that's why in 2002, the first heater was dismantled and we take -- some samples were taken section by section and took them to the lab to measure hydrological property, for example or the content, the identity, also do a lot of tests on the mechanical properties, like concentration in the pore water and the mineralogic phase change.

And then after they tested it and then they use concrete short grade plug to seal this area and then heater two continue running for another 20 years until 2015, the second heater was dismantled. And after the second heater was dismantled extensive laboratory tests were carried out to characterize THMC properties of the bentonite, of concrete and also even liner and also granite. It was actually the – actually they also looked at the microbial activities in this site.

So, when we have this nice comprehensive data set for 18 years we will use a model to understand the process by interpreting the field test results, so we developed a THMC model. So, to develop this model, we said first we need a simulator, so Jonny mentioned we use a TOUGH-FLAC so we eventually expand this code to link this – you expand this code to a TOUGH-REACT-FLAC3D. So, this might be used – it's a THMC code.

As we heard the THMC process have been mentioned a lot of times in previous talks, actual simulator that can simulate THMC processes. Simultaneously one code only appeared a couple of years ago, and some successful simulation cases generally appeared in various entities that's because the challenge of simulating every process in one simulator, and also another challenge is the constitutive relationship between different processes. For example, how do we simulate the coupling between mechanical and the chemical processes is really challenging.

So, when we developed this code, we spent a lot of effort to test the different coupling constitutive relationships. So, once we have these tools and actually now although my career is most like about developing coupled THM sub-process, I personally am not a big fan of a really complex model. I would like to start with very simple model, as simple as possible unless there's a necessary requirement that we need to consider the process.

So, actually when I simulated this test, I started with a simple TH model, just to see how it does. So, after I failed to explain the evolution of relative humidity or content, then add the mechanical process, then add chemical process, then I found out I have difficulty to explain the constituent profile and the coupling between different, and especially the change of porosity and permeability as a result of swelling.

So, I have a poster, you can check all the detail of this model. So, here I'm going to give you two examples, the match between model and the data. Here I’m showing water content. The red symbols and the red lines are the result of the dismantling of first heater here is 5.3 years.

The black lines by the symbols are the content measured after the dismantling of the second heater. You can see the model and the data match pretty nice. And also, here is a chloride concentration profile along the spatial distribution along the radial distance, and, again, the black line and the symbols are for the 5.3 years the dismantle of first heater and the red ones are after the dismantle of the second heater.

So, after I have this model can explain basically all the THMC data, we have done a lot of sensitivity analysis to sort out which are the key processes, how does a parameter uncertainty affect the model results. So, all these things I show some examples in my poster, you can check it out.

So, actually, we learned a lot by modeling this field test. So, I'll just quickly go through some lessons we learned. The first one about the lesson learned just from the testing itself. Actually, I took some of this conclusion from Nagra.

So, one of the lessons learned actually the in situ, one to one scale experiment has been very useful in terms of engineering aspect, process and understanding, and monitoring, something on the modeling.

FEBEX actually, this project was started by – when the FEBEX project started, the major objective initially actually is to demonstrate the engineering feasibility. Later, in the later stage, that objective evolves a little bit from demonstration of engineering feasibility to process understanding.

And another conclusion is bentonite was performed as expected, for example, in terms of saturation and the model shows we wouldn't get fully saturation in 18 years and the dry density just varied around 1.6. Initially, FEBEX bentonite bricks, has dry density 1.7. but you can see that gaps between bricks, so it averages out at 1.6.

So, eventually was varied between around 1.6. But to close the – in the area close to granite, you have lower dry density, and the area close to the heater have higher dry density. So, in the area that bentonite has become fully saturated, the swelling pressure reached the design value, which is about 5 Megapascals.

And the clay minerals have some minimum change. Another observation here is the international collaboration among several partner organizations is widely beneficial.

