# UNITED STATES

# NUCLEAR WASTE TECHNICAL REVIEW BOARD

## TRANSCRIPT

## WORKSHOP ON RECENT ADVANCES IN REPOSITORY SCIENCE AND OPERATIONS FROM INTERNATIONAL UNDERGROUND RESEARCH LABORATORY COLLABORATIONS

Thursday
April 25, 2019

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

# OFFICIALS OF THE NUCLEAR WASTE TECHNICAL REVIEW BOARD PRESENT

## BOARD MEMBERS

Jean M. Bahr, Ph.D.
Steven M. Becker, Ph.D.
Susan L. Brantley, Ph.D.
Allen G. Croff, Nuclear Engineer, M.B.A.
Tissa H. Illangasekare, Ph.D., P.E.
K. Lee Peddicord, Ph.D., P.E.
Paul J. Turinsky, Ph.D.
Mary Lou Zoback, Ph.D.

## EXECUTIVE STAFF

Nigel Mote

## SENIOR PROFESSIONAL STAFF

Robert E. Einziger
Bret W. Leslie
Daniel G. Ogg
Roberto T. Pabalan

## ADMINISTRATIVE STAFF

Davonya Barnes
Jayson Bright
Sonya Townsend
Casey Waithe

# INDEX

# INDEX
(continued)

BAHR:  Okay.  So if you can take your seats, we're going to get started with the second day of the Nuclear Waste Technical Review Board's Workshop on Recent Advances in Repository Science and Operations from International Underground Research Laboratory Collaborations.  We need a better acronym for that.

ZOBACK:  No acronyms.

BAHR:  No acronyms.  Okay.

Yesterday, to open the meeting, I gave an extended version of introductory remarks including a considerable amount of logistical information. This morning I'm only going to make some very brief comments, mainly for those of you who are on the webcast who have just signed in for today and may have missed some of the points of yesterday's introduction.

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 the technical and scientific validity of DOE activities related to implementing the Nuclear Waste Policy Act.

The objectives of this two-day workshop are to review Department of Energy Research and Development Activities related to underground research laboratories and to elicit information that will be useful to the Board in its review as well as to the Department of Energy in its implementation of those research and development activities.

Today, I'll skip introducing the individual Board members. You can refer to the NWTRB Web Site; that's www.nwtrb.gov. And there, you'll find photos and bios of all the Board members.

So, I hope you all enjoyed the first day of the workshop. The workshop began yesterday with a presentation on the purposes and types of underground research labs and the kinds of research and development activities that are conducted in those facilities. That was followed by a series of presentations on programs in underground research laboratories in Switzerland, Sweden, France, and the United Kingdom, and that was followed by a facilitated panel discussion by the participants in those first presentations.

Then we heard from Department of Energy representatives who provided information on the Department of Energy's geologic disposal research and development program and how they are integrating that with international underground research laboratories. And then we had some specific presentations on Department of Energy research and development activities on the effects of near-field processes on engineered barrier integrity.

We also had following the webcast yesterday a very lively and productive poster session and I'd like to thank all of the poster presenters who brought your -- brought your work and thank all of the participants, the discussions were going on quite -- until everyone had to leave for dinner. So that was -- I think that was a very useful part of the meeting.

So, we've had an extensive exchange of information and we plan to continue that today.  Today, we're going to have presentations on additional Department of Energy research and development activities related to engineered barrier integrity, groundwater flow and radionuclide transport, research in -- related to salt repositories that are being planned and conducted at the Waste Isolation Pilot Plant and also an overview of the geologic disposal safety assessment framework.

And then we'll close out the workshop at the end of the day with a facilitated panel discussion on key issues and lessons learned from Underground Research Laboratory research and development programs.

So that's an overview of the general agenda for today.  We are scheduled to end at 5:00 PM.  As was the case yesterday, we will have an opportunity for public comment at the end of the day, if you would like to make a public comment, please sign in at the registration desk out there.  Also, we are happy to receive e-mail or written comments, any comments that are provided as part of this meeting will eventually be posted to our Web Site as part of the public record.

So, at this point, I'd like to welcome today's first speaker, Carlos Jove-Colon who will give a presentation on thermal implications of transport in bentonite using Full-Scale Engineered Barrier Experiment-Dismantling Project samples for laboratory studies and model testing. Thank you, Carlos.

JOVE-COLON: Can everybody hear me? Good. My name is Carlos Jove-Colon. First of all, let me thank the Board for having me here and listening to our presentation in the FEBEX-DP and work -- the phase characterization work that actually we did there.

I would like to also acknowledge my contributors, Florie Caporuscio from Los Alamos National Lab. Patricia Fox from Lawrence Berkeley National Labs.

As you can imagine, I mean, this is, of course, a collaboration between labs, myself, Clay Payne, Melissa

Mills, and Jessica Kruichak from the Sandia National Labs. Florie Caporuscio has been instrumental.  He's actually the person who has the laboratory and he does most of the experimental work.

I'm not going to be talking much about it, just one slide, but just to give you a nutshell on what we're doing. Michael Cheshire, he's right now at Oak Ridge National Labs and actually he was a post-doc of Florie a few years ago, but a lot of it the work I’m going to be presenting in terms of bentonite metal interactions, he was -- he actually was the person who was behind it.

Kirsten Sauer, another post-doc of Florie, and, of course, the group at Lawrence Berkeley that in one way or the other we collaborate a lot in terms of discussion, et cetera, and they're also involved in the FEBEX-DP project.

Just to give a quick recap of what is an engineered barrier system, I just here put two definitions which are actually very similar. For the United States Nuclear Regulatory

Commission, engineered barrier system means the waste package in the underground facilities.

If you go to the Nuclear Energy Agency, the NEA, the engineered barrier system represents the manmade engineered materials placed within a repository, including waste form, waste canister, buffer materials, backfill and seals.  Here is a cartoon courtesy of Jim Jordan at Argonne National Lab, basically just to represent a typical configuration of the engineered barrier system.  You have a bentonite buffer here, you have a reinforced buffer material underneath to sustain the canister load, then you have the waste canister here, then you have the spent fuel assemblies inside and depending on the disposal concept, let's say you're talking about argillite, you have a liner of cement around it in contact with the host rock.

So today we're going to be talking about FEBEX-DP.  FEBEX-DP is quite a  unique heater test in the sense that it ran for the longest time.  I mean, 18 years total.  It's kind of hard to come by with that type of heater test and basically the heater test, just two heaters in place and surrounded by compacted bentonite blocks, basically it's almost like assembling a puzzle.  And this compacted bentonite block is emplaced readily around the heater.

Heater number one ran from 1997 to about 2002, only five years.  After that, it was shut down, they excavated and they started sampling there.  But heater number two actually kept running and that's -- actually the focus of the talk today.  Heater number two actually operated for about 18 years and a lot of the samples actually from various labs and various organizations were obtained for a post-mortem -- what we call post-mortem analysis.

So, the goals.  Investigate the effects of temperature on bentonite clay barrier interactions.  This is important because we were talking about dual purpose canisters, these are larger canisters, more spent fuel assemblies and, of course you know thermal loads are higher which means they're going to be higher temperatures in terms of the decay heat.

So, temperature drives a lot of chemistry, hydrology, et cetera, and one of the things that we were looking for is to see what are the clay phase change and degradation reactions that occur in response to higher temperatures, is that impacting smectite swelling and, of course, structure and composition.

But also, we wanted to see what are the -- because of that, what are the actual effects of -- thermal effects of changing the chemical conditions in terms of uranium adsorption and, of course, diffusion. And basically, the reason for why we're doing this is to actually have a better grip and reduce uncertainties in terms of actinide diffusion and sorption, since -- actually when we conduct performance assessment modeling, these are important processes to be represented in these models.

This is a slide, this is a portfolio, Jens actually showed this yesterday. Just to give you an idea where FEBEX and HotBENT actually are located. FEBEX is actually in crystalline rock, but most of the research actually is dedicated to understand what happened to the engineered barrier system.

Again, this is a cartoon that Jens showed yesterday, and one of the things that we are looking in terms of targeting the thermal period actually where this red curve here is basically used to represent the temperature evolution with time, and most of the time we actually try to understand what's going on in the thermal period just because if there's something that happened there, it might impact anything that in the engineered barrier system that -- the performance in the engineered barrier system can be actually impacted for years afterward.

So, understanding radionuclide adsorption, the clay under realistic conditions, well, as I said already, the waste is going to generate some heat, but also you have groundwater intrusion interacting with the engineered barrier system, that causes variable saturation across the clay barrier from the heater surface towards the interface with the rock. That, of course, changes pore water chemistry, also there's going to be changes in the accessory mineral assemblage.

For example, you have carbonates or you have pyrite for example, those things can actually degrade, and also changes in the clay structure and composition.  For example, illitization that happens, of course, ion exchange.  And then all these things are going to be affecting changes in the aqueous radionuclide speciation, mineral sorption and swelling behavior.

In a nutshell, just to show you where the FEBEX- DP samples are focused on, this is actually heater number two and the section that actually Sandia got, I mean, each lab got kind of a different section, it's actually Section 49 which is close to the center of heater number two.  And what we did is to actually take the samples, conduct bulk composition analysis using x-ray fluorescence.  We actually recovered core from the cement plug in contact with the bentonite interface where we conduct x-rays, CT-scan, I'm going to show you some of that.  We also conducted micro XRF, basically a bulk composition analysis but at a thin section scale, also SEM EDS and XRD, many of the samples and, of course, thermal analysis.

Oops.  What happened here?  Can we go back?  All right. Sorry.  So, in the bulk bentonite XRF analysis, one of things that we noticed and actually it was not only us, the -- our European counterparts actually noticed the same thing, is that magnesium actually increases as you get closer to the heater surface.

At this point, we don't know,  I mean, we suspect that some exchange process of sorts, but that concentration of magnesium close to the heater surface is quite interesting, it's something that actually is reproducible in many of the samples that we did.  Calcium actually stays more or less within the plot of points.  I mean, I'm actually plotting here data from the European counterparts, just a comparison. The gray dots is the Sandia data.  And, of course, falls within the scatter of the data from other groups.

We conducted also SEM EDS in these samples, and I was actually looking forward to see if there's any magnesium rich phase going on.  I mean, there's something actually precipitating that was doing so in response to the temperature, for example close to the heater surface and I found none.  So, this is something that we're still investigating.

For the other components, for example, silica, I put here basically bars representing the data from just the range of data from the other groups, and pretty much fall for silica, sodium, sodium actually we have -- we’re at the detection limit of the technique, so we actually probably have to redo the samples using a better technique, but just because the uncertainties are too large.  But overall, they kind of fall within the scatter of the data from other groups.  Potassium also just the same, a little bit higher than iron but not much.

This is a map of the slides.  Basically, the way this is done, actually they excavated different sections of the heater and they basically sampled radially from different areas, and basically the Sandia samples are the ones -- Sandia samples are actually the lower left quadrant, and in the next slide I'm going to be showing XRD spectra for samples that are actually close to the heater surface.

And the reason is it’s like the samples close to the heater surface are the ones that are going to experience most of the brunt of the thermal load. And one of the things that I wanted to do is basically here in the bottom we have the spectra for the unheated raw FEBEX bentonite material and then stacked on top of those actually are the spectra for the -- XRD spectra for samples close to the heater surface.

And basically, I use two types of treatment to these samples, one is to glycolate it, just to make sure the smectite expansion is to a maximum. And the numbers actually we got in terms of what we call it D 001 spacing is consistent with that. And that is sometimes a result that is expected.

Anyway, as you can see, the maximum expansibility of the samples, even those close to the surface line not very well with the FEBEX bentonite which is, again, an expected result. I should mention that the FEBEX bentonite is about 90 percent swelling clay, smectite. So however, when we actually dried those samples at a 60 degrees C, I mean, as part of the treatment to do the oriented XRD, when we compared that to the raw bentonite, they are slightly shifted, and that shift actually gives you a slightly higher

D-spacing, now this is actually in terms of the sample treatment is consistent for all the samples that we did.

So, I'm using this as a baseline just to estimate the extent. What are the difference in terms of the swelling extent as you move away from the heater surface. So basically, showing a different form of what I've shown in the previous slide, again, glycolated samples they pretty much have the same D-spacing. However, when you actually do the same -- when you estimate the percent of swelling which is basically the difference between glycolated and dry, you get that slightly lower swelling extent for samples that are close to the heater surface. And the other -- the rest actually fall pretty much within the scatter of the data. We actually repeated many analyses just to make sure that this value here is actually consistent.

So, another thing that I want to mention is that the lower sodium extent also correlates with the marked difference in the composition of the bentonite. One thing that I also did -- we looked at actually is there were actually drilled cores through the cement plug after heater number one was actually excavated to extract samples, et cetera, they actually put a shotcreted cement plug, basically they have a core that goes through the cement plug down into the bentonite and they do an interesting and quite remarkable or recurring technique  in which they actually drilled cores around the central area and this is the interest of the -- and they actually fill them up with epoxy.

And they recover in a quite pristine state the shotcreted bentonite core with actually a very well-preserved interface.  So, we took this and conducted x-ray CT-scan and just to see basically probe what's going on in terms of the structure across the interface.  And it was interesting to see that there's a lot of cracks, pores, et cetera and this is what I call -- people call it craquelure or chicken wire micro-crack pattern which is typical of desiccation of clay.

And there's some embedded granular material but overall, the chicken wire pattern actually dominates throughout.  One thing about the CAT scan is actually you can try -- you can go in a 3D form and basically scan how these cracks actually extend, how they -- they collide with other -- basically intersect with other cracks, et cetera, and most of what you see is isolated pores, but also you can see that some of these cracks actually they kind of grow, but then they basically disappear as you go towards the interface.

Another thing that we did in here is micro XRF, basically it's a typical x-ray fluorescence technique except it is at a thin-section scale, this is a typical glass thin-section about 35mm by 24mm and this is actually being cut across the interface between the bentonite and the cement.  And the reason for doing this is mainly to see what is the distribution of calcium or the major components in the cement and how that actually goes across the interface.

So, what we found for example I'm showing here three x-ray fluorescence maps for calcium, sulfur and silica.  And for calcium, we can see that there is a noted decrease, I mean which is expected across the interface, but then we have a blip in here.  It's an increase and actually it's because there is a calcium rich band, it's kind of hard to see from here, but something that we did across -- I did across the same thin section using SEM EDS, by the transect that I'm talking about here is actually this line in here, it doesn't show very well.

But it's remarkable that actually you can see this calcium band pretty constant.  And then once you get into the bentonite region, everything goes back to normal.  So a lot of the so-called leaching across the interface in here is pretty much confined to the bentonite-cement interface.

So, this tells us a little bit about what might happen as a reaction front and at least for the samples that I got, I mean, it doesn't really go deep into the bentonite.  There are other work -- there's other work actually in which they see more of an extensive centimeter scale extension of the leaching zone.

So, this is actually a quite interesting thing, sometimes you cannot look too in a small scale because you can actually miss some of these features.  This actually is work that Florie Caporuscio at Los Alamos is doing, and this is not actually related to bentonite, but it’s also related to exposure of bentonite to higher temperatures and interaction with bentonite with metal.

And one of the things that we noticed is that for example, this is Wyoming bentonite, it has -- contains a fair amount of glass, at least the one from this side from the Colony mine, Wyoming and we noticed that when you expose this to temperatures above 300 degree C, you have a sodium chloride brine as a liquid -- the solution phase.  We actually generate analcime, which is a silica rich sodium -- silica rich zeolite.

And not only that, I mean in most of the experiments we actually managed to get, you can call it a solid solution or a compositional join in which you go from sodium rich to also calcium rich and by the way the calcium rich analcime is called wairakite, and basically the take home message in here is that depending on the solution compositions and the composition of your reaction rock, you can -- this actually widens the stability field for zeolites when they're reacting with clay.

Here in the upper right corner, this is actually the glass composition, this is silica aluminum ratio in the Y axis and also a kind of clinoptilolite which has a very similar composition to the glass. Anyway, one of the things that also we notice here is that almost it's little or no illite formed in any of these experiments.

Again, this is work in which Florie actually conducted experiments of this Wyoming bentonite interacting with the metal. And one of the things that we found is that you have this mantling or just covering of iron saponite which is a clay, and along with the iron saponite, you have also -- it's kind of hard to see here but there is inside those petals of iron saponite that actually growing perpendicular to the stainless steel surface, we found also pentlandite or sulfite phases growing on in there and it apparently occurs concurrently.

What is the sulfur source from, well, the brine actually used in this experiments contains some, but then we also realized that a lot of the pyrite in the bentonite degrades almost totally and is actually a consistent feature as a result of these experiments. Here we have the 316 stainless steel, we have the leach layer which is a chromite rich chromium layer. Then we have -- also sometimes we find some magnetite in here, it’s of course kind of hard to see, but then we have that iron saponite growing perpendicular to the stainless-steel substrate.

And one thing that I did is basically generate a high temperature Eh pH diagram and with updates in thermodynamic data, the thermodynamic analysis actually predicts that sequence in which you tend to oxidize your surface and then start forming all this passivation type of surface that you commonly see in stainless steel corrosion.

Okay. This is work from Patricia Fox in Lawrence Berkeley, again, Sandia got some of those samples from FEBEX, and she got actually those samples from Section 40A which is actually very close to the center of the heater test and what she did is basically take samples close and far from the heater surface, and essentially conduct sorption experiments -- uranium sorption experiments with it.

She actually reported results for two batches of uranium size less than 63 microns and samples are actually more pure, that it means that all the carbonate phases were removed and those are less than two microns. So, for the uranium sorption experiments as a function of pH, basically the samples that were closer -- the two set of samples are like the 95 degrees C which are closer to the surface, but then she also compared her results to samples that were in the cold zones that were not directly exposed to the heating.

And essentially you have about 10 percent lower sorption for the 95 degree C, the samples closer to the surface relative to those that were actually in the cold zones. And the same goes for uranium sorption as a function of dissolved inorganic carbon and, again, the same type of pattern, the samples that are actually were closer to the heater surface experienced a little bit of sorption -- I'm sorry, 10 percent lower sorption of uranium.

And there are possible reasons in here is due with the structure composition of the clay, the aqueous speciation, of course, of the uranyl in solution and although a relative fraction in clay montmorillonite is pretty constant among all of FEBEX samples, that also could be playing a role in here and, again, accessory minerals like carbonates or others. For the less than two-micron fraction which is actually samples that are more pure in terms of the montmorillonite fraction in the bentonite, again, you observe a similar behavior in which the 95 degree C samples have a lower sorption of the uranium, the same goes for -- and this is also as a function of calcium concentration in solution.

And the reason for doing that is to see, just to kind of eliminate potential impacts of calcium complexation with uranyl in solution.  But it tells you that independent of that, calcium complexation with uranium, the same lower sorption of uranium on those samples exposed to higher heating is being the same.  So -- and the same goes where as a function of dissolved inorganic carbon.

So, this -- the bottom line here is that this behavior actually persists even after purification of the smectite in the bentonite.  So just to summarize, again, this type of international collaboration activities provide unique opportunities, not to only obtain samples and data but these are actually difficult experiments are hard to come by. Particularly when we're looking for long-term effects, let's say for example, heating, on the engineered barrier, particularly bentonite which is the choice for backfill.

The characterization, sorption studies and post mortem of FEBEX-DP bentonite indicates, number one, magnesium enrichment in the clay when you actually go to the surface, so yes, there is an effect in terms of the change in composition.  There is a slight decrease in the bentonite swelling as you get closer to the heating surface.  Lower uranium sorption, for example, samples subjected to temperatures close to 100 degree C relative to those that are actually were left under ambient conditions.

Bentonite-cement interaction, cement leaching effects, they are or tend to be confined to the interface region.  In terms of bentonite-metal interactions with higher temperatures, the glass component in the bentonite turns into zeolites that increases silica activity or keeps it high and that probably prevents illite formation. Iron saponite growth grows perpendicular to the metal substrate, so basically the smectite fraction on the -- that is close to that interface with the metal not only changing composition but actually there is a phase change where that is aids in passivation of the surface, it's something that needs to be looked further.

There is little or no illite forms in these experiments and I have to emphasize that these high temperature experiments were done under saturated conditions. Anyway, this is -- this is it. Any questions?

BAHR: So, thank you. We have -- we have lots of time for questions and I'm going to turn it over to Sue Brantley to lead the questioning.

BRANTLEY: Thank you. That was great. Brantley, Board. This is obviously a really good opportunity to get some samples that otherwise you wouldn't get. So, I mean, it's a great example.

I just have a couple of series of questions, can -- you started with goals which I thought was great, how did you come up with those goals?  I'm interested in the process by which you defined your goals.  Were they given to you?  Did you propose them?  You know, how were those specific goals the ones that you decided upon?

JOVE-COLON:  Well the main goal about studying temperature is an effect.  I mean, it's something that -- it's almost like a gap in knowledge.  We -- you know, most repository science programs, they don't look at temperatures or at least by way of effect we have on bentonite for example or clay or barrier materials for that matter at higher temperatures.

So, starting from there is a knowledge gap and -- number one.  Number two, we also realize that in order to assess that, there is also knowledge gaps in other things like we don't know much about for example let's say, I cannot do an experiment, let me do some thermodynamic analysis.  There is no thermodynamic data high temperatures for clay until very recently.

So, if we are actually going to analyze the problem and in many ways whether theoretically or just doing experiments, et cetera, basically -- it was basically a key knowledge gap that given the conditions in which we actually are dealing with let's say high thermal loads, it's something that has to be done in my opinion and it's something that it might impact performance.

And especially when we are talking about reactions at EBS interfaces. EBS interfaces, for example, metal, bentonite, cement, bentonite. And why is that? Well, cement interface, that's where all the action happens. That's basically difference between two materials. So if there is any temperature-driven processes, reaction, et cetera, this is where actually we should be focusing on.

BRANTLEY: So, it was driven by you're looking at the problem, you're looking at the experiment that it was done and you're understanding of where the fundamental gap was in understanding…

JOVE-COLON:  Yes.

BRANTLEY:  …from your -- from your perspective, from your geochemical perspective.

JOVE-COLON:  Yes.

BRANTLEY:  Okay.  Thinking about the interface and your puzzle about the MgO, as you know, when one element leaves it can make another element become more concentrated.

JOVE-COLON:  Exactly.

BRANTLEY:  Oxide leaves and then -- so did you think about that because all of your plots were absolute weight percent as I remember, and if you calculate the normalized to something else, sometimes you can see what's actually happening and, a spurious increase could be rethought as just maybe that the MgO is just sitting there.  Did you think about that?

JOVE-COLON:  I thought about that and yes, because sometimes I would say, "Well, what is exchanging?"  I mean, if I have to bring more magnesium in, where is it coming from and this didn’t make much sense to me.

So, I know the FEBEX bentonite has magnesium in it to begin with.  So, I must be concentrating magnesium by getting something out like you just suggested.  So, I thought about it but I wondered, "Okay, so I'm getting something out, what is it?"  And then I have to charge bound and that is where I am stuck.

BRANTLEY:  Right.  You ended up still with a puzzle even though you thought about it that way.

JOVE-COLON:  Exactly.  Exactly.  And I know clays exchange even 100 percent RH to then to get into exchange, zeolites do the same thing, but I'm still puzzled in terms of how can I represent an exchange reaction in which I concentrate the magnesium that is already in the clay, but I need to get something out and then something to compensate, that's where I'm stuck.

BRANTLEY:  The other thing that I know could be complicated just from work that I've done is loss or gain of water.  So, it depends on whether your weight percent is on an ashed basis, now this is XRF I think.

So, the ashed and non-ashed, I don't think you're doing that.  But in other words, if you're losing or gaining water, that can also affect your weight percents.  And then if you're doing this on a thin section which I'm not -- you know, some of your work was thin section but some of it I wasn't sure, gain or loss of porosity can actually come into play.

JOVE-COLON:  Yes.

BRANTLEY:  So, what about those pieces in that MgO puzzle and those?

JOVE-COLON:  Yes.  For the XRF, I mean since we're getting -- we got a very consistent result, I mean -- and, yes, the loss of water might implicate, also we did thermal, we did TGA on these samples and the TGA was very consistent in terms of the water content.  You have to be careful…

BRANTLEY:  Across that interface, the water content…

JOVE-COLON:  Across the interface -- no, not across the interface, just with bulk.

BRANTLEY:  I mean, what I'm trying to say is all these things are coupled, right?

JOVE-COLON:  Yes.

BRANTLEY:  You're doing a weight percent…

JOVE-COLON:  Yes.

BRANTLEY:  …and it depends -- well, it was a weight percent -- it kind of depends how it was measured but the change in porosity across an interface could make a difference, the change in water content could make a difference, it's very…

JOVE-COLON:  Yes.

BRANTLEY:  I mean, as you know, it's very complicated.

JOVE-COLON:  I haven't looked at that.  I mean, I -- since for the micro XRF, the sample was pretty much kind of pristine and all -- I mean, it was very pristine.

I don't perceive the change in porosity to be that big, however, because I actually looked at other parts of the thin section, I didn’t show them here more into the bulk, not far from the interface and they were not that different.

So, yes, you're right.  I mean, the change in porosity might play a role in here.  Let's say for example, you have a higher porosity at the interface, you have big cracks and all that but for that matter actually I looked inside within the bulk and most -- you see, most of the gradients that happened at the interface and, yes, I haven't looked at that into a lot of detail now that you mention it but -- yes. I mean, it's something that I never thought it could be significant in terms of at least giving me an idea of what the depletion zones are across the interface.

BRANTLEY: And then last question for me would be, I've been learning about gases and the microorganisms and some of the posters last night were really interesting in that respect. Have there been gas measurements here or microorganism growth experiments in here?

You know, is that possibly, you got a very non-equilibrium system, you got redox active elements, microbes, that's what they do for a living, right?

JOVE-COLON: Yes. Well I don't know, first of all, how much organic matter is in the bentonite to begin with. Even microbes needs -- I mean, there's some food, I mean you're talking about the conditions of H2 for example generating there -- I don't -- I have to claim ignorance here because I don't know much about microbial studies on FEBEX bentonite.

BRANTLEY: Are some of the other people working on it? I mean, I -- you know, I can understand not everybody can work on everything themselves, but are some of the colleagues from your -- in this particular experiment think about that?

JOVE-COLON: Yes. I have to defer…

BRANTLEY: I mean, there are chemolithotrophs that, you know…

JOVE-COLON: Yes.

BRANTLEY: …they can -- they can fix CO2, so.

JOVE-COLON: Yes, that's true. And I have to defer that question to my Berkeley -- Lawrence Berkeley colleagues and to see if there is anyone. I think there's someone at Berkeley that is kind of looking into it. And Liange -- yes. Liange is actually going to comment on this.

BRANTLEY: I mean, it's very complex. I mean, not one person -- like one investigator can't look at it all. So --

and that's where this kind of collaboration really makes a big difference.

JOVE-COLON:  Yes.

BRANTLEY:  All right.  Did you want to say something?

JOVE-COLON:  You want to say something, Liange?

UNIDENTIFIED PARTICIPANT:  Yes.  Would you please introduce yourself and then…

ZHENG:  Liange Zheng from Lawrence Berkeley National Lab. Just address those questions.  Actually, it's -- maybe (Inaudible) more information about the test.

There's another group in FEBEX DP to look at microbial activities.  If I remember correctly, they concluded is the microbial activity is fairly minimum or moderate.  So -- and then regarding the gas measurement, they do have gas measurements in the FEBEX.  Some small diameter pipes have been drilled into FEBEX and maybe the gas evolution in the test, but as far as my understanding, when they drilled those holes, it also interfered the gas…

BRANTLEY:  Right.

ZHENG:  …local initial gas condition, so those information are useful but has to be used with a lot of caution, yes.

BRANTLEY:  Once you drill the hole, you've changed the system a little bit…

ZHENG:  Yes.  Yes.  Yes.

BRANTLEY:  To his point,?

ZOBACK:  Mary Lou Zoback, Board.  While he was speaking, I was curious.  I know nothing about geochemistry and I Googled FEBEX microbial activity, and there's a Spanish group that found microbial activity, did all the X things that you were doing, and attributed some of the observations and said that spores in the bentonite, dormant spores were reactivated.

BRANTLEY:  I'm sure there's organisms there at least below 120 degrees…

JOVE-COLON:  Oh, absolutely.

ZOBACK:  …so.

JOVE-COLON:  Yes.  And I believe that too.  One thing I want to add about what Liange says, you have to be cautious in terms of the measurements.  A lot of the samples next to this hole that was drilled across the bentonite to extract gas, the thermal analysis show it was like an outlier, those samples were really, really dry.

BAHR:  Yes.  Getting the -- getting good measurements is really hard but that's why it's brilliant to have this kind of collaboration.  I mean, it's good.  So, either John or Dave Bish, maybe you have some questions?  Yes.

BISH: This is David Bish, consultant to the Board. Very nice opportunity you had to use the FEBEX experiment. We don't normally get 18 years’ worth of field data.

I want to start out by trying to understand how you think your measurements mimic the conditions in the FEBEX experiment because as you said at the outset, the temperatures were set at 100 Celsius at the heater, and so naturally had a gradient and we've seen some nice measurements and the model results showing us that the temperature gradient is such that temperatures away from the heater are fairly moderate, mild.

And in addition, the degree of saturation is low towards the heater, only reaching maybe 80 percent, 90 percent relative humidity near the boundary. So, can you give us an idea about most importantly for me a maximum pressure that was reached. So, there's like a concrete, a shotcrete shield. Was the system under pressure or was it, effectively did you have enough cracks so that you were at the ambient pressure in the borehole outside of the shotcrete?

JOVE-COLON: Yes. From the top of my head, I don't -- I mean, for that particular, the shotcrete plug and the bentonite, I don't know if they put pressure sensors. Usually what they do, they embed this in the bentonite. But I have no idea. Right now, from the top of my head I don't remember. I don't think so, but I may be wrong.

BISH: Okay. Because I think that's a crucial piece of information when you're working with a hydrated system, whether what the degree of saturation is and it seems looking at it it's likely that it was probably maintained -- there were enough cracks and leaks that it was maintained near the…

JOVE-COLON: Yes.

BISH: …ambient pressure.

JOVE-COLON: It's a very good point in a sense that I cannot tell you if the micro cracks were mentioned is because of in situ or ex situ or just sampling itself, you extract that core and it equilibrates with whatever is on the tunnel.

So, it's a -- it's very hard to tell. I mean, and I think the same goes for -- you know, there were a lot of cores actually around that plug and they observed similar features and then these are my -- they were European partners actually and basically they didn't -- it's very hard to tell if those are actually very representative of the in situ conditions and which -- anyway.

BISH: So, given that, I was curious when I -- when I read some of your materials before the meeting and listening to you today, how applicable are the quite high temperature results, the 200C to 300C, I think one of them said 80 bars, another one, I thought I remembered 150 bar experiments.

So those are quite different from the kinds of conditions at FEBEX -- they're far from what FEBEX…

JOVE-COLON: Yes.

BISH: …has experienced.

JOVE-COLON: And, again I show you -- I put these experiments in here for various reasons. Number one, we don’t have -- you know, you only have few weeks or months to actually run experiments to certain temperatures.

Higher temperatures, your rates go up. So if we want to observe something in the laboratory scale, time, we actually crank up the temperatures and actually is quite helpful. Sometimes not directly representative of the conditions of the repository, but it tells a couple of things.

Number one, what might be the likelihood of observing clay degradation on lab scale experiments? Number two, the conditions of saturation a lot of those experiments were done and the water to solid ratio was pretty high. So that is also something to look about.

The thing is that when you do experiments directly relevant -- not relevant but directly representing the conditions of saturation and temperature, sometimes our autoclave experiments cannot go for six months.

BISH: Nothing happens.

JOVE-COLON: Not only nothing happens, something may happen but may not be, let's say a significant result. I mean, number two the difficulty of growing these experiments as well.