Here I'm going to show you the lessons we learned by modeling the FEBEX in situ test. So, after we modeled this test with such a comprehensive data set, what we suddenly note, understanding has been deepened and the modeling activity has greatly improved. For example, in terms of the process we need to model the bentonite, the THM evolution, we know to simulate the thermal behavior we need the data of thermal conduction and convection, and we need mass flow, gas and liquid to simulate the water infiltration from host rock to bentonite. And we need to consider pore elasticity or any kind of mechanical or really complex like using Barcelona itself, the expansive clay model, or simple swelling behavior like Jonny just mentioned. And also, we need to consider porosity and permeability change as a function of swelling.

So, about the geochemical chloride evolutions, what we observed is we saw really high concentration near the heater, and really low concentration near granite, and the profile of ion concentration in bentonite was largely shaped by transport process by advection and diffusion but also affected by mineral dissolution precipitation and chemical change.

And this alteration of carbonate minerals and gypsum, across the entire internal barrier but the alteration to clay minerals are very moderate and mostly occurred near the heater. But, unfortunately, when the content of montmorillonite or smectite was measured, the uncertainties are fairly large, so the uncertainties are too large to be useful to verify the model results.

Also, one other thing just from lessons learned from modeling point of view is to increase robustness of a critical model I think there are two things that will be very beneficial. One is long term measurements. And after I developed this base THMC model I changed some parameters, I found out actually if we – some model actually did a pretty good job in managing the short-term data. But the deficiency of this model only manifested if you compare it to long term data so that's why I think we need a long-term measurements.

Another lesson I learned is we need a multi type of data, thermal, hydrological, mechanical and chemical data. One case I play with different constitutive relationship for porosity and permeability change, actually this model did a pretty good job in managing the THM data, but it fails to manage the chemical data. So, what I learned actually the chemical data give us another layer of information to calibrate a THM model. So, the multi-type of data is really helpful, long term measurement is very useful.

So, of course, the knowledge gap has been narrowed, but also there's a lot of work ahead of us. And in the immediate future I think one thing we are working on is to understand the geochemical change, at the interface area at the canister bentonite and the concrete and bentonite and also granite and bentonite. This picture actually shows the interaction between corrosion products with bentonite. You can see these all the corrosion products penetrates into bentonite have this reddish color.

But you will see this phenomena in some area but not the other are.   So, it's a very interesting processes we need to understand. Another thing is we tested the constitutive relationship in the FEBEX in situ test but it is 100 degrees Celsius test. The question we have to answer is do those constitutive relationship still valid in other conditions, for example, 200 degrees Celsius or other type of clays. Also, the understanding could be deepened by multi-scale studies ranging from micro-scale, pore-scale, the laboratory scale and to in situ scale.

So, the next couple of slides I will discuss what are the effect of high temperature on the alteration of bentonite. So, why are we interested in the high temperature? One of the reasons is as Jens mentioned in his talk, the dual-purpose canister will lead to the high temperature to the surrounding environment, engineered barrier system and also natural barrier system.

Another reason actually we look at the high temperature is the thermal limit of 100 degree Celsius for the small PWR canister. Yes, I think Mary Lou has asked this question, sometimes how do assumptions affect our results.

I think a lot of people throughout the world, 100 degrees Celsius limit is imposed in the repository. One of the reasons we thought is it had to do with transformation from smectite to illite and it is believed that the illitization will dramatically increase if temperature is higher than 100 Celsius. And we will check it out if this assumption is valid so we can do this by model work, by lab work and by field test to find out if it's really true that illitization will become significant with temperature that is higher than 100 Celsius.

So, with this work, actually the key knowledge gap we're trying to narrow is first, bentonite evolves from partial saturation to full saturation at 200 degrees Celsius, how does bentonite change, hydrologically and also mechanically such as boiling, and high pore pressure, high stress, and gas transport. Also, what kind of mineralogic phase change in bentonite in a short term and the long term? For example, illitization, and the question is if there is illitization how does it affect the swelling capacity of bentonite?

And also, one thing we are trying to answer is are the models we keep up for low temperature, for example, 100 degrees Celsius suitable for high temperature conditions. Are those processes and the constitutive relationship parameters we learned in low temperature can still be, hold for high temperature conditions.