So usually, I don't know, I'm talking about as an experimental petrologist you know that I have to ramp up the temperature in order to observe some changes. We are actually talking about performance periods in the order of hundreds, I mean thousands of years and lab scale experiments at least will tell us something even if the conditions are not quite there, but we need to actually.

BISH: I encourage you to keep in mind a couple of your initial figures, the figures showing the experimental layout and the figures showing the temperature as a function of time, you've got hydration as a function of time.

But I think your experiments are quite far away from those conditions, so that I really wonder how applicable they can be, because as you and I have discussed yesterday, the highest temperature portion of these systems will be near the heater in the early times, those highest temperature parts of the system will be the driest parts of the system.

They will not be saturated and when you -- when you do reach the period, eventually a hundred thousand, a million years where you are saturated, the temperatures will be very, very low. Not quite ambient but they'll be probably judging by some of the modeling results below 50 Celsius. So, I understand the need to make things happen.

One more comment about your smectite work and comparing the smectites as a function of position and how high they were heated. I think your -- I believe your expansion measurements, but I think they're probably more related to what you did say you saw was essentially maybe you didn't use this term but you saw cation exchange. And the number one thing that determines the swelling behavior of smectite when it hasn't been altered to or partially altered to illite for example is the exchangeable cation in between the layers.

And we've seen several examples where there's evidence of sodium, calcium, magnesium migration near the heater, and I think you're probably showing evidence of that rather than some fundamental structural change. And you could easily do that in the lab, change -- if you change from a sodium dominant smectite to a calcium versus magnesium, the swelling behavior changes completely.

JOVE-COLON:  Absolutely.

BISH:  The other important thing is you need to do it at a constant humidity.

JOVE-COLON:  Yes.

BISH:  If you -- if you measure in this room right now, it's going to be pretty expanded because it's pretty humid, and you go outside and it's not so humid.  So be careful.

JOVE-COLON:  Yes.  Can I have an -- I just -- well, I would like to have an opportunity to respond to actually one of your comments, is that Okay?

BISH:  Okay.

JOVE-COLON:  One of the things to assess that effect of temperature and saturation and this is an idea that I have, I'm going to -- I think I shared with Florie a couple of weeks ago is to use cold seal, a cold capsule and then control.

Let's say you put -- you can seal a capsule under certain average or you can actually put a little drop of water. What I'm saying is just change the water solid ratio in order to represent or closely represent those conditions in a closed system and in a cold seal basically it's fairly easy, it's straightforward.  So, we have been thinking about this particular issue that -- so we are still -- first of all, we need a cold seal experimental set up and number two, we need to actually test and do experiments long-term, it has to be probably months and see if we actually observe the same thing as you observed in the high temperature ones. I mean, at least in that direction in terms of its…

ZOBACK: John, did you have any questions?

MCCARTNEY: Yes, very quickly. John McCartney, consultant to the Board. I was also very interested -- I found your presentation very interesting, in the cracking process. And so it seems that this cracking was in a very small zone and was in saturated bentonite.

JOVE-COLON: Yes.

MCCARTNEY: And I was first curious, was the bentonite actually the filler material or was it the compacted block? Could you discern that? Because it looked like the bentonite -- the images was filling in sort of the gaps in the shotcrete.

JOVE-COLON: I don't -- I think the bentonite was filling material. This is actually after the first excavating -- excavation, the heater number one, yes.

MCCARTNEY: Did you have the opportunity to also look at other images of bentonite closer to the heater?

JOVE-COLON: No, actually. We couldn't recover the -- it's kind of hard. I mean, the -- if we're going to make a thin section and preserve the texture as much as possible, it's very hard. But we -- in terms of the CAT scan, no we couldn't.

This one basically was epoxy, so it was actually maintained in terms of the integrity. The sample, the block samples, if you start actually cutting it just crumbles apart, it's kind of hard to maintain that texture.

MCCARTNEY: Yes. I think that's an important topic that could be considered in the future is try and image that behavior right at the heater to see if the heating process really affects the…

JOVE-COLON: Yes. And one of the problems is I try to actually cut as best as I can a slab or a sliver close to the heater and away from it and it was -- we couldn't. I mean, the -- we put in the wire saw, we tried many things, just crumbling to pieces.

MCCARTNEY: Okay. Thank you.

ZOBACK: Questions from the Board? Paul?

TURINSKY: Turinsky, Board. I'm wondering how you take your results and incorporate them into the safety case which is, everything is big, macroscopic in nature and your results are down at, not the ultimate extreme but quite a different scale, spatial scale.

Is this to inform some macro-oriented experiment or is it to rule out things and say, "No, we don't have to go there: or, you know…

JOVE-COLON: Well…

TURINSKY: …how does this feed into the final safety assessment?

JOVE-COLON:  Well number one for example is take uranium adsorption, which is you're going to have sub-models that actually is going to represent that process of the clay material grabbing some uranium.

TURINSKY:  Right.

JOVE-COLON:  But in the PA, sometimes you have bounds.  I mean, like for example, you have to sample -- let's say for example we call it KDs, how much uranium goes into the clay.

Well, those KDs, those are values, those are numbers and there's wide range of them.  I mean, there's almost like an uncertainty, let's put it this way.  So this at least tell us that if you're talking about bentonite exposed to a high thermal load, we should consider this range, let's say for example, of KD values for let's say if you're actually sampling let's say adsorption close to the waste canister, far away from it, I mean, it's a way of actually capturing the temperature effects on the adsorption for example as a process of -- or something that actually can be a safety function within the safety assessment.

TURINSKY:  Okay.  I was thinking in particular with John's questions on the interface out…

JOVE-COLON:  Yes.

TURINSKY:  …knowing those details of what's happening at the interface.  How that really impacts the more macro case.

JOVE-COLON:  And, again, it's something that the -- this is only a hundred degree C, we only need as you suggested, I mean things happen so close to the interface, but let's say dual purpose canisters, the thermal loads are going to be much higher.

So maybe that zone or what we call a sacrificial zone in the bentonite is going to be farther apart -- farther away from the interface or the heater surface, the heater canister surface.  So basically, it allows us to understand how far we're going to go in our assessment models to at least represent and actually reduce the uncertainty in terms of the chemical models that represent adsorption or any other interactions in the engineered barrier systems.

TURINSKY: Okay. Thank you.

ZOBACK: Any questions from the Board? Questions from the staff?

PABALAN: Pabalan, Board staff. Carlos, you mentioned sorption as an example of how you plan to incorporate process into forms assessment. You -- in slide 21 you presented some data on uranium adsorption on heated bentonite. Have you done any surface complexation modeling that would allow you to extrapolate the results from this limited set of experiments to something -- to extrapolate to the other conditions?

JOVE-COLON: I think Ruth Tinnacher conducted this surface complexation modeling, I have to actually consult with Patricia Fox to see if she has done and thus in the samples. And I think she has. I mean -- but I'm not entirely sure. I know that Ruth Tinnacher actually was looking into that and she used to work and actually the same as him.

PABALAN:  Following up on the -- my question.  You listed four possible reasons for lower uranium sorption.  So the experiments were done on heated bentonite samples which were crushed and sieved to less than 63 micron fraction, did you compare or maybe Patricia, I don't know if she's here and answer the question, can you guys compare the characteristics of the unheated and heated bentonite to narrow down the possible reason for the lower uranium adsorption?

The simplest explanation I can think of is there's a difference in the surface area of the heated and the unheated bentonite.  And that knowing that then you can probably scale the sorption, percent sorption with surface area.

JOVE-COLON:  Yes.  I have to defer that to Patricia as I'm not sure if she actually characterized surface area as a function of the size fractions that were used in the experiments.

PABALAN: Okay.

BRANTLEY: I'm going to return to Paul's questions a little bit. So, what he's wondering about is why we're interested in the reaction front which is whatever it is microns in thickness and centimeters or something.

That reaction front could be moving with time, I'm not sure I understand this well enough to know, if you have two time points, sometimes you can see where a reaction front is and even though it’s micron scale thickness, it might have moved between those two time points, there was a heater removed after a couple of years.

Do you have -- you know, again, I get mixed up about the details of all these experiments, but you have -- there was that experiment where they removed heater after a couple of years, is there any way to go back and look at that and compare it to this and see if their reaction front is moving?  Is that -- and I -- am I just mixed up about these two experiments entirely?

JOVE-COLON:  Yes.  Actually, you're talking about the core across the cement plug and the bentonite, right?  And those actually were unheated.  So, there was no…

BRANTLEY:  Oh, Okay.

JOVE-COLON:  It is actually a cold zone in the…

BRANTLEY:  Okay.

JOVE-COLON:  …in the drift.  In terms of if that reaction front moved, the gradients are so large.  First of all, the cement is going to be much higher pH and one of the reasons actually looking at this leaching effect is just because the clay is going to, it’s a silicate, it’ going to react to a high pH environment.

But also, calcium, and any kind of effect in terms of potential cation exchange across the interface, et cetera.

So whether that reaction front moved, I don't know. I -- once it equilibrates, I mean, I don't think it's going to be…

BRANTLEY: It just sits there.

JOVE-COLON: It sits there and there have been others, I think I may be mixing up. On the Bure side, actually they look at after 20 years the cement liner they actually cored through, but it was actually a core between the cement and the argillite and they were actually looking at how -- you know, how -- that reaction front, how far it went varies depending when you actually sample.

But there was -- if I remember the results, there was no indication that their reaction front actually moving back and forth. Just going one direction.

ZOBACK: Okay. We have two questions also. Go ahead.

UNIDENTIFIED PARTICIPANT: Someone else can go first, it's fine.

ZOBACK: She wants you to go first.

LESLIE: Okay. Bret Leslie, Board staff. So, I look back at your slide four and Sue asked the question and I don't think you quite answered it. The heater one operated for five years were -- when feedbacks of DP samples were obtained only from heater two.

JOVE-COLON: Yes.

LESLIE: So, what she was asking for was when the heater one was turned off, did you take similar samples next to heater one to look at the distance the reaction had proceeded into the rock or the bentonite and compare it to the one that ran for 18 years.

Now, if you don't know the answer we've got someone from NAGRA here who could really explain. So, if you don't know the answer, that's fine.

JOVE-COLON: Oh, in terms of what -- you know, in terms of what happened and that, no, I don't know the answer. I mean, for heater one…

GAUS: Gaus NAGRA, what we did see is that there is an extension of the front, which was called…

ZOBACK: Can you speak up, Irina? I have a hard time hearing.

GAUS: Yes. Between the sampling of the first heater which was not open for U.S. partners, so there was a group of E.U. partners who did that. They have sampled the interface and we see that with the excavation of the second one, there was an extension of the interface but it was very small.

Also, the first heater was taken out in 2002, so the characterization techniques have been quite different. So, it's not a one-to-one comparison possible with a kind of a linear extrapolation between the two sampling campaigns. But there is a -- it's clear that there was some reinforcement of the chemical reactions which took place on the interface.

I also have to say something else regarding the experiment, because I think this is really important in the context here. The FEBEX test was started in '98 with the aim to check the THM behavior of the bentonite and the emplacement demonstration. Now, at the last DP sampling campaign, a lot of other samples were taken, but the experiment was not designed to be gas-tight first of all, so there was oxygen leaking into the experiment which generated this mixed regime between the oxidized pockets and reduced pockets.

And it was not designed to -- for microbial sampling, but we decided that it would be wise to do so and there have been reports on microbes published, and we could see that around certain instrumentation, there was an intense microbial activity, but this was attributed to the fact that the conditions were oxygenized and were not representative for repository conditions.

So, the fact that the goals of the experiment slipped over the 20 years which is kind of logical, we have to be really careful what we take from the experiment and say, well, this is represented for repository environment and what is experimental artifact in that case.

ZOBACK:  Do you have another question or no?  Jean?

BAHR:  Well just getting back again to this issue of how much difference does a small zone of altered properties make.  If the heater -- the zone in which sorption distribution coefficients were reduced is a very narrow zone adjacent to the heater and you still have a large amount of the bentonite block in which the sorption characteristics haven't changed, how do you scale up that composite behavior in a retardation type of model?

Does it -- does a small zone near the source that has essentially, very limited retardation, does that really accelerate movement over the near-field when you have a zone of enhanced retardation that's adjacent to that?

JOVE-COLON: I haven't thought about it much. I mean, how -- you know, first of all, I need to know how big the zone is that got altered. And going back to the so-called sacrificial zone, it could be very narrow like you said, right, at the interface, it could expand more.

BAHR: And that's -- and from looking at the poster last night it seemed that that zone that had been impacted by the heating was very small.

JOVE-COLON: And -- yes. I mean, basically it's pretty confined there as well. So, yes, it's very small. How that actually affects, maybe the effect is minimal, it's just that we didn't know that until you actually look at the experimental results and analyze and characterize the samples.

So mainly the purpose here is to actually see how that zone extends. I mean -- and, again, these are 95, 100 C temperature, big temperature exposure. What would happen if we actually increase those temperatures? How far that zone will extend in which that probably rippled down to enhance transfer further down from the interface.

But you're right. I mean, the -- what we found so far is like this is actually a narrow, very narrow zone, which is expected. I mean there -- this -- there are very strong chemical gradients in there, there is different materials across the interface, so that's when you find -- that's when one would expect to have the biggest difference.

My goal is to actually see, I mean let's say HotBENT can provide in the future some information, I mean how far that zone of let's say sacrificial in quotes, I mean because that doesn't mean necessarily that the bentonite is going to stop sorbing but it's going to be impacted by heating.

BAHR: And how are you going to be able to project the growth of that zone over long periods of time? What kinds of process models do you need to be able to make those projections?

JOVE-COLON: Well, good question. One of them, what I would do is number one, if we know very well the temperature distribution of, from the heater surface outwards into the barrier, it would require knowing a lot about the stability of the clay as a function of temperature. I don't think today we are actually there.

Number two, there's going to be probably some other processes going on, exchange, et cetera, the clay stability will depend on its composition, its structure. So, to answer the question, right now I -- that's what I would do. However, are we going to get there sometime? I don't know. That requires very, very detailed information about the clay stability as a function of temperature.

BRANTLEY: Brantley, Board. Do you think geological analogs could help you with some of these? I mean is there -- I don't know because I’ve never thought about this before, but emplacements of lava flows into bentonite packages or something where there's long-term transformation. I mean, do you think geological analogs are useful in this context?

JOVE-COLON: I don't know any really geological -- natural analogs that actually represent the same. I mean, there are times -- the ones that we looked at is basically uranium mines for example in which there's -- let's say a caprock that is argillite for example.

We know that actually the uranium doesn't really migrate too far, but in terms like temperature effects and things like that, I was once looking into geothermal systems, I mean people have done coring, but that -- those are let's say too active, too perturbed. I mean there -- there's a lot of diffusing processes going on in here, geothermal system tends to be more convective and, I don't know if you can call those directly representative of what's going on here in a heater test.

Although there's convection here but there's a lot of diffusion control processes that I -- let's say as a natural analog I couldn’t find something that at least convinced me that it's going to be representative of what happened in the heater test.

BRANTLEY: I mean, we never have the perfect experiment. I mean, Irina just talked about how the fact that these experiments are being run and weren't even planned means that we never have the perfect experiment in geological analogs when you're a geologist. So, I'm speaking to the choir hopefully. I think geological analogs could actually be really useful in many cases.

JOVE-COLON: Absolutely. You know, in fact -- I mean what we started this sort of generic disposal -- generic disposal concepts work, one of the first things I did was to look at natural analogs and back in the day I even actually included those in a report and all that.

But, again, it was mostly looking at uranium -- for example, uranium -- natural uranium formations like Oklo natural reactors, you know. And the role of the argillaceous or clay rock around it. So, it was -- I was mostly looking at for -- you know, these things have been confined in many ways for a very long time and uranium doesn't seem to transport that far from the ore. So -- but in terms of the heating aspect of it, that's the part that…

BRANTLEY: I know the Columbia River results of paleosols and then lava flow, paleosol , lava flow, I mean that's like heater placed right on top of a paleosol over and over and over again. So, I don't know, maybe this is not the kind of thing DOE does.

But the geological analog is a piece of the puzzle as Irina said yesterday. Are there any more comments? And does anyone in the audience have a comment? I mean, we're talking about experiments in Europe -- yes, by all means. We have a couple of minutes here before we're finished. I mean, I got all the questions right from the Board and the staff and our consultants.

BIRKHOLZER: Jens Birkholzer, Berkeley. Since we have the time, I want to quickly go back to David who is asking about the experimental conditions and the high temperatures, maybe not completely in agreement with conditions that you might have in a hundred degree max repository.

I think there's something to be said to go to envelope pretty broadly to see where actually -- do you see detrimental effects, right?  So, you might get to a maximum temperature, to certain the chemical conditions that you wouldn't have and that's a good result because it tells you 100 degrees, I don't have detrimental effects.

So, you have to kind of envelope and I think that's what's done.  In any -- in a way, we're planning HotBENT with the other teams which is a big field experiment where you tried to bring all the realistic aspects in, but  we're facing one question, it's done at Grimsel Test Site, the water flowing into that bentonite is pretty dilute compared to what you might have elsewhere because it's fairly close to the surface.

And then the question is should we in fact change the water chemistry to -- which would perhaps be more prone to some of these minimal alterations, and we're still trying to figure out should we actually push that test towards potential detrimental reaction or shouldn't we?  We haven't decided yet.

And maybe quickly back to the question of the -- you call it a sacrificial zone, we could put some of these results in a performance assessment model and see if you have a zone with maybe less sorption, ten centimeters, five centimeters, twenty around your canisters, what would that mean really in radionuclide transport and performance space?  So, something like that could be done just like if you have a big -- a damaged zone that is existing overlong and doesn’t heal and seal over long periods of time, you might have some effect of transport and then diffusion further away.

So, some of these if you have estimates, you could place that into those models that Emily will talk about later.

BRANTLEY:  So now we have a line of people that wanted to speak and I don't know…

BAHR:  But we actually are at time for this.

BRANTLEY:  Okay.  So, can I just say one thing here really quickly, because we didn't get to introduce you and I didn't want to give that short shrift. Dr. Carlos Jove-Colon got his PhD at Stanford University in Geological Environmental Sciences, 20 years of experience, geochemical modeling, fluids, solids. So, I just wanted to give you the credit that you deserve. Thank you.

JOVE-COLON: Sure. Thank you.

BAHR: So, I believe that the -- are you going to introduce the next speaker? Okay. Mary Lou is going to introduce --

ZOBACK: Mary Lou Zoback, Board. I'm acting as Tissa's voice again today.

We're now going to hear the third in the DOE talks on Engineered Barrier Integrity Activities by Jonny Rutqvist from Lawrence Berkeley Lab and he spoke yesterday. I hope he was properly introduced then.

His title is gas migration in clay-based materials international collaboration as part of the development of coupled models and their validation against experiments project.  Thank you.

RUTQVIST:  Thank you.  So, I will first introduce the team. We are a relatively small team working on this and we actually started on only a few years ago, so it's a team from Lawrence Berkeley Lab and also from Sandia National Laboratory.

Also, in the project we have -- we are working on the DECAVOLEX project and with the task, leading this task with the international project is Jon Harrington from British Geological Survey.  So, he's really a world authority on gas migration in clay and claystone and he also provided the experimental results for this.  And so he's an experimentalist and also dealing with task in the DECOVALEX. And then we have eight research teams in the DECOVALEX product who's working on this data, trying to understand the data.

So, I will talk about sources of gas migration.  So, I'm not a geochemist, I don't know much about it but I'm just restating what are already in the literature and then having those sources.  Then we -- for -- as a -- for when we model the gas migration, needs to be provided by a source, like the rate of gas migration -- rate of gas generation when people think of the models.

So, this could -- so the sources could be corrosion of metals, radioactive decay, radiolysis of water, and also as I understand, microbial activities. So, if the production then exceeds the diffusion capacity, you can form a gas phase and this can actually migrate into the engineered barrier system and host rock if you achieve sufficiently high pressure.

So, understanding the gas generation and migration is a key issue for assessment of the repository performance and thus it is explained in the next slide.  So, this is a cartoon from the, actually I took this from the Swiss concept of nuclear waste repository in argillite and at that what the gas is kind of the gas generation and gas pressure buildup might change the system.

The question is, where will the gas go if it's produced? Actually will -- the rate of gas production and this is actually related to the rate of gas production versus migration and the release.  Will you actually increase the pressure so much where you can actually fracture the rock or can you damage the excavation disturbed zone if gas is -- high pressure gas is going in through the system here and through the seals in the system.

Also could gas actually dehydrate the buffer.  If you dehydrate the buffer, you may not develop swelling pressure in the system.  And there’s also a question of colloid transport and erosion of the buffer material in this gas migration, and microbial activities I think you saw a poster yesterday where it says that actually microbial activities consumes some of the gases that are generated.

So, this is for the importance of the -- this issue for the performance.  Here we see this figure again.  So, we are -- we are -- what I'm going to talk about today actually -- is actually gas migration through the EBS, so through bentonite.  And this here you can see where it is located.

So, it is located a little bit further on in the system, and this kind of gas generation maybe can become more important over time.

So, the state of the art, so transport of gases in clay-based material has been the subject of several international projects in the past.  LASGIT is the large-scale gas injection test conducted at the Äspö Hard Rock Laboratory in Sweden.  FORGE is the fate of repository gas -- gases and this is a -- was a European Union collaborative project to study this kind of phenomena.

So substantial insight has been gained on gas transport, but still the basic mechanism for gas transport in bentonite and lower permeability host rocks are not understood in full detail, so therefore the predictive capabilities are still quite limited.  And so, this is something we are now trying to develop along with participating -- participation in DECOVALEX 19, 2019.

So, through this collaboration then we have access to experimental data for modeling, testing, and validation.

So, this is quite useful for us since we just started this work some years ago.  So, this is the DECOVALEX 2019 task, the purpose is to better understand the processes governing advective movement of gas in low permeability material, this could be bentonite and claystone.  So far, we have a -- in DECOVALEX we have a focus on the bentonite.

And this is a conceptual picture on different mechanisms of gas transport in low permeability clay material.  So, if you go from this end to this end, so here you have a more basic -- more basic gas migration.  So, this is a fully saturated sample from beginning and then the green color represents the gas phase.  So, you can have in this case if the pressure is not very high, you might have diffusion dominated, so advection and diffusion of dissolved gases like a continuum into the sample.

And then they have a more complex processes as visco-capillary flow of gas in water phase, so this is a two-phase flow, you may have fingering developing like this if it's heterogeneous and gas can migrate over to the other side.

The third one is the dilatancy controlled gas flow, so you can form pathways through the -- through the medium between the particles and if this happens maybe when you get close to the injection but when the pressure -- gas pressure gets close to the minimum principal stress in the -- in the medium.

And then if you -- if you increase the pressure, gas pressure much higher and maybe if you don't have less confinement on the medium, you might actually develop a pure hydraulic fracture, Okay, like similar to hydraulic gas pressure.

So, these are the -- these are the mechanisms we are studying and maybe somewhere around here in the -- in the experiment we are studying.  So, the experiment is provided by the British Geological Survey, also they provide expertise and lead the task 2019 for this -- for this task. There are eight research teams from eight countries participating, and these are listed here, so there are country -- there are research teams from Asia, Europe, and

United States, so the DOE-supported teams are LBNL and Sandia National Laboratories for this DECOVALEX task.

So, these are the experiments we have been studying so far. So, this is a test cell BGS, British Geological Survey, test cell and here is the bentonite sample itself. So what you do here and this is MX-80 bentonite from Wyoming they put in the bentonite into this cell and confine it and saturate the bentonite with water and this then develops swelling stress to kind of mimic the conditions you have in a bentonite buffer in the field, you have a fully saturated and fully developed swelling stress at that time.

Then they inject hydrogen gas, and thereafter monitoring the pressure, gas flow and stress during four months. So, there are two types of tests, one is the 1D gas flow test and the second one is the radial gas flow test.

So, for the 1D gas flow test they inject the saturated sample and then inject gas from this side and measure the outflow on this side. They also measure the pressure at several locations inside the sample as well as stress on the radial boundaries of the -- of the sample.

For the Stage 2A, the radial gas flow test, they inject gas into the center of the sample and they measure of gas flow out from this monitoring points along this kind of rings at the radial -- some radial -- at the radial boundary at different -- three different locations.

ZOBACK:  Excuse me Jonny, how large is that sample?

RUTQVIST:  How long?

ZOBACK:  Yes, the size?

RUTQVIST:  It's 120 millimeter long and 60 millimeter -- 6 centimeter barrier, 12 centimeter barrier.

ZOBACK:  Thank you.

BAHR:  Are those the same samples for the two tests or are they different samples?

RUTQVIST:  Is the -- yes, it's the same material.

BAHR:  But is it the same physical sample or do you replace the sample…

RUTQVIST:  No, it's a different -- two different sample but exactly the same material.  And it’s the same -- the same test equipment, it’s just that they inject at different points.

Okay.  So, I will describe one of these test data which is very complex.  And I will try to describe it.  So, this -- what you see here is the evolution of stress, gas pressure, and injection flow rate and outflow during 120 days of testing.

So, if you will see here, here you have a pressure or stress magnitudes, given in kilopascals.  On this access you have a gas flow rate given in cubic meter per second at standard conditions.  So, if you first, up here you have stress and then you have some pressure and flow rates.  So, if you --

if you -- from beginning, this part here, so you first emplace the bentonite into the sample and secondly, we saturate the sample and develop swelling pressure. So, they saturate the sample from all sides here.

So, what you see then here is that the stress goes up like this, up to a certain level, we are measuring both axial and the radial stress and the axial stress is a little bit higher because they also -- they also can push on the -- on one side of the sample to actually increase the stresses that way.

So, what the stress develops to about six mega -- six -- between six and nine megapascal of stress measure at the boundaries of the sample. So, this is during the saturation phase, there's no gas injection during this phase. Then at some point you start at this point, you start to increase the gas pressure at this end of the -- of the sample.

So, increase the gas, you inject the gas into the system and this means that the -- that the gas pressure increases slowly in this chamber here. But no gas goes into the sample still, because we are measuring -- we are measuring gas pressure away and at these points which is these curves and during this initial phase, which is from 40 days to 60 days, we just increase the gas pressure here, but nothing actually goes into the sample.

And then when the -- when the injection pressure, gas pressure reaches about 10 megapascal, there is sudden pressure response inside the sample, it is shown here, going up there, these are pressure measured at this point, here in the sample, you can see all of these points, the measure, a sudden increase in pressure.

Some days later, they also measure outflow of gas from this end here. So, this means that there is a sudden breakthrough of gas into the sample, takes some days and then it reaches this side of the sample and you have a gas outflow. Some days after -- sorry. So here they increase the injection pressure and then they actually shut in the system, they don't -- they don't inject any more gas, they just keep the gas volume constant.

And the gas -- actually the gas pressure then goes down as gas flow is moving through the sample.  And what you see also here that actually that this strong gas outburst is shut down very fast almost completely.  But there is some remaining pre -- there's some remaining small gas flow seeping through the sample still here, but much less than this breakthrough we have here.

And there is pressure and stress in the sample also develop declining slowly with time here.  So, this is one experiment we are trying to model, and you see there is a quite complex.  So to model this, so we are using two different approaches for LBNL, so the one simpler approach is to use a continuum model, similar code as I used yesterday but we are considering the gas -- that gas flow can go through the medium, break through the medium as fracture dilatant gas flow.

And this is simulated by changing the permeability or kind of in an aperture fracture-like behavior.  So you have an aperture, depends on this dilatant flow path depends on the effective -- minimum effective stress, and if you increase the pressure so you are -- so you are close to the -- effective stress become close to zero, you get the increase in permeability because we are small fracture opening.

Another important thing in this modeling is the gas entry pressure, this is preventing the gas from going into the sample in the beginning.  And we also include some moisture shrinkage into the system to -- this is to – actually to be able to model the stress evolution.

So, this is the simulation results for the continuum model, so we use a 3D model like this and in this case, we assume homogenous material, we don't put in any heterogeneity at this point.

And this one shows the evolution, the contour of pressure, litho-saturation and vertical strain just before you have a gas breakthrough.  So, you have some gas entering the system but the -- it's not sufficient to actually -- to have -- before we even get this flow going out of the sample. You have -- you have started to break through into the sample but there's no outflow here because there's nothing over here.

And what you see here, so you see that the solid lines are the data and the dash line are the modeling. So there, you can almost not see them because they are a very good match to the -- to those experimental results. So, what you can see here, we can simulate this very abrupt gas breakthrough and the gas pressure goes up and then it goes down like this. And to simulate this, we really need to use this kind of gas entry pressure into the model.

The peak, and then we look at the gas flow. So, you can see that the red is the measured gas flow, outflow through the sample. Green one is the modeled. So, what you can see is that we match quite well the starting point and the peak after the -- you don’t match this shutdown that you see in the experiment. So, the flow and stress actually after the peak, we did not -- did not match perfectly, but the magnitude and the start we matched quite well.

And this is a simple -- quite simple model, several calibration parameters should say to calibrate how this -- how the flow -- the flow goes into the sample through this stress permeability relationship.

The second modeling approach is the discrete fracture model approach.  This is called the rigid spring block network. So, you are connecting -- you're creating a initial mesh like this and you can actually create fractures below. Below -- behind or between these Voronoi elements.  And both fracture and matrix can deform.  Fracturing represents a breakage of springs, lattice is experiment linking the adjacent cells.  And fracture permeability depends on the aperture.

So here is the one simulation result for this.  So, we can see the -- if you saw from the beginning, I think it's going to start again.  So, we can see the -- this is when they inject at the center of the sample.  You see the dilatant flow path developing and spreading towards the boundaries. And as you remember, the outflow in the -- in this kind of experiment where they inject in the center is actually measured at the -- at the boundaries here.

So, you measure injection flow rate and outflow rate as well as injection pressure.  So, these are some dilatant flow path created for (Inaudible).  And you see the same thing up here and then you can follow the pressure evolution for the modeling and the experiment here.  For the outflow, it’s really -- this is the -- the blue one is measurement, so you see there’s oscillations like this.

In the model, it’s more smooth, but we can -- we can capture the general lens of the increased inflow and outflow and then declining.  We also have stress results and those are following the measurement results but they’re more -- actually more difficult to fit.  For the DECOVALEX teams, eight teams, there are many -- a wide range of approaches including two phased flow continuum models, preferential flow path in continuum models, discrete fracture approach, which is only our team did apply.

And then Sandia National Laboratory, did something called chaotic dynamic model to study this chaotic phenomena of oscillating pressures and flow rate.  Some model fits the data better than others.  I mean that -- and but these -- some of them are models, Okay, if you look at microscopic changes and then you may calibrate some parameters to fit the data, but it doesn’t mean that it’s correctly -- models, they underlie in micro, macro scale mechanics.  And also, the question if it can be up-scaled to apply the -- in the repository field scale.

So here is a -- is a fine -- it is detailed study -- detailed picture of a -- of a bentonite.  So, you have the pore size diameter and the pore size distribution here.  So, what we’re seeing -- typically see is that there is two types of porosity.  One is the micro-grain, micro-pores in here.  The second one is the macro-pores between these bentonite aggregate -- or between the clay aggregates.

And the gas flow actually tends to go through these kind of -- the macro-pores, but it is also impacted by the micro-pore changes during this.  This is probably something you’d keep in mind when trying to model the underlying mechanism. And they have also actually started in great detail to actually confirm that you can have this kind of discrete flow path going through the medium.

This is gas injection with nanoparticles along a flow path here. So, they can see the nanoparticles migrate along here and then the flow path is sealing out diversion and trapping in those particles. This has been demonstrated actually for a Boom Clay from the -- from the site that, in Belgium. So, for future model development, we are thinking about -- we have this dual structure modeling in TOUGH-FLAC. We should -- could utilize that into the continuum model to model the different structural levels.

TOUGH-RBSN, it could include sealing and healing of flow path to try to simulate that shutdown of the flow, but these needs to be validated against field data maybe and possibly applied to large scale. So, what you’re also looking forward to is to -- for DECOVALEX-2023, they’re going to maybe be an extension of this work, where we look at large-scale gas injection test at the Äspö Hard Rock Laboratory.