So, basically, we use three methods to tackle this issue. First, we use historical generic models then use a multi-scale experiments and eventually we have checked out in the largest scale in situ test.

So, this is one of the generic models I'm using to evaluate the impact of high temperature. Here, we simulate a generic case with a tunnel at 500 meter deep. We'll assume that the EBS bentonite has properties of either Kunigel bentonite which is Japanese bentonite or FEBEX bentonite which they used in the FEBEX in situ test. We assume the property of clay formation of host rock is Opalinus clay.

So, by changing the heat release we create two cases. One is called the High-T case. In this case, the temperature near, at the canister surface, reaches 207 degrees Celsius and for the Low-T case, the temperature of canister surface reaches only 100 degrees Celsius.

So, we can see, these are fairly complex chemical models, reaction rate, aqueous complexation, and mineral dissolution and cation exchange. Also, the illitization is modelled as a dissolution of smectite and precipitation of illite. This is the kind of reaction I'm using.

The key to simulate this process is the reaction rate. So, before we developed this model, I first calibrate the reaction rate based on the field data. And another thing is for the mechanical coupling, we used dual-structure expansive clay models. Here, I'm showing the results based on the linear swelling and all this work has been published into papers you can check on, I have a reference later in my presentation.

So, due to the time constraint, I won't go through the detailed model results, I will give just two examples for the key findings from this modeling work. One thing we learned is that illitization does occur and the temperature play a key role. For example, if you look at here I’m showing volume reduction, the dissolution, yes, I'm showing that dissolution of smectite. Where there is a dissolution of smectite there will be a precipitation of illite roughly at the same amount.

So, you can see the black lines, the high temperature case, solely the red line is the low-T case and the dashed red line is a case which has no heat, imagine hypothetical case. You can see high temperature that there's more dissolution of smectite. Here is the result of point B, point A. Point A is inside the bentonite barrier near the heater and point B is inside the bentonite barrier but near the host rock.

And the point C and the point D are two points in the host rock, the clay. Point C is right near the interface area. Point D is 10-meter deep in the host rock.

You can see I put two green lines here. Before 3,000 years the evolution with smectite at point A and point D are fairly similar, but after 3,000 years, you can see that the point B was dramatically, dissolution of smectite. But we didn't see that in point A.

So, what happened? What happened actually is you see in the host rock, if you look at the smectite dissolution at host rock after 3,000 years, here this has become flat, means dissolution of smectite stopped mainly because there's no more smectite. So, when the illitization process stopped in host rock, the potassium which was used by the illitization in host rock now is free to be transported into the bentonite barrier.

So, after that, and the potassium was transported into the bentonite barrier, then you can see dramatically dissolution of smectite. Here is a good example how host rock bentonite interaction effect the property change in bentonite barrier. And also, I should mention actually for illitization process, the supply of potassium is very important.

So, another finding we found out actually swelling stress decreased as a result of chemical change and the decrease will actually vary case by case. Here, I will show you the swelling stress reduction by ion concentration and or by dissolution of smectite. This is for Kunigel bentonite and the two points, point A and point B. And this is for FEBEX bentonite.

You can see the value varies a lot from a couple of percent to like 50 percent. So, what I learned actually from here is stress could be reduced by chemical effect, but it will vary from case to case, depends on the chemical condition.

So, after we run this generic model, we learned a lot what happened, what could have happened in higher temperature condition, we want to check out by experiment. This is one of the experiments that we are planning at Lawrence Berkeley National Lab. It is a column test. The column is 50-inch long, with a diameter of 6.5 inch. There will be a heater in the middle, with sensors buried in the column.

The column will be hydrated from a center layer between the cylinder wall and the bentonite column with water chemistry exactly the same as Grimsel granite. So, that this test actually, we try to use this column test as a lab analog for the HotBENT experiment. And we will run two columns, one is the heated one, another is a control where you see there’s no heater there.

And we have pre-modeled clay columns with embedded sensors and also we will measure temperature and ERT wires installed and we measure ERT data. And also, we will take this to a CT scan periodically to look at the change inside the bentonite.