And so, this is also a good opportunity for us for -- through the international collaboration to get access to a unique data set for model validation at a relevant field scale.  So, this really is a very good way to test the model so that we really can apply them at the repository scale.

And for the input to the performance assessment, this could be that we simulate this kind of the near-field gas processes and see if you have damage to the system, this will inform the PA model of this kind of development of created flow path, the change in flow properties to the large-scale model.

Just to summarize, so study of gas flow migration has been a topic of many international studies, increasingly so over the 5 to 10 -- last 5 to 10 years because it has become a hot topic in many of the programs over the world for nuclear waste disposal.  Still, the basic mechanics of bentonite and alternate host rocks are not understood in full detail.  You see it’s very complex and it’s difficult to know what’s really going on inside a sample where you measure things on the outside of the sample.

And therefore, still predictive capabilities are limited so further work should strive to better represent the underlying physical mechanics I think to -- such as the dual structure behavior, but still needs to be applied at the repository scale.  And this kind of projects -- international project such as DECOVALEX really provide an avenue for faster capability developments through exchange of ideas and collaborations and through access to experimental data.

So, this has been really helpful for us, because it started just a few years ago and then we could tap in to all this knowledge that has already been developed in European programs.  Thank you.

ILLANGASEKARE:  Thank you very much.  Thank you very much for the, Tissa Illangasekare, Board.  So, I actually -- I think I agree, fully agree with you that there are lot of need improvement to understand the physics and your conceptual models.  So, my question has to do with the conceptual more in the context of the traditional thinking of diffusion and advection because we are familiar with diffusion and advection in traditional porous media.

RUTQVIST:  Yes.

ILLANGASEKARE:  So, in your -- in your figure -- slide 9, if you -- if you look at this, so you are basically using the word diffusion there.  For me, diffusion -- the traditional thinking is molecular diffusion, but the question I have for you is that when you look gas migration, is it going to be always an advection process?  That's question number one.

Second question is that in this conceptual model, you assume that the gas is already formed, but some of the work I have done in my group, we are looking at gas formation itself. You have nucleation for the gas to form as a phase.  So, when you become a traditional continuum two-phase flow, first the continuum has to be developed.  Can you expand on this idea of traditional diffusion?  Is it -- does the diffusion exist or it's mostly advection in these systems?

RUTQVIST: I guess there could be both diffusion and advection. So, advection -- maybe this is advection of gases in the -- is all in the -- in the liquid talking about here I think. And then in addition there is -- could be also be diffusion.

ILLANGASEKARE: So, the diffusion happens -- like if you go to the next figure, the diffusion happens in the -- in the matrix and advection happens in the fractures, is that correct?

RUTQVIST: I think in this case if you go to this one...

ILLANGASEKARE: Yes.

RUTQVIST: ...here you develop this dilatant flow path between the -- that opens up, you get the...

ILLANGASEKARE: Yes, yes.

RUTQVIST:  And then you have some changes in the -- in the aperture or porosity where it is -- these are very small changes.  I see some -- what they calculate this apertures, they calculate this not really like a fracture, it’s like a fraction of a micrometer or nanometers opening of fractures. In this case, very small.

Whereas, here, I think it’s more like you have a -- if you have heterogeneous clay material -- this is not completely homogeneous, you will develop this kind of fingering of the flow path.  It’s either, for example, the capillary pressure and function I think so will not be all homogenous, you will develop this kind of fingering for the gas flow into the sample.

ILLANGASEKARE:  So that is dissolved gas or other...

RUTQVIST:  Well, in this is your injecting gas in the sample here from this.  It is just pure gas.

ILLANGASEKARE:  Pure gas.

RUTQVIST: Yes, but the sample is fully saturated with water from beginning.

ILLANGASEKARE: Yes. So, the gas...

RUTQVIST: Of course, there might be some dissolved gas in the water.

ILLANGASEKARE: So, the gas dissolves into the water now.

RUTQVIST: Yes, I'm sure there are -- could also be gas dissolving into the water, yes.

ILLANGASEKARE: Okay. So, then it brings our next figure so...

RUTQVIST: Okay.

ILLANGASEKARE: So now, when you go to the fracture then you have had entry pressure as one of the parameters, which determines that the gas is going to go back to the matrix. Is that correct? So, gas, the entry pressure...

RUTQVIST: Yes. The gas entry pressure, it’s for the whole sample, for the -- for the whole in my -- in my model, I mean I'm using -- I did not consider two different levels, so in my model -- in both models here, you have the gas entry pressure, which represented the equivalent continuum medium including fractures and the -- the fracture -- these fractures, or if you can call it fractures, does not exist from beginning, they form due to increased pressure in order to gas at all be able to penetrate the sample, you need to exceed that gas entry pressure. So maybe it represents more closely kind of a matrix for…

ILLANGASEKARE: Capillary pressure saturation is for the matrix --

RUTQVIST: That was capillary pressure curve measured as about for bentonite.

ILLANGASEKARE: For the bentonite.

RUTQVIST: And then we apply gas entry pressure.

ILLANGASEKARE:  Yes.  So, when the gas enters the formation, you are still assuming that it’s going to be a continuum, like it’s going to be a – bubbles.

RUTQVIST:  So, in my continuum model, that’s the continuum, in the discrete fracture model, we assume there’s forming discrete fractures.  There’s two types of models.

ILLANGASEKARE:  So, the discrete fracture model, these bubbles move as -- still as a continuum, they are connected, not bubbles, individual bubbles, they are just moving.

RUTQVIST:  It’s a connected path -- connected at gas flow path.  I don’t think they seem like bubbles, but it’s kind of a connected flow path and it -- you actually create the flow path by failure, so it could be shear failure or tensile failure in this small flow path and when you…

TURINSKY:  So that -- does that crack initiate that point because you put some defect on the surface, to cause a...

RUTQVIST: The what?

TURINSKY: ...higher stress there? The initiation of the crack itself...

RUTQVIST: Yes.

TURINSKY: Okay. How do you decide its -- how is its location decided? Do you put a defect on the surface?

RUTQVIST: So, the -- we did not -- we did not put in any heterogeneities into the model here...

TURINSKY: Okay.

RUTQVIST: ...but still you have a discrete fracture model and you have -- it will be some -- it will be one point, you will first initiate fracturing depending on the direction of the crack at the boundary or at the --

TURINSKY: So, the initial -- the initial condition has a crack there to begin with?

RUTQVIST: There is no crack. There is a -- you put in an element in the model, but the properties of that element is same as the properties of the matrix, so it’s we assume in a way that there’s no crack there from beginning. The crack only forms inside -- through these elements, not...

BRANTLEY: You should show slide 15 in this respect, right?

RUTQVIST: Hmm?

BRANTLEY: Shouldn’t you show slide 15 in this respect?

RUTQVIST: Yes, yes. Oh, yes. You’re right. Slide 15. Okay. So, for the -- what you call the discrete fracture model, so actually this is the -- this is the mesh, here you see these are Voronoi elements. This is a Voronoi element. And then the Voronoi element is connected by these kind of lattice elements or springs, kind of springs.

And you can also see the same thing, the Voronoi elements here. So Voronoi elements, you represent kind of the matrix. And if you exceed the tensile shear strength or the shear strength or tensile strength at this -- at this lattice here, you can -- you break the spring here. So, then you open up and you increase the permeability of this one. Then it can go farther, here, you can -- if the pressure increased more, you may form a flow path like this. But the properties of these boundaries here are the same as those of the intact material from beginning.

TURINKSY: Okay. I can basically select the location by changing your elements.

BRANTLEY: Implicitly, those are heterogeneities, right? Implicitly...

RUTQVIST: If you’re not -- it will not be perfectly homogeneous.

TURINSKY: Yes, yes.

RUTQVIST: And there will be a weakest link somewhere where you first...

ILLANGASEKARE:  So maybe let’s give to the consultant.

UNIDENTIFIED PARTICIPANT:  Sure.

UNIDENTIFIED PARTICIPANT:  John?

MCCARTNEY:  Hi.  John McCartney, Board consultant, so I think this is a very complicated problem.  My main question was related to their experiment, which as well as it’s related to your model because you’re able to capture the results very well here.  So maybe in slide 12 -- yes.  I was surprised to see that when they injected the gas pressure, they’re actually -- they had axial stress of 10 MPa and a radial stress of 6 MPa.

And they didn’t see basic failure of the specimen when the gas pressure was almost exceeding the major principal stress.  And then suddenly after about 60 days like the major and minor principal stresses also increased together with the gas pressure.

RUTQVIST: So, the stress increases because you are increasing the pore pressure in the sample, you get the poro-elastic effect. If you increase the fluid pressure in the confined sample, you will increase the total stress. This measures the total stress. And as you can see, if you look for example -- yes, so gas pressure in the sample goes from here -- it increases by almost 10 megapascal.

And the stress at this point -- I mean the axial -- the radial stress, it is -- it is lower than that. But you have also some certain amount of strength in the material, so the input into the small -- we input the tensile strength and sheer strength also. And this happens very sudden. So, the -- I mean the -- here, we see that the pressure response in the sample a little bit inside, but it may already have been started to penetrate into the sample before that maybe it’s started when you have a -- when your -- when the pressure is somewhere here.

MCCARTNEY: Yes. It’s also interesting that the gas pressure doesn’t affect the pore pressure inside of the specimen.

RUTQVIST:  Gas pressure does not impact the...

MCCARTNEY:  Until almost 60 days later.

RUTQVIST:  Yes.

MCCARTNEY:  Yes.

RUTQVIST:  So, this is the gas pressure in the injection chamber...

MCCARTNEY:  Yes.

RUTQVIST:  ...and so this means that not -- we don’t -- we don’t see any -- much gas going into the sample and there is a filter -- there -- this is kind of a steel filter here. Steel filters are...

MCCARTNEY:  You have to break the steel filter first and...

RUTQVIST:  I mean it’s open, but still there is a -- yes.

MCCARTNEY:  Okay.

RUTQVIST:  So maybe -- yes, so the gas, otherwise if you put -- the gas pressure doesn’t simply -- in the channel doesn’t create any axial -- additional axial stress looks like, must enter into the sample.

MCCARTNEY:  Maybe just real quick.  So, your solid retention curve, this is like representing the case where the temperatures are all back to ground temperature after 10,000 years, correct?

RUTQVIST:  That’s -- I guess that’s what when I think this kind of gas generation will become important...

MCCARTNEY:  An issue.

RUTQVIST:  ...important to...

MCCARTNEY:  Because there’s definitely a big effect of temperature on solid retention curve and together on the gas entry pressure, so I'm wondering is there a -- I suppose nobody’s really studied that...

RUTQVIST: I’m sure they have done measurements of retention curve at different temperature for -- I mean for the early part, I cannot recall how big it is. You don’t put in -- in our models we did not put in such a relationship between the retention curve and temperature. We might put in a relationship between porosity and retention curve.

MCCARTNEY: Yes, I'm wondering if this -- that initial heating process changes the solid retention curve, that after the cooling if that could change your gas entry pressure. I don’t know.

RUTQVIST: I mean we could take some samples from FEBEX, maybe a retention curve...

MCCARTNEY: Yes.

RUTQVIST: ...for -- maybe I don’t know if they’re doing, but if they’re done, but maybe, I'm not sure.

ILLANGASEKARE:  Yes.  It seems like the capillary pressure, there’s a temperature fix on there, the surface tension, that may be different.

RUTQVIST:  Yes.

UNIDENTIFIED PARTICIPANT:  Yes.

TURINSKY:  Turinsky, Board.  How repeatable is this measurement?

RUTQVIST:  How what?

TURINSKY:  Repeatable.

RUTQVIST:  Yes, that’s a good question.  So actually for the -- especially for the one with the radial, if you will think about this one, inject radial gas and then there’s all kind of -- this all response in -- pressure response in -- initial flow response,  initial in this one, but finally, it only selected one path to one, all the outflow went out through one point.  And if you do another test, maybe that will go to another one.  And so, it will not -- this is kind of a -- it’s not -- it’s not something that -- so it could vary, yes, there is some stochastic variability here.

TURINSKY:  Yes, some in the -- I'm involved more with the reactor side of the thing and two-phase flow interfacial phenomena.  And people have sort of given up on the physics and they’re going to deep learning now, if you’re data-rich it doesn’t tell you anything about the physics unfortunately directly, but it gives you a model that could be very, very good if you have a wealth of data, which you may not be able to get.

RUTQVIST:  I mean -- yes, I mean there are many experiments -- I actually -- I mean we tried to actually fit to this data as good as we could, but maybe that will not fit -- if you do another experiment, the flow path will go another way and it will not exactly fit that experience, so that’s something, maybe you should try to fit rather a range of different experiments rather than work very detailed on one experiment.

TURINSKY:  Yes, yes.  That could be.

ILLANGASEKARE:  Any other Board questions? With staff?

BISH:  David Bish, consultant of the Board.  Do you assume that the gas does not interact with the solid chemically?

RUTQVIST:  In the models here, we are not -- there’s no chemical interaction.

BISH:  So, do you think you can accurately model diffusion of water vapor that does interact with the solid?

RUTQVIST:  Water vapor, yes.  I -- I mean we do that all the time for the -- for this initial thermal part we have modeled there.  Experimentally, it is kind of a thermal diffusion -- vapor diffusion in the gas phase...

BISH:  Does that incorporate though the interaction with the solid, with the bentonite?

RUTQVIST:  Interaction with the solid, there is no -- we don’t consider chemical interaction...

BISH:  Thank you.

RUTQVIST:  ...but we modeled the experiments and the data fits the experiment, but maybe there are some underlying processes.  We are, that is there but we don’t see if we do this.  We only see what happens outside the sample, right? I'm not sure what happens, outside, pressure, flow and stress.

ILLANGASEKARE:  To keep on schedule, is there any -- okay, thank you very much and it was very interesting.

BAHR:  Okay.  We’re a little bit ahead of schedule but I...

UNIDENTIFIED PARTICIPANT:  We’re right on schedule.

BAHR:  Oh, my watch is off.  Okay.  We’re right on schedule, which means that the coffee should also be coming in imminently, so we have a 15-minute break until 10:15.

(BREAK)

BAHR: Okay. So welcome back. I hope everyone enjoyed some coffee and tea and we’re going to continue on with talks about DOE research and development. Our next speaker is Hari Viswanathan. He’s a senior scientist in the Earth and Environmental Sciences Division at Los Alamos National Lab with expertise in flow and transport and subsurface porous and fractured media at a variety of scales. His work has related to both radioactive waste disposal and also a large variety of energy applications as well. And he’s going to be -- this is the first in a pair of talks on flow and radionuclide transport activities. This one relates to flow and transport in fractured granite.

HARI VISWANATHAN: Okay. Thank you, everyone can hear me just fine? Thanks to the Board for having me present and to the public. And so switching gears a little, this is going to be more about flow through -- flow and transport in fractured granite, crystalline rocks. And so we have two field tests that we’ve been participating in. One, which actually kind of connects some of the bentonite work that you’ve been hearing about and fractured rock experiments, and so this is about how as the fractures, are they capable of re-wetting the bentonite and what’s going to happen in that interaction, so that’s the BRIE test.

And then the second one is the long-term diffusion experiment. And so even though I'm talking about fractured rock, the two examples I’ll be discussing are actually very different scales. The BRIE is actually kind of like a 10-meter by 10-meter kind of block kind of size, larger scale and the diffusion experiment is actually looking at the micro-structure of fractures and how that can lead to fracture matrix interaction and increased retention of radionuclides as they transport. And so, in general, crystalline rocks are going to have fractures and at a bunch of different scales and they do affect things.

And so, the team at Los Alamos is listed. We also collaborate with Sandia. I’ll describe some of the different conceptual models we have with discrete fracture networks on the Los Alamos team, the fractured continuum models that Sandia has developed, and it’s been really exciting to work with the Swedish Task Force and SKB.