So, at the same time we also try to understand the fundamental processes, how exactly the chemical change affected the structure and the swelling of bentonite. This is one small scale study we are running, it’s a pedometer test. The cool thing of this test is we can measure actually the pore development during the hydration.

By the large-scale experiment, we understand and it will change the chemistry or the solution you use to hydrate a dry bentonite, we got a different swelling, but exactly what happened, why the swelling stress is lower. So, one thing we're going to look at through this test is to look at the pore structure change during the hydration processes. At the same time, we will use molecular dynamic simulation to understand these processes.

Well, I've seen a lot of processes are site specific, but also some process actually if you understand from the fundamentals the basic processes can be applied to different sites. With all the generic modeling and the lab test and the microscopic study eventually as we know we need to test out everything in a larger scale experiment which now comes the HotBENT experiment that is planned test, the project is led by Nagra and with partners from, of course, us and from Canada, Japan and the UK, also Súrao from Czech Republic.

But the test will be conducted at the same tunnel that the FEBEX in situ test was conducted. The major difference is the temperature will be much higher. We are looking for temperature from 150 degrees Celsius to 200 degrees Celsius.

So, this is – we're still in the test stage to finalize the design. This is one example of the modules I'm going use in the test. It's going to be a multiple modular test. You can see here four modules. The modules differ in terms of the type of bentonite, the duration of the test and the temperature.

For example, here, we used Wyoming bentonite and the test would be – the bentonite will be a granular bentonite and this one will run longer and this one is shorter. The reason we have the same setup where one test run longer, another run short, it will allow us to have two snapshots for the spatial distribution and this is a timeline of the test, currently we are in the detailed design phase.

So, the question you may ask after this presentation is how eventually all those processes model, all those lessons we learned from modeling lab studies to in situ test will eventually be integrated in the generic disposal R&D, so that the process we are using here is we will use the macro structural analysis to understand the fundamental coupled processes and build a robust constitutive relationship for the coupled processes.

All these lessons learned will be built into advanced modeling tools and we will construct multi- physics coupled process models, and then we will test these models with large scale experiment. And once we've done that, we will put – we can use this, all lessons we learned to supply generic performance assessment model with a reliable conceptual model and parameters. And we can also provide generic PA model with valid test a constitutive relationship. And the process model itself can also be integrated into the PA model either directly or indirectly.

So, just to summarize my presentation, just a few key talking points. Actually participating in a larger scale in situ test for example, FEBEX in situ test conducted by international collaborations has significantly enhanced understanding of the alteration of EBS and then improved our modeling capabilities. And also, as we go through all those processes, the knowledge gap I think has been narrowed but there is more work needs to be done. For example, models and experiment at high temperature conditions, the multi-scale experiment and models, and also the integration of PA models.

Okay, that is all I have.

ZOBACK: Thank you. Do you – does Dave Bish have a couple of questions? You want to start? Or do you want me to start? Go ahead.

BISH: David Bish, consultant to the Board. Thanks for a nice presentation and you did a nice job of answering some of the Board's questions, I appreciate that.

I have some questions about several aspects. First, you emphasized nicely the need to have a good understanding of the constitutive relations, and for bentonite, that means a lot of different things and I wonder if you can tell me if you include – you include the volumetric changes as a function of change in H20 content, is that right?

ZHENG: We included volumetric change as a result of the swelling.

BISH: Right. Right. Do you – does your modeling incorporate as stepwise volume change at relative humidities below 100 percent? Because we know that is how smectite expands and contracts in a step-wise manner.

ZHENG: No. We are still not continuum any change.

BISH: OK. I thought you said you did.

ZHENG: Yes.

BISH: Yes. The data are clear that the layers expand by the thickness of a…

ZHENG: Yes. Yes. Yes.

BISH: OK. So just a linear. And then when you reach the osmotic swelling region, you continue to have a linear model?

ZHENG: Yes. Yes.

BISH: OK. OK. And…

ZHENG: So – maybe I can add to that, you know, the hydration of bentonite is a really complex processes, you can model from different scale. What you just mentioned actually is a microscopic phenomenon, we know the hydration layers and by stepwise.

Another way to simulate it from macroscopic point of view, the difficulty of simulating a couple of processes, you know, you have thermal hydrological, mechanical, chemical. If you'll simulate a mechanical process or hydrologic process using the microscopic crystal relationship, can't do the same for the chemical and also process. So, everything has to be consistent. So, the approach I'm using is, I have aligned everything in the macroscopic phenomena. So those relationships is largely macroscopic. So, we didn't simulate a stepwise based on continued phenomena. Yes.

BISH: OK. Do you also incorporate with that the variation of the amount of H20 that's in the smectite as a function of that volume change? I assume you do that because you modeled the H20 content.

ZHENG: Yes. Yes.

BISH: OK. So that's explicitly incorporated

ZHENG: Yes.

BISH: Do you consider the fact that the H20 and smectite have a different enthalpy of dehydration or hydration than liquid water?

ZHENG: No, we didn't.

BISH: OK. So that would – that would have the effect of dampening the temperatures to which you – that you reach, because to take a mole of H20 off of smectite takes more energy than to evaporate a mole of water.

ZHENG: Yes. Actually, a couple of weeks ago I look at this issue in how much can enthalpy change effect the thermal regime in a barrier.

But here, one of my thought is that in initial stage the thermal regime is still driven at by heat release from the waste package and is still moderately controlled by the conduction and the convection. So, yes, it might be interesting to look at, how enthalpy will be changed or affect, you know, the thermal regime in such a condition. Maybe very important, maybe not. Yes.

BISH: Yes. It would be interesting to try.

ZHENG: Yes.

BISH: The data are available. And lastly, one thing I think I – we mentioned to you in some questions is the issue of heating bentonite or smectite in a steam environment and the behavior of smectite, particularly the longer-term behavior, at say temperatures of 150 to 300 – 250 degrees is pretty well-known both from geologic data and from experimental data.

But there are some nice data actually produced probably 30, 35 years ago in relation to using bentonite as a backfill, showing some very large changes in the properties of bentonite when its heated even in – for short time periods in a steam environment, which means unsaturated. In some of the conditions that you modeled, you would – it seems that you would have had a steam environment. Have you considered that literature on the effects of steam?

ZHENG: I did read that literature before I started my modeling work. Actually – the issues actually is really complicated than I initially thought when I started modeling at high temperature in addition processes.

Now, a couple of things, for example, you know, in a geology formation is very evidenced the illitization. But if you look at the lab tests, you know, the conclusion is really not – so the findings is not so conclusive. For example, in Los Alamos National Lab, they have done a lot of high temperature heating process, heating bentonite to see if it is related to the process. And we didn't see any additional process.

Regarding that paper you found out, actually, his second paper repeat the same study and found out probably saw largest change actually is dealing with the steam pressure. So maybe interesting to look at it. Yes.

BISH: Yes.

ZHENG: So, yes. So, you know, as I mentioned, this system actually really complex. Variable mineral change and, you know, we need a lot of study to understand the fundamental interaction between the different – the water and mineral phase.

BISH: Yes. I'll make one more comment and I'll stop for a while. The reason that's important is that as you emphasized, one of the reasons for using a bentonite backfill is that its saturated permeability is very, very low.

It's used in lining reservoirs for example, and a short-term, and by that, I mean, four days at 200C above the liquid vapor curve will eliminate the ability of smectite to osmotically swell. So, you lose that major benefit by a very short-term treatment in steam atmosphere. So, it's an interesting thing at least for you to consider. I'll stop now.

BRANTLEY: Brantley, Board. One of your plots showed chloride concentration versus radial distance away from the center. What's the chloride coming from?

ZHENG: So, chloride – bentonite initially has higher chloride concentration.

BRANTLEY: Bentonite has high chloride concentration?

ZHENG: Yes. So, bentonite usually…

BRANTLEY: You mean naturally it has chlorine…

ZHENG: Really low – really low granite concentration. So, you imagine, you know, you have high concentration in bentonite and the granite has low concentration. When the granite infiltrates into bentonite barrier you first dilute area near the granite bentonite interstitial area.