Some of the people that we list here, Vladimir Cvetkovic, Andrew Frampton, Bjorn, Jan-Olof, they’re all experts in fractured rock experiments and simulation, and so it’s been really good for us, because one of the issues with being able to validate our fracture models is that constraining these models and knowing whether you’re actually being predictive versus just fitting is very important and actually having field tests at a bunch of different scales and such nice measurements has been pretty critical for our work.

And so kind of where this fits in in the bunch of different things the DOE has been participating in, I’ve kind of circled both of the tests I’ll be describing.  They’re both in the crystalline rock, but BRIE actually is now the connection between the near-field and the crystalline rock because we’ll talking about how the -- how fractures could actually introduce perhaps freshwater from a glacial event or something like that, and how that could destabilize the bentonite potentially.

And so that interaction is something that BRIE is very much trying to capture.  And then if you want -- if you ever have radionuclides making it out to a fracture network, LTD is very much interested in is a standard matrix diffusion model sufficient because some of the experiments actually show somewhat anomalous behavior and increased retention of radionuclides and is trying to explain that.

And so, in the big picture, why is this important to post-closure repository safety?  And so, if the near -- if we were talking about a multiple barrier system, fracture networks in crystalline rock could be one of the primary pathways for radionuclides to transport from the near-field. And so, some people often ask why is crystalline rock being considered if it’s something that tends to have fractures and fractures can have pretty high permeabilities?

And actually, some of the things that are common to the crystalline sites that we look at is that the reducing conditions and so actually many of the radionuclides of interest have a very low solubility and have very high retardation factors in these kind of formations, and so they actually don’t transport very much. And so that’s actually pretty attractive about many of the sites that are considered, and then also the matrix rock is very low permeability, fractures are often very -- not well-connected.

At the previous meeting, we described that you may have an extended fracture network but many of those fractures are not open. They’re not connected and so I’ll actually get into a few questions from the previous meeting on how we try to consider that in our models.

And so, the conceptual model here is you know fracture statistics in general, and in some of these very nice field tests, you know -- you really try to do a good job mapping out the fractures in these particular experiments. However, in a -- in a full repository scale environment knowing where every fracture is is something that’s not going to typically be possible and they’re also occurring at a bunch of different scales.

And so, you know statistical properties of fractures from things like outcrops, you have measurements at your repository sites and typically one conceptual model is to actually do a statistical discrete fracture network model. And so, what you’re looking at here in the outcrop is these are a bunch of just fractures and they actually often can look pretty planar and here, every single plane is a fracture and all these planes intersect one another and they result in a fracture network, and for crystalline rock, the permeability of these fractures tends to be orders of magnitude more than the matrix.

And so, the structure and the connectivity of this fracture network actually comes into play.  And so, homogenizing that into a continuum model might work if you have a dense network of fractures, but it becomes less effective, it’s a more sparse -- sparse network of fractures.

And then what are we often interested in, we’re often interested in, if you’re transporting through a fracture network through like this, you’d want to see, well, how long does it take to get to get through a system like this if you have a conservative solute, if you have a weakly adsorbing solute, then reactions if you could boil it down to a retardation factor, it would just delay things, but as we’ve seen in other talks, you could have multi-component reactive transport come into play when geochemistry and things like that are changing as a function of time and space.  And then you’re not going to just have a simple delay.

And what’s really been driving our fracture models is the amount data that is now available.  And so, like at the tests in SKB, it’s just really exciting to finally have a bunch of fracture data on orientations facing aperture distribution, matrix diffusion.  And then to add to that, some of the discussions at the previous meeting, how do we know what amount of the fractures that we have are actually the flowing fractures.

And so actually Posiva, they have a flow meter as was talking with us about Patrik yesterday where they can try to infer of the fractures that are intersecting a borehole which of those are actually the ones that are flowing.  I think Dr. Zoback had techniques that she was proposing to also kind of get at that.  On top of that, you’re dealing with things like in the oil and gas industry advancing, there’s tools such frac ID where they’re putting them into wells and you get a much better picture of natural fractures intersecting.

And so finally we’re going from something that really statistical to something where you actually have at least an idea of what’s interesting your borehole, and you can actually consider this kind of structure.  And when we want to go to just -- if you want to look at the transport, what do you need to know of something that’s going to transport through a fracture network, you need to know all the same things you would need to know in a non-fractured system, the fracture roughness, surface area, these are all pretty controlling features.

And so as far as the state-of-the-art, I think what’s really been driving this area is, like I said, increased data that’s now available. And so, since it’s the primary flow pathway in crystalline rock, structure very much matters. And the discrete fracture network models, complex continuum approaches, and pipe flow models are sort of the gamut of the way people have been modeling these systems.

And they’ve evolved to take advantage of the kind of complex meshing, all the kind of THMC processes you’ve seen in other talks. And for a mechanistic representation of flow and transport in fractures. It’s also been moving towards using the latest high performance computing, being able to compute these things in parallel, that’s one avenue of research. The other avenue is how you do robust uncertainty quantification in these systems, since you don’t know where every single fracture is, typically you’re not going to be able to map it all out and it’s a bunch of different scales. What level of complexity is actually warranted. I mean, can we get away with something much simpler?

So, I’ll kind of go through the gamut of more complex models and then simpler models. And someone had mentioned machine learning. Can we actually use the simple models, train on the more complex models to actually adjust the simpler models so you can now run it within uncertainty quantification? These are the different things we’ve been looking at.

And so, if you were kind of going through the history of this, complex continuum approaches have been around for a long time, homogenizing the system and this is a very short subset of the works on these things. There’s enormous literature and one advantage of the SKB Task Force is it sort of is pretty much so many different people who work on discrete fracture network models get together and you really talk about whether you’re fitting versus being predictive and so on.

Discrete fracture network, these are sort of FracMan has been mentioned and we actually work with FracMan and SKB on some of this work, the one down here is our research group. And the area that we very much been getting into lately are being able to develop these graph-based machine learning approaches to mimic the physics-based models to do more robust uncertainty quantification.

And so, what are the outstanding questions for transport in fractured rock systems?  So, I think one of the big questions is discrete fracture network models do quite well if you really map out every single fracture and you know all the connectivity, but most of the time you only know things statistically, so is this complexity warranted?

Continuum models kind of try to smooth things out so they can be more efficient, but are they good enough, especially if you’re just talking about statistical representation? Should we be going even more simpler?  I mean are these reduced order models, I mean graphs pretty much capture the same structures as the discrete fracture network model but it’s basically making a link between the pipe flow work that was done 20 years ago to the high fidelity models that exist now and basically trying to come up with a correction between the two to see if you can mimic the behavior. And as I’ll get into, the field tests at SKB have been really critical for us to try to determine what is the level of complexity that’s warranted.

And because as more and more data started coming in and we started realizing that the connectivity of these networks can completely control the behavior of what flows and transports through them, pretty much became clear that hey, we could take advantage of all the latest numerical techniques, the latest computers. And so actually when we started working with SKB, it kind of led to us developing this tool dfnWorks and this basically tries to take advantage of the latest meshing techniques, the new computer architectures, the multi-physics modeling that’s being done.

And so, sort of started under 2013 and 2017, we got this R&D 100 award in this area and we applied it for fractured systems not just for nuclear waste, but for hydraulic fracturing, carbon sequestration, nuclear non-proliferation, and so this has actually turned out to be a pretty important area for us.

And so now, getting into the actual tests that we’re looking at. So, the Äspö Hard Rock Laboratory is a dream for a fracture modeling person when we have so many different models and so little validation data. And so, this is where it’s at. You’ve heard Patrik describe the system, but they just have such a nice set of systematic tests that explored different physics, and you very much can start answering the questions of -- can we be predictive in these systems or are we just fitting, which is something that I think is critical in fracture modeling?

And so, getting into the first test, I should have the scale on here. This is about a 10-meter by 10-meter cubed sample where we actually want to understand how bentonite, which is a lot of the EBS talks you’ve been hearing about interact with fractures, because a lot of the tests in the past were looking at bentonite but not necessarily how they interact with fractured systems. Why is this important if you’re talking about way into a different way forward in time and you have, for example, a glacial event or something like that and now you are getting freshwater that’s actually able to get in through fractures?

And let’s say it intersects the bentonite. We know if freshwater interacts with bentonite, that could destabilize the bentonite so trying to understand that kind of interaction is pretty important. Actually, it turns out to be fairly challenging even for -- or for just doing the modeling for us because the discrete fracture networks are a bunch of 2D planes and now we have all these boreholes and we know exactly where they are, so basically trying to get this 3D volume meshes to intersect with the 2D actually was somewhat challenging for us.

And then another thing that the SKB Task Force enabled us to do is have a dialogue, because everybody had so many different conceptual models of how they approached these problems but one thing that wasn’t being done as much in the past but I thought DOE, actually Stefan Finsterlane particularly at LBNL, I thought shaped a really nice integrated effort, like what did we learn from all these different conceptual models and where does uncertainty quantification kind of fit into this fractured system work, because it kind of felt like the American system was more running performance assessment models, simplifying and doing more UQ and because the Europeans -- maybe this is a broad brush description, but since they have such nice field tests, they could be doing all these really nice physics-based models. And so, it’s kind of intersecting of the two was a nice place to be.

And so, this is kind of an example of the fractures that we know intersect the borehole at the BRIE test. And the question is, when we start bringing, water is injected, what’s going to happen, and basically what are -- the bentonite is going to start out somewhat unsaturated. And so, it actually imbibes an enormous amount of fluid from the -- from the fractures and what’s interesting here is where the fractures intersect.

There’s a very sharp gradient. I mean it’s very much the re-wetting is controlled by the intersections by the fractures. And actually, some of the -- I don’t think Hakim was necessarily talking about that today, but I mean he’s setting up experiments with bentonite and intersecting fractures in the laboratory to look at this process.

But since the re-wetting is very much controlled by the fractures and they can actually dry out, the bentonite soaks up the water so much it can actually dry out some of the area around the boreholes of these kind of tests, but I think the interaction between fractures and bentonites is an important process and especially if you want to think about how could a different type of fluid get into the near-field and affect things.  I mean fractures are much higher permeability in crystalline rock, I think this is a pretty important process to be able to consider.

And we kind of came in at the tail-end of this test, but I mean it really did motivate us to step up our game and being able to simulate these type of processes, and also get plugged in with the rest of the international community. The next test I'll describe we've been involved kind of from the get-go.  The other thing this test did for us is just realized wow, there's a lot of different way people handle these systems.

And so even with the National Labs, Sandia does things with fractured continuum model, we do things with the discrete fracture network model and basically just trying to make sure we can even get those to agree and make sure we understand what our models are doing.

So, I’ll just kind of quickly step through it, because it may be of interest to see what goes into these models. And so, the first thing we wanted to do for this comparison is just come up with the statistics from Forsmark and basically have a bunch of different fracture statistics. I'm not going to go through all these equations and everything, but it’s basically to just say that we have angles, we have apertures, we have fracture densities and we basically put that in to a DFN and we have a pretty, at this scale, when you’re dealing with fracture network as opposed to just a single fracture, the cubic law is what’s typically done to related permeability to the aperture, so the permeability of a fracture is often related to just the aperture cubed.

And we’ve done a lot of work just on single fractures which show departures from cubic law, but once we get to the network scale this is what’s typically done and that’s what we’re doing right now.  And so, we generate this discrete fracture network.  And this is a statistical distribution of the fracture network, and then we map this onto Sandia’s fractured continuum model and the goal here is to just make sure we’re getting things on the same page.

And we map on to this fractured continuum model, and bottom line, I mean the take-home message is, it actually took us quite a while to get these two models on the same page.  And so that’s also something on the SKB Task Force that’s been helpful.  When you have a bunch of different conceptual models and you’re kind of finding different things and there’s non-uniqueness and different ways to match the experimental data, it’s been helpful to understand what are the strengths and weaknesses of different models and how to actually get a more collective picture of the entire situation.

So now moving on to the next step.  The next test was actually quite different in scale, and so this is the long term diffusion experiment in fractured rock, and from the get-go this turned out to be kind of an interesting test in that you’re looking to see how a radionuclide like cesium gets retained by crystalline rock, and in the initial test, a standard diffusion model would just predict this much penetration into the rock, whereas you actually get quite a bit more penetration into the rock.

I mean you can see this is at a very small scale, but when you’re talking about flowing through a fracture just a little bit of retention goes a long way to the safety case. And so, if you can actually, should we be taking advantage of more retention in these rocks than we are, that’s sort of one of the things that was looked at.

And since we’ve done a lot of discrete fracture network modeling and since we can do it on high-performance computers, our task was to do micro-structure DFNs for this process.  And so, it was new for us to go down to a much smaller scale and just starting to look at micro-structure, but actually on other missions on Los Alamos, we look at micro-structure with DFNs all the time, metals and so on.

And so here, the idea would be -- the experimentalists told us they don’t know how far this kind of micro-structure damage that may have occurred from well bore emplacement or could have happened from something else, how far in it goes, so take a look at one where it goes all the way through, it’s the furthest they thought it would go, go halfway through just a little bit of penetration.  And then basically, let’s see what happens when you do particle tracking to see the kind of penetration that you might see.

And basically, what we’re getting here is when you do include the micro-structure, you can definitely get this kind of increased penetration profiles into the matrix.  And again, it becomes somewhat of a question of non-uniqueness. I mean, in this test we do have very good characterization of what this micro-structure looks like.

And what we were very much interested in is just generally, are we getting the right shape of the curve and the right amount of penetration when we do include this micro-structure damage, and then it also becomes important is this micro-structure damage just kind of unique to this particular task because something happened, or do most crystalline rock kind of have this level of micro-structure that actually leads to increased retention?  And so I think that’s actually a pretty interesting question and it actually could be a pretty good -- different matrix diffusion model that could be considered.

And so now kind of shifting gears into where this could all fall into the safety case, I mean one of the big things that we have going at Los Alamos not just in repository science for radio waste storage, but actually for everything we do in the subsurface, these fracture networks are controlling a lot of the systems we work on.

We often only know things statistically and we just have a few really nice tests to really map everything out.  We often do these really gung-ho HPC calculations that require really powerful computers to mesh every single fracture just perfectly when we don’t know where they all are necessarily, and we can show that you need to run this like a thousand, 10,000 times to bound system behavior on what actually percolates.

And then also going between an interesting thing Patrik had said is the difference between the flowing fractures in the system and just the fractures in the system at SKB, he was saying is about a factor of six.  And it is nice that we have these tools like this Posiva flow meter to actually try to constrain that, but you still know that we're just getting the intersection of what intersects the borehole and what's out into the rock, this is not going to be completely known and you're going to be dealing with statistics at some point.

And so, graph theory is graph theory is used all over the place in the sciences.  It's used for connected systems. And so, you use them for cybersecurity, you use it for the Google search, basically any connected system can be treated as a graph and that's what people are doing even for biology and so on.

We do this all the time for smart grid at Los Alamos.  For me, this was really exciting because this is almost like Graph Theory for Dummies because I was new to this.  You can basically have a physical representation of your graph here. It’s not abstract like in cybersecurity. Every single fracture plane can be a node on the graph, every single intersection can be an edge.

We’ve tried different mappings and then the question becomes can we just solve very simple physics on the graph and basically see what kind of breakthrough curve do you get, you will get an error, but then can you basically correct this error by just learning, using machine learning on what the standard deviation is. This is kind of one of the most simple machine learning exercises you can do.

The other thing that we would do is this worked great for single-phase flow. We can get like three orders of magnitude speed up and real accurate solutions to the point where all of our DFN people were kind of shocked that why were we doing this.

But if you go to multi-phase flow and reactions, this workflow falls apart and so you actually have to see if you can a priori figure out which part of this fracture network is the flowing part.  So this could be a multiple -- this workflow could be somewhat complex, you could either take the statistics and generate your DFN and you -- if you could be calling that your hydraulic DFN if you use like the Posiva flow meter and you’re just down to what you think is flowing, but even when you get down to what you think is flowing, it’ll often not be the majority of what’s flowing in a simulation.  So now you basically do that a priori, you identify this, and you prune your DFN and now you have a much smaller one and you can do the full physics on this. And so, this is a more robust workflow, but this is the really quick workflow, and it kind of depends on the physics on which ones you want to do.

So as far as like we’ve been looking at all these different pruning schemes and I'm not going to go into a huge amount of detail but just look at -- if we were saying that we want to mimic this curve, the dfnWorks breakthrough curve, you can see that for single-phase flow using machine learning with a corrected graph gets you four orders of magnitude speed up and almost perfectly matches that curve.

And that will fall apart when you start talking about reactions in multi-phase flow and we’ve shown that, but I think what we’re trying to make the case is really pay attention to what is the quantity of interest that matters, and what is the level of the model that’s warranted to do this stuff, because do not over -- do not make your model too complex, don’t put in extra knobs if you don’t have to.

And if you want to put it into a safety case, uncertainty quantification matters, and we think this is a fairly decent approach to do so.  And another thing we’ve been doing with Professor Rajaram is introducing time domain random walk schemes for incorporating matrix diffusion.

And so, this is basically, can we get -- I mean we show when you can get the classic kind of scaling behavior of matrix diffusion and when you deviate from it.  And this is the type of model that could also go in pretty nicely into the safety case, and for fractured rock, retention and matrix diffusion is pretty critical, so having a good matrix diffusion model and capturing the structure of your fractures are two of the key things we want to get into the safety case.

And so, I think I want to really emphasize that being part of the international programs for me and our research group has really been exciting because we just feel like for fracture modeling, validation cases are few and far between especially at the level of detail and characterization that the Swedish Task Force has done.  On top of that, they’ve been working in this area and they kind of know what are the gaps so we sort of try to fill the gaps in areas like high performance computing, some of those machine learning graph theory.  These are areas where we feel like we can contribute, and uncertainty quantification, but they just bring so many years of research and all the pitfalls that we try to avoid.

And I would pretty much credit a lot of this work to developing dfnWorks, fracture continuum model at Sandia and working with world leaders.  And so, I’ll just kind of leave you with -- I think DOE’s a pretty important contributor to the Task Force in physics-based modeling using the latest leadership class machines for high-performance computing, and bringing in these ideas of uncertainty quantification and reduced order models. And so, I’ll kind of conclude with that. So, thank you.

BAHR: Thank you, Hari. When you developed these reduced order models, you’re starting with some block of material in which you’ve created this discrete fracture network. How does that scale if you go to a larger volume, and can you use the same corrections for your breakthrough curves from one scale to another? I'm thinking of cases where there was work done on sort of fractal dispersion, and you can match things at one distance but you -- but you don’t...

VISWANATHAN: Yes. So, the...

BAHR: ...map -- and you get -- you don’t get the same increase...

VISWANATHAN: Exactly.

BAHR: ...in spreading as you go to larger scale.

VISWANATHAN:  Yes.  So, the scaling breaks down, so the correction factor at a particular scale does not hold at a scale that’s higher, so you still have to somewhat do like -- the reason for the reduced order model is sort of when you want to do many realizations of the fracture network.  So you still need some sort of you could call hero calculation or DFN calculation at the appropriate scale, but basically we’re -- yes, where you’re going is exactly what we’re trying to do, sort of like what are the multi-fidelity approaches where you can do just a few physics-based calculations and then do a bunch of these kind of quick graph-based calculations and use them together to kind of get your answer because, yes, it doesn’t hold.

I mean even if you go from one lithology to another lithology, the correction factor -- you know, machine learning kind of the lesson I’ve learned so far in it because we’re on about three different machine learning projects, it is extremely good at interpolating and extremely bad at extrapolating.

And so when you see all the really amazing image kind of things that you see out there and what -- you know, self-driving and how they’re doing certain things, once you go out into an interpolation type regime, things really start breaking down.  I mean we’re -- they’re moving towards physics-informed machine learning that tries to put in more of these constraints to make things more predictive, but yes...

BAHR:  So, when we think about putting these things into performance assessment models where you’re really trying to look at far-field transport, you do have to go to the much larger scale, but you’re not going to have the experiments to constrain that.  So how can you know that you have the right...

VISWANATHAN:  Yes.

BAHR:  ...adjustments for scale?

VISWANATHAN:  So our -- so our workflow is basically that the physics-based model, which would be the DFN should have the appropriate physics to work at different scales, right? And the thing that sort of changes is -- I think the biggest gap is how do you get the appropriate parameters into the physics-based model to be able to scale up, because going from the physics-based model to a reduced order model, that workflow seems to be pretty decent, and then knowing that the physics is mostly Okay unless you’re really going to really small scale but if you’re sort of at some sort of reasonable BRIE-like scale to larger scales, I feel like what’s the issue is how do we -- and there’s a lot of work that people have been trying to answer this, but I still feel like it’s a gap. Like what is the appropriate parameters do you put into the DFN at the scale of interest? I do feel it’s a gap.

BAHR: Okay. Thank you. Are there questions from Tissa and Mary Lou who are the other leads on this?

ILLANGASEKARE: So, Hari, thank you. Tissa Illangasekare, Board. So, you are making a case for the continuum model versus discrete fracture models, so that -- the assumption is that at least in the real world hopefully you are looking for places that don’t have fractures. Okay. So you are already starting with the system which are very sparse fractures. Only time I can see is that if you have the borehole itself disturbs the fractures and then that becomes a network.

So, my question is that the geo-statistical methods people use assume that certain distribution -- normal distribution, et cetera, so the geo-statistical work based on the fact that there are some correlations. So, my question -- my question in a disturbed zone whether the statistical models work because it’s not a natural process, it is a -- more of an imposed process. So how good are these statistical models in this type of fractures which are artificially made?

VISWANATHAN: Okay. Yes. So first, I'm not making a case for more continuum models. I mean I would say in general -- I would say for fractured systems the reason we’re doing all this graph stuff and everything is basically that we think structure dominates the system, connectivity dominates the system.

ILLANGASEKARE: That’s right…

VISWANATHAN: Oh, okay, that part. And so, then the part of like the LTDE experiment where the what’s happening right up against the borehole is very much an unknown question. I mean even when we talk to their experimentalists and I don’t know if Patrik has more to add on that, but I mean when we talk to the experimentalists, it seems like it’s not totally clear what is causing that, if it’s just simply damage upon emplacement and so on.

So, I think it’s an unknown question on -- if the kind of power law distributions that we typically use to populate what a fracture network looks like would be followed at that scale, and also, you’re saying because it’s man-made. I mean -- I mean there will be some people who sort of think that power law distributions capture all sorts of behavior, right, at different scales and different mechanisms and then I'm sure -- but I think it’s still an unknown question.

I mean all I would say though is that for me it was just interesting that when we did include micro-structure based on what the experimentalists told us the characteristics of that micro-structure was, then we actually kind of got the rough shape of enhanced penetration that a standard diffusion model would not do.  I mean it wasn’t -- that wasn’t much of a fitting exercise, we just put in the fracture parameters, we just saw what happens and immediately sort of got that enhanced penetration which felt pretty good.

ILLANGASEKARE:  So, do you like have data to at least test the idea that these stochastic methods work for this type of I call them natural fractures, because like I said most of the geo-statistical methods used assume that there are some correlation may and it's a natural process because of the depositional processes, and in a fracture network you may also argue that during the (Inaudible) but this one is a completely different fracture.

So, my question is do we have data this size to see whether your assumption of the geo-statistical model works.

VISWANATHAN: I mean, I think the closest avenue of research that we do along those lines is not with necessarily data, but we have a bunch of physics-based models that actually try to create the fractures that would occur due to various processes.

ILLANGASEKARE: Yes.

VISWANATHAN: And so, that's supposed to be saying Okay, what fracture network do you expect to get when you create the fractures, maybe kind of like some of Jonny kind of described things along those lines. And so now, that's physics-based and now you have a DFN that's sort of just saying what's your distribution.

And so, some of the typical questions we're trying to look at is, a lot of the DFNs are X-fractures like every plane goes through and goes right through another fracture. You look at any of our experiments and a lot of fractures T, like you have a fracture and it hits another fracture and it dies.

And so, when we look at a percolating system, we have basically -- we've got a couple of papers that show that the scaling behavior of percolation between that statistical representation in the physics-based model is actually fairly similar even though when you look at the two they look quite different. And so, that was sort of our initial attempt at this. But as far as just having data to support the man-made fracture patterns, we have not pursued that avenue.

ILLANGASEKARE: Thank you.

BAHR: Mary Lou?

ZOBACK: Yes. Thank you, Hari. A really nice talk and thanks for giving us the background and things.

And I have one question of clarification on slide 14 if we can get to that. So, I don't know anything about discrete fracture network models, but I'm trying to understand how you say three fracture sets are generated based on the data from Forsmark. And the three sets you list are...

VISWANATHAN:  North-south, east-west...

ZOBACK:  North-south, east-west and horizontal.  And then there's kappa, alpha and all those numbers which I don't know what they are, and they're not defined.

VISWANATHAN:  Sure.  Yes.  Yes.

ZOBACK:  But then on page 15, I don't see a set of north-south, east-west and horizontal fractures.  I just see random noise.

VISWANATHAN:  Yes.  Okay.  But basically, there would be. So, it's basically going to be the fractures that are going, let's say, you're slicing one way, you're slicing another way and then the other thing is that there is going to be like an additional noise added to the orientation and everything.  So, what you actually end up seeing here is the combination of those three different fracture sets.  I mean, yes, it's probably because of the -- yes, that is what you end up with.

I mean, so the usual discrete fracture network model is you're going to have experimentally kind of someone interprets.  And says, Okay, we've sort of got fractures going in this direction.  This is the spacing of them.  This is the orientation.  But then there's also going to be sort of plus or minus something.

And so, yes, I guess I see what you mean.  I mean, when you look at those, you're not just simply seeing that that would break into three.

ZOBACK:  I see a lot of things dipping 45 degrees.

VISWANATHAN:  There are three but there are actually a bunch of vertical fractures in there.  There is a bunch of horizontal fractures in there, and there's also going north-south and east-west.

ZOBACK:  And there's a little bit of everything else.  Okay.

VISWANATHAN: Okay. But the one lesson there is there is a little bit of everything in the fracture network that's measured in Forsmark. I mean, if you basically look at things, there's going to be north-south, there's going to be east-west and there's going to be horizontal. And so, you could look at it as, yes, you could easily boil this -- it's just sort of like how does the model take it, right?

So, it's sort of like someone's interpreting oh, yes, there's some going in this direction, some going on in this direction and it does -- I think your takeaway message, although I'm lost now, I should go forward. The takeaway message is in this particular rock at Forsmark it’s pretty densely fractured and the fractures are going every which way.

ZOBACK: Okay. I'll accept that there's something that you do when you put it in the, creates that. On slide 23, I didn't understand, you have two paths. You start with your high fidelity DFN and then you go to the graph representation.

VISWANATHAN:  Right.

ZOBACK:  And physics, you can do physics on graph or physics-informed pruning.  What's the difference between the two?

VISWANATHAN:  Okay.  Yes.  So, once you -- so, the way to think of the graph is it's captured the structure of the high-fidelity model, right?

ZOBACK:  It's some kind of representation of every little plane showing.

VISWANATHAN:  Yes.  Think of it as a bunch of pipes that are sort of trying to represent what the DFN would have, every single plane, there's a bunch of spatial nodes and intersections and so on.

ZOBACK:  Okay.

VISWANATHAN:  But now, if you follow me on the bottom pathway, what you're doing is you're just going to do everything on the graph itself. So, you can basically solve for pressure and transport and everything on the graph itself. And so, that's like a super -- you're simplifying things from every single fracture plane typically having like 1,000 spatial nodes and you saw the mess of fractures that you're skeptical on being north-south, east-west but it is.

Basically, that simplification is a major simplification that's going to lead to a deviation. But the reason it doesn't lead to a crazy deviation is the structure so much controls the system that actually that is the dominant mechanism that controls the breakthrough time for a single-phase flow.

But if you now want to deal with more complex physics, it's a different idea. You've got your graph and you're basically trying to use the graph to just figure out where is most of the important stuff happening. And so, the idea here is you're just saying Okay, if it was physics-informed pruning, you would look at the fluxes on this graph and see where the maximum fluxes are passing through, that's our backbone.

ZOBACK:  Okay.

VISWANATHAN:  And then now you're just back to DFN and you can do all your reactive transport and multi-phase flow, but it's on a much smaller DFN and so you save a lot of time.

ZOBACK:  Okay.  So, I see that now.  So, when we had the pre-meeting in Las Vegas, we talked about critically stressed fracs, the observations and all boreholes in crystalline rock that you always have hydrostatic pore pressure whether you are at three kilometers depth, five kilometers depth or eight kilometers depth in the German deep borehole.

So, fracturing in crystalline rock is ubiquitous, and that's how you keep hydrostatic pore pressure everywhere at depth. That means that the pressure of the fluid, water, brine, whatever at depth is just equivalent to the weight of a column of water and it is that because you've got these open fracture networks.

So, the idea that we're going to find granite, you might find small blocks of granite that don't have fractures but it's ubiquitous.

VISWANATHAN:  Yes.  Right.

ZOBACK:  That's the process of the earth's crust.  So, we also talked about the fact that in these same boreholes, you can use a borehole televiewer to map all the fractures intersecting, their orientation, even their aperture.  And then you can run a high temperature probe down the same borehole and say of all of these fractures that we've mapped, which ones are flowing because you got a little temperature kick.  And those all are fractures that have the orientation of faults that are the most likely to slip in the present-day stress field.

So, to me that's physics because it's not taking the -- anyway, it's physics.  So, can't you add that as...

VISWANATHAN: Yes, I guess, I didn't explain that properly but that is basically what we are -- we use that kind of information, right? So, and SKB has this Posiva flow meter which is doing exactly what you're saying. It's trying to figure out what are the flowing fractures.

And so, for their safety case, they sort of have, Okay, the flow meter is telling us these are the flowing fractures. We also know that there's this whole bunch of fractures that are probably not flowing. And so, I think it's basically a factor of six difference between which is flowing and which is not at the Forsmark site.

And so, you would construct a DFN which would just be the ones that we think are flowing. But even when we do that, that's what I was trying to explain, like even once you get the ones that we think are flowing and we could do a statistical DFN on that. It's not like that entire thing is going to necessarily percolate in our model, even a smaller subset than that because yes -- do you understand what I'm saying?

Or you could just simply do if all you want to do is rely on the flow meter measurements, right, we would just simply construct the DFN with the Posiva or the kind of flow meters that you're describing. We would just simply take that entire DFN, forget about any of the pruning stuff. We would just turn it into a graph and then we basically use that. So, that would be your...

ZOBACK: I guess my point is you can take the observations and replicate the example from Forsmark. But there's a predictive capability in using the stress state and the fracture orientations, and for every plane you can calculate the shear stress and the normal stress. And then that ratio tells you how likely it is to slip.

So, to me that's applying actual physics of how faults slip to -- and in fact, it's fault slip that's creating this -- that's keeping the permeability open in the earth's crust.

VISWANATHAN:  So, maybe the thing to do is since I'm not fully getting your concept, right, but if we talk more, I mean, it's really...

ZOBACK:  We're not getting each other's concepts, so that's fair.

VISWANATHAN:  Yes.  Yes.  Yes.  Well, look, I think the way it's done now is they think these are the ones that are flowing.

ZOBACK:  Right.  Right.

VISWANATHAN:  You have statistics, you create a DFN.

ZOBACK:  Right.

VISWANATHAN:  You've got physics on top of that that can constrain the DFN better, right?

ZOBACK:  I think so.  I think it's worth a try.

VISWANATHAN:  Yes.  Yes.  Yes.  And then I think it would totally fit within this kind of workflow.  I mean, we would just have to use the way to constrain your DFN, create it and basically use that as a conceptual model.  And then that would be a more physics-constrained generation of the DFN, so I've got no arguments.

ZOBACK:  And there's lots of borehole data published in the open literature that…

VISWANATHAN:  Yes.  So, I think it sounds compelling.  The only thing I'll say is I don't fully understand it.

ZOBACK:  Okay.  Then maybe we can get together.

VISWANATHAN:  Yes.  Yes.  Yes.  That's good.

ZOBACK:  Let's have a beer.

VISWANATHAN:  Yes.  Yes.