Then they gradually push the bentonite water towards a heater, so it's kind of like concentrated near the heater area. Of course, there's a…

BRANTLEY: Why does the bentonite have high chloride?

ZHENG: Just when bentonite was mined, you know, initially it may – it may contain some of the residual chloride concentration from, you know, geology time, you know, it depends on the type of bentonite, you know, just for this type of fibrous bentonite.

BRANTLEY: It's like you have one mole per liter, that's a huge concentration, isn't it?

ZHENG: Well that part is no longer because initially bentonite has high concentration, also because there's evaporation process. Basically, you know, you've evaporate, you go through condensed…

BRANTLEY: All right.

ZHENG: …you know, the solution.

BRANTLEY: Right. OK.

ZHENG: Yes. And also, we will go through this evaporation and condensation process, you keep reinforce the concentration of chloride near the heater. So that's why it has very high concentration.

BRANTLEY: You also mentioned sulfate, where is the sulfate coming from?

ZHENG: Sulfate is initially in the bentonite contain a very small amount of gypsum.

BRANTLEY: OK.

ZHENG: So, it's like 0.2 percent. But at that amount will dissolve fairly quick as water infiltrate into bentonite and when it dissolves it has fairly high sulfate concentration.

BRANTLEY: And whenever I've done reactive transport models I never did thermo-mechanical. But when I do reactive transport, I always use surface area just as a fitting term, is that what you're doing also?

ZHENG: Actually, I used the reaction rate as a fitting parameter. You know, it is essentially the same thing. Yes.

BRANTLEY: Yes. OK. The other thing I was wondering, because bentonite is clay particles and such tiny particles, the particles themselves could move in water. Is that something that you think about? I mean, it happens in natural systems all the time, that the actual clay particles just move, they don't dissolve.

You know, maybe something dissolves around them and then particles can actually move in the water. Are you thinking about that? Is that important?

ZHENG: It could be an important process, we have fairly large fractures. Yes. But in this case, because the test that was conducted in area has, doesn’t have fractures, most of the bentonite is highly compacted. So, have rehydration, so this is not an issue in this case.

Although but it actually has been looked at in international collaborations, you know, about…

BRANTLEY: I mean, we see it in shale, weathering shale, like shale rock particles just move out of there and…

ZHENG: Yes. Other types, I’ve been look this issue. Yes.

BRANTLEY: And is your model similar or different than what your European collaborators are running? In other words, are there folks that you're collaborating with that are making models just like this or somewhat like this?

ZHENG: Some models are, but unfortunately for this coupled THMC model, we are still the only team. Although we joined, you know, for some guys SKB task force is modeling framework with multiple teams more than the same test. But because our limitation with some simulator, they couldn't do the THMC we’re still the only team doing that. But hopefully I hope there is more team can join us, so we can learn from each other.

BRANTLEY: OK, thanks. John, did you have any questions?

MCCARTNEY: Sure. John McCartney, consultant to the Board. I had two kind of comment questions.

The first is definitely I think you're going to have to develop new constitutive relationships for the higher temperatures especially for this issue of thermal volume change. I don't think that the bentonite is necessary is going to behave thermo-elastically once you go to higher temperatures.

Several people have seen like when you go above 60C you start to contract. So, if you're going up to 200C, nobody really knows what's going to happen.

ZHENG: Yes. Yes. I think with the first, you know, if it was for essential use, 100 Celsius can still work and, you know, I wouldn't be surprised if these are surprise coming out so, yes.

MCCARTNEY: So, it may be good to plan some experiments to calibrate some of these different model components. So that you have that planned out.

And the second was on your bentonite column, the multi-scale bentonite.

ZHENG: Uh-hmm.

MCCARTNEY: I think that's definitely a very important physical modeling approach to try to give you some additional data to calibrate your model, maybe using some inverse analysis. I'm not sure of your plans with that.

ZHENG: Yes.

MCCARTNEY: But I think it's important to try to capture all of the different phenomena that could happen during the test. Looking at the setup that you showed, it may look like you – going to be like the temperature distribution and then maybe the electrical resistance at the boundaries, is that the goal?

ZHENG: Yes. Yes, absolutely. Now that's the reason we have those column tests to – you know, to supplement the field test which help us to conceptualize the model, help us constrain parameters and it help us to try, you know, different constitutive relationship, at scale and you can – you know, if we can use the same concept, the same relationship in the large scale model, we will feel very confident in the future, when we model repository.

MCCARTNEY: Yes. So, I mean, the risk is that if other phenomena are happening like volume change or other things and you aren't measuring those, then you may lump them into another physical process.

ZHENG: Yes. That's the – that's the challenging part, to measure everything, and also, we have such a complex system, and also the process may interfere each other so you may end up with a model which can match with it but not exactly, you know, process would, what really happening. I think this is kind of like inevitable for modeling such a complex system.

MCCARTNEY: Yes. But there's some approaches that you can…

ZHENG: Yes.

MCCARTNEY: …physically sample the soil at different points.

ZHENG: Yes. That's why we know when you think about it, those multi-scaling experiment, hopefully we get evidence from other scale or tests, from other scale, so we can try to constrain the process.

Because you always have two uncertainties one is called the process uncertainty, which means which processes you should consider. Another is the parameter uncertainty, for example, it could vary, you know, couple fold. So if you have other evidence from other scales you can like constrain your process, then you can focus on parameter uncertainties. So, you kind of have both sometimes. Yes. Maybe really hard to nail it down the right model, yes.

MCCARTNEY: OK. All right. OK.

BAHR: OK. I think Tissa has a question over here.

ILLANGASEKARE: Yes. Tissa, on the executive Board. So, I have two questions. One is I like to explore a little bit what you mentioned about simple models and you said you like to start with a simple model. So, in this particular case, did you start with the simple model? What you are presenting was not a simple model.

ZHENG: By simple model that means just start with a TH model, just with thermal and hydrologic model assuming the permeability and porosity is constant. But the geometric would be the same as the field because I tried to explain a field test.

ILLANGASEKARE: Yes. Second question is that this came in the previous talks that one of the challenges, the constitutive two models. So, if you look at the coupling of TOUGH to FLAC, it seems like from the equation side, so in the previous slide, you still have the relatively permeability appears as separately in the – in the TOUGH code.

Whereas if you look at the FLAC model, I assume that the stressors and all that is going to change both structure and then it will affect the relative permeability function. So how do you – how do you incorporate in that coupling the constitutive relation themselves change because of the coupling? Do you understand the question?

ZHENG: Yes, I understand the question. So, of course, when porosity change, you know, your relative permeability function also your capillarity function will change. You know, currently we use one rather simple scaling function to consider the capillary pressure function change. But we didn't consider the change of relative permeability as a result of such a porosity change.

So, I think the challenge is, you know, there's too much nodes you can play with, too much things you can change and, and the field data is from a – is macroscope data. So, it might be interesting to look at, you know, if we incorporate the change of relative permeability as function of porosity to see how it plays out in terms of model results.

ILLANGASEKARE: And this is my last question, so a lot of the data you're showing are field experiments, but then you also mentioned that the constitutive models are pretty complex. And are you running any experiments just to look at the constitutive models? Just control condition, you know, traditionally you can get a capillary pressure saturation curve is simple. But any experiment been run to generate the constitutive models in an independent experiment rather than a field experiment?

ZHENG: Actually, for my model, all those relative, for example the relative permeability capillary function was measured independently by our European collaborators in the lab. So, what I'm using just their modeling, their measurement results. Yes.

ILLANGASEKARE: OK. Thank you.

BAHR: Other questions from the Board? From the staff?

EINZIGER: Bob Einziger, the Board staff. This is all new to me. I'm a physicist by trade, but questions, how long does a bentonite once it is in place have to maintain its capability of performing whatever safety function you're giving it?

Then, how do you take the data you've gotten from 20 or 30 years and extrapolate it to that timeframe? Do you have any evidence to show that, you know, in the longer timeframes there's not some mechanism becoming active that's going to change in the results of your model?

ZHENG: Well let me answer the second question first. FEBEX test is the longest as far as I know, the field test we have, is 18 years compared with lifespan of repository 100,000 years, it's getting really short.

So, this is one of the challenges of, you know, modeling a repository. So, the best thing we can do is to construct a model with fundamental understanding of the processes and test it at different scale from microscopic to large scale. Then get the physics right, then I think the scaling in the time is relatively considered scaling from – with some spatial scaling.

So how long should we like bentonite to maintain such desirable properties, how would I say, you know, as long as it is possible for the, maybe for the lifespan of the repository. Maybe someone can weigh in.

BRANTLEY: Did someone want to help – does someone have an answer for how long the bentonite has to last as a seal, as a buffer?

BIRKHOLZER: This is Jens Birkholzer. I really think it depends on your safety case concept and how much you rely on your engineered barrier versus your natural barrier.

So, in – and I think maybe my colleagues can talk about their respective safety cases. I think in a clay repository where your host rock has low permeability, maybe your bentonite in terms of retention capability isn't all that important in the end, one can test that again with safety case evaluations.

But the other thing I would like to say is that bentonite even in its hardened state is a natural material. So, there are analogs for bentonite and how long it sticks around in natural environments. What we don't know so well is what the early – what these perturbations do to a powder that hydrates while its heated, while its stressed, while it does all these things early on, that's kind of the stuff that we're testing with models that are somewhat at that time scale. So, you might extract what – from that point on, you might extrapolate looking at analog situations.

ILLANGASEKARE: Thank you.

ZOBACK: Can we hear from the Swedish and Swiss?

ZHENG: Yes. Irina, you want to – you don't want to weigh in?

BAHR: Well we are – we are at time for the meeting. So maybe this is something that people can discuss at the poster session which is going to follow this.

But before we have the poster session, we do have a time set aside for public comment, and I have at this point just one person signed up for a public comment.

BRANTLEY: But Jean, can we thank our speaker and let him sit down first?

BAHR: Oh yes. Yes. Actually, I'd like to thank again all of the speakers from this morning and this afternoon. It's been a really interesting and provocative set of talks.

We have one person signed up for public comment. After that, we will formally adjourn the meeting, but Bret Leslie will give us – after we've turned off the webcam, will give us a little introduction to the poster session that's going to be following this. So, Judy?

TREICHEL: Judy Treichel, Nevada Nuclear Waste Taskforce. I think the meeting has been really good and I'm so happy to see collaboration. I think that needs to happen and it should have started way back when we all started this.

I know that what you're talking about is sharing information and studying collaboratively internationally, and the question that keeps coming to mind is that in the U.S., we haven't integrated anything. There's waste being made at reactor sites, various utilities are going with different sorts of storage, they're using different – well, even different reactor designs.

So, all across the country you've got different kinds of waste forms, different sorts of burn-ups and we're now talking about storage sites, interim storage sites and those seem to be talking about also in a very individual way. It’s sort of like these silos with each thing. And the interim storage proposals that are out there are looking at something that may be very different from what is at the reactor.

And then when you get done with that and you get to a repository someplace. The design and the concepts for that also seem to be different as well. And so, I'm wondering with the research that's being done collaboratively, is there kind of standardization there that we really don't have in this country? Are they thinking about a particular waste package of a certain size? A certain type or a certain size and a standardized heat output? Or can you have all sorts of different sizes of packages at different heat temperatures?

The fuel maybe in different conditions inside those packages, and I'm just wondering if that matters with what's being discussed here? And I don't expect an answer. So, thank you.

BAHR: OK. Thank you for those questions, and there may well be people at the poster session who can discuss some of those issues with you. Since we have representatives from a number of different countries and also we have Board staff members who've been looking at the diversity of spent fuel in the U.S.

So, that is the end of the official meeting. So, we can turn off the webcam. Goodbye to people…

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