BAHR:  Okay.  Well, I think we are out of time at this point we're going to have to move on to the next speaker but thank you very much, Hari.

VISWANATHAN:  Thanks.

BAHR:  And Sue is going to introduce our next speaker.

BRANTLEY:  So, the next speaker is going to be talking about, more about flow and radionuclide transport.  And our speaker is Hakim Boukhalfa from Los Alamos.  He's the team leader for the radionuclide geochemistry team at Los Alamos and he's a geochemist by training.  He's been a staff member at LANL since 2007.  And he got his PhD in geochemistry from Duke University in 1999.

Welcome.

BOUKHALFA:  Thank you for the introduction.  And thank you for the opportunity to present.

I'm here to present, talk about Colloid-Facilitated Transport; Studies Related to the Colloid Formation and Migration Project at Grimsel Test Site.  I just want to give credit to Paul Reimus.  He prepared the presentation and he's the main person from our team who's involved in the CFM project.

This was a great opportunity for our team to use the CFM data to validate some transport models that were developed at LANL.  So, in addition to the LANL team, colleagues from Sandia and Lawrence Livermore National Labs also contributed to the formulation of the mathematical model that takes into account colloid-facilitated transport.

We want to acknowledge help from Prasad who was very helpful during the formal DOE participation in the CFM project.

So, before I go into the details of the CFM experiment, I want to take a few minutes to go over some definitions.  So, we use the term colloids to refer to insoluble particulates that are suspended in water that range in size from few nanometers to few hundreds of nanometers; particulates that are smaller and likely to play a big role in transport that will probably diffuse in the matrix.  Particulates that are higher than a few hundreds of nanometers are likely to filter out and will not contribute to the large-scale transport.

Our interest in colloid transport comes from the fact that colloids in most cases will transport in fractured media at a rate that's faster than the fluid flow.  So, if radionuclides associate to colloidal materials, they could transport to significant distances.  So, this cartoon here shows a conceptual fracture with fluid flow.  If you have a solute radionuclide that's in a soluble form and you have no colloidal materials in the system, what will define the transport of your solute is the interaction of the solute with the fracture wall surfaces.

Now, if you have colloidal materials in the system, they will compete with the fracture surfaces for the sorption of radionuclides.  The result of the competition for radionuclide bindings will define how things will transport. It's kind of similar for intrinsic colloids and by intrinsic colloids in this context which are the red dots here, these are insoluble forms of radionuclides.  It can be oxides or hydroxides of radionuclides, or it could be radionuclides incorporated into corrosion products.

So, their behavior in a fracture system will be also defined by how they attach and detach from the fracture surface, but also the competition between colloidal materials in the system and how they attach and detach from these colloidal materials.

So, the CFM experiment was specifically designed to answer questions related to the far-field of transport of radionuclides in association with colloids in a crystalline media.  So, the CFM experiment developed a CFT which is called colloid-facilitated transport ladder and it basically asks a set of questions that are relevant to colloid-facilitated transport.

So, for colloid-facilitated transport to be relevant, you need to have -- there's a set of five questions that need to be answered and they are related to the presence of colloids, their mobility in fracture system, their stability as suspension, their affinity to radionuclides and the reversibility of this interaction.  So, in order for colloid-facilitated transport to be relevant in a system, all these questions need to be answered yes.

So, the CFT ladder here developed for the crystalline media is also valid for any rock type.  You can apply it and get answers to help guide you on whether transport in a colloidal form is relevant or not.

So, the CFM project was organized or structured with three components to help answer these questions.  It has a lab component, a field component, and a modeling component.  The lab component focused on studying colloid generation and interaction of radionuclides with colloids and inter-comparison between different bentonites.

The field component focused on the site characterization and the characterization of the hydrology of the site.  The modeling component focused on supporting the in situ test measurements and preparing a performance assessment model to take into account colloid-facilitated transport.

Our team was involved in the modeling component of the CFM project with some experiments done at the lab scale to validate some of the concepts that I'll explain in a little bit.  So, the CFM experiment which is at the Grimsel Test Site is interesting because it is set up at a tunnel that intersects a shear zone with high formation flow.  This is one of a few sites where you can actually perform experiments and inject radionuclides including plutonium.

The CFM project started in 2004, but was preceded by projects that date back to 1998 and focused on colloid and radionuclide retardation projects.  So, the U.S. was a formal partner between 2013 and 2015 with informal involvement since 2006.  I just want to reemphasize that the CFM experiment has always focused on bentonite transport in fractured crystalline media.

The relevant scenario here is you have a waste package that's breached and allows radionuclides to sorb onto the bentonite field material which subsequently erodes into flow and fractures which then would carry radionuclides away from the disposal site.

The CFM project target scales are two to six meters, and time scales of 1 to 60 hours and progression went from smaller distances to longer distances and shorter to longer time scales.  In 2015, the CFM experiment changed from injecting cocktails of colloids with pre-sorbed radionuclides to the emplacement of a bentonite plug with radionuclides and looking at how colloids are generated in that system.

So, this is a cartoon showing this scenario where a waste package is in place in an area where it intersects a fracture.  The breach of the waste package would allow radionuclides to sorb onto bentonite backfill which subsequently would erode into the flowing fracture and carry radionuclides away to longer distances.

So, this is the test bed of the CFM project.  So, as I showed before and the tunnel that intersects this high flow shear zone is set up as the radiological controlled area where experiments could be -- radiological materials including plutonium and americium were used to set up an experiment.

So, the early tests were cross-borehole experiments where boreholes were drilled to intercept the high shear zone and radionuclides were injected at an injection point, and their breakthrough at an observation point was recorded. The results weren't great because the flow rate was too high, and the breakthroughs were very quick.

So, the team set up a giant packer shown here, it's a 3.5-meter diameter packer which was in place to intersect this high flow area, and it was emplaced there to provide a way to control the flow in the formation. It was instrumented with packer sensors and boreholes that would access the shear zone at different locations.

The testing and control data setup is shown here which was emplaced outside the packer area and allowed the injection of the tracers and monitoring of performing in situ measurements. This is a planar view of the tunnel area and all the boreholes that were drilled to intersect the high flow area.

Before the emplacement of the packer, initial experiments were performed, were cross-borehole experiments and interrogated a path of about 2.2 meters. After the emplacement of the packer, the next set of experiments were performed to interrogate a longer path of about 5.7 meters. So, most of these experiments were performed by injecting a cocktail of radionuclides pre-sorbed on colloidal materials. There was one test where radionuclides were injected without colloids to interrogate this path.

In total, there were six colloid-facilitated transport experiments performed; three were done with tri and tetravalent homologues and three were performed with radionuclides including plutonium and americium.

So, this is the type of data that you get from the breakthroughs, and this is where our team was most involved in the CFM project, is we used our models to model the breakthroughs.  Showing here in the lower left is in the log scale a breakthrough of a conservative tracer, the colloids and different radionuclide breakthroughs, shown here on the linear scale an example for the breakthrough of colloids, plutonium and americium.

So, the modeling was performed in a staged approach.  So, the first stage of the model was to just model the conservative tracer to get the hydrologic parameters of the formation.  Then those were fixed, and the colloid breakthrough was fit to recover the rates of colloid filtration.  And then the last step was to fix both the colloid and the hydrologic properties of the formation and then fit the breakthroughs to get the radionuclide desorption rates from the system.

So, this slide shows the summary of all the results obtained from 2000 to 2013, and it shows both the results, the early results with the 2.2 meter travel distance and the longer travel distance.  The top plot here shows the bentonite filtration rate, and basically you don't see any significant difference in the filtration rate as a function of the transport time.

However, if you look at the colloid recovery for short transport times, you get almost 100 percent recovery. But as you go to longer transport times, this is after the packer was set up, you get a significant loss of colloids and it's not clear if this loss is due to flow diversion or if it's due to the colloid attaching to the matrix.

On this side, we show the plot of the desorption rates as a function of the transport time for the trivalent and cesium and for the tetravalents here. The one thing to note here is that the desorption rates for the tetravalents are in order of magnitude shorter than the trivalents.

But the more important thing here is that for the same radionuclides, the desorption rates are a function of the transport time. What does this mean is that you don't have one population of sorption site on colloids but you have a distribution of sites that sorb radionuclides. And the more you increase the transport time, the more you have the ability to interrogate these slow desorption sites.

This poses an interesting question for up-scaling. If you assume that this correlation between the desorption rate and the transport time holds, and you extrapolate to transport times that are relevant for a geologic repository, then if this holds then you get to regimes where a subset of your colloids will have sites that will actually effectively transport radionuclides to longer distances.

But you can't perform experiments at these scales in the field; it would be too long and too costly. So, this is a limitation of what you could do in the field. And this is where going back to the lab and doing more collaborative experiments to kind of answer some of these questions becomes relevant.

So, this is an example of exactly what we did. We developed a approach that we call repeat injections to try to get to some of these very slow desorbing sites. So, basically what we do, we take a cocktail of bentonite colloids, we pre-sorb cesium onto them and then we inject them through a column system.

We get these breakthroughs. We collect the fraction of the effluents at the peak of the concentrations and we re-inject them in a second column. We do the same thing for the second injection, we collect the effluents and inject them into a third column and we get these breakthrough curves.

What you see here in red is the breakthrough of cesium, and you could see in the first injection we get recoveries of C/C0 of about 15 percent. But as we inject this solution into a second column and into a third column, the recovery rate of cesium increases significantly. When we processed these breakthrough curves through the same model that I showed in the previous slide, we were able to measure the desorption rates. And what I want to highlight here is that through the third injection, we can actually measure desorption rate that are an order of magnitude slower than that we were able to measure in the field.

These desorption rates are very close to zero, which means that the cesium on these sites is sorbed irreversibly to these colloids and will transport at the same rate as the colloids.

So, in terms of this is a summary of what we learned from the CFM model, so we learned that for the time scales of hundreds of hours and six meters that we are able to interrogate in the CFM experiment, the answer to whether colloid transport is relevant is yes.  But for these specific conditions, going beyond these distances and time scales is a big uncertainty.

Our lab experiments did bring some answers here and found that the answer is still yes, there is a sub-population of sorbing sites that are strong enough that will facilitate transport.

So now, I will move to the second concept, where instead of injecting a cocktail of radionuclides into the shear zone, the experiment shifted into setting a bentonite plug in the shear zone and isolating it by two packer systems and looking at how colloids are generated and how radionuclides are transported from this system.

This slide shows more details on how the experiment was designed.  So, basically the bentonite was machined into rings that were emplaced on a cylinder and isolated by two packer systems which were instrumented with pressure sensors and other pH meters and other sensors.  The radionuclides were introduced into the bentonite rings here that were put in glass vials.

The idea is as you emplace this setup in the shear zone and as the formation water comes into contact, the bentonite will swell and will develop enough pressure to break the glass vials and release the radionuclides in situ, which will then sorb to the bentonite materials and as bentonite starts releasing colloidal materials, radionuclides will get transported with the flow.  So, this is the concept of the experiment.

This slide has a video that illustrates the concept.  So, this is the tunnel area where the packer is, and the bentonite is isolated between two packer systems. And as soon as it's emplaced in the system, formation wall will come into contact with bentonite which will swell and start to release colloidal materials which then will transport with the flow towards the observation point which is set at the tunnel level, or at least this is the conceptual model.

After 400 days, these are the initial results. So, what we have here is a planar view of where the bentonite plug was emplaced and satellite observation holes. Initial characterization of the system showed that most of the flow in the system goes from the main borehole to this red observation borehole. So, instrumentation was set here initially, and this plot here shows that after 100 days we start to see the arrival of the tracer.

These plots here show that immediately after emplacement, the pressure increased significantly in the other packer and there was a little pressure gradient between the back packer and the front packer. This is a summary of the results after four years of monitoring. So, basically, there was some recovery of the tracer, but very little compared to what was injected.

There was a gradual increase in turbidity which is meaning that the colloids are being generated from the bentonite. The electrical conductivity of the system increased significantly compared to background and then drop down, this is consistent with dissolution of salts present in bentonite. The redox conditions in the system went from oxidizing back to reducing which is the natural redox condition in the formation; pH also reverted to the formation conditions.

In summary, after four years of observation, they only observed trace amounts of colloids in boreholes that are five to six centimeters away. There were very trace amounts of technetium also observed in these observation holes but it's important to note that they did not see any trace of either the tracer or the colloids at the tunnel level. And there were no indications of any transport of the actinides injected in the system.

So, this is a summary of our participation in the CFM experiment.  So, it was a unique opportunity to validate or test some of the models that were developed at LANL. Insight was gained on how to actually obtain defensible answers to predict radionuclide transport in association with colloids.  And more importantly, a mathematical formulation of colloid-facilitated transport was developed to take this into account.

Two reports were produced in 2016 and '17 that summarize the state of knowledge in colloid-facilitated transport and the mathematical formulation on how to implement this is a PA system.  Site-specific investigations will still need to be performed to gain confidence for a specific site.  And the colloid-facilitated transport ladder can be applied to gain an understanding of the potential for colloid-facilitated transport in any rock system.

This slide summarizes the two conceptual models for colloid-facilitated transport.  If you assume your system is controlled by equilibria, if you have a non-sorbing radionuclide, it will come out immediately.  If you have some retardation, it will come with some retardation. The colloids in the system will tend to push the breakthrough of radionuclides towards an early exit because artificially they reduce radionuclide sorption to the surface.

If your breakthrough is controlled by kinetic consideration, then the most important parameters in the system are going to be the desorption rates of the colloids from or radionuclides from the colloids and the filtration rate of the colloids in the system. So, for colloid-facilitated transport to be relevant, you need to have very slow desorption rate and very slow filtration rates.

Intuitively, when you think about this, the only case where you would think that this could be really relevant is the case where radionuclides are generated from the waste form degradations and they are incorporated into the structure, which basically would give desorption rates close to zero. That might be the one case where colloid-facilitated transport would be relevant. That's all I have.

ILLANGASEKARE: Okay. Thank you. And really your conceptual slide is very useful. So, I think I'm going to follow-up with that question we had for you. So, one of the things we said in the question was that a lot of colloidal work have been done in various other applications.

So, are there any differences in the conceptual model for this type of situation, we are looking at very low permeability material and fractures. Any new concept for the -- are there any differences in that concept compared to traditional conceptual models of colloidal transport?

BOUKHALFA: So, the CFM experiment really focused on this specific case where you have a fracture system that's flowing and then you have colloidal materials that will be mobilized into this fracture system. And then that's how we get the transport.

What we learned from this experiment is the only relevant case here where you will have significant transport is if you have a very dense population of colloids and if radionuclide sorbed those colloids in an irreversible manner. Those are kind of two critical conditions that will define on whether you will have transport or not, and it's applicable to any other system.

So, what's important is how much colloids you are producing in the system and how strong your pollutants are associated with those colloids, and you can apply this for radionuclides or to any other contaminant.

ILLANGASEKARE: Yes. So, follow-up, so in your modeling, you are using still classical colloidal transport ideas, is that correct?

BOUKHALFA: Yes.

ILLANGASEKARE: Okay. So, there are no differences you see in these type of scenarios, traditional colloid models may or may not work.

BOUKHALFA: What do you mean by traditional?

ILLANGASEKARE:  Yes. I mean, colloid transport have been studied in other applications, Okay, but this particular application is on features, the way the colloids are formed. And then you mentioned that you may also have different types of colloids forms because of the reactions. And then my question has to do with not what you did but I think what you could do.

BOUKHALFA:  Yes.  I mean, ultimately if you look at the way the mathematical formulation is set up for colloid transport, it all comes to if the transport is controlled by kinetics, it all comes to how things desorb from the colloids and how the colloids filter out.

You can go back and look at the properties of the colloids and their charge and how they attach and detach from surfaces to kind of get a better idea on why things transport or not.  But ultimately all that is compounded in this desorption rate.  So, if you look at materials that are like corrosion products or intrinsic materials that are just the oxide or hydroxide forms of radionuclides, this term will be zero. So, basically, you have favorable transport because this will push up.

The other thing is the filtration rate here, too, which if you have positively-charged colloidal materials transported in a positively-charged surface your filtration rate is likely to be really high and the colloidal materials will filter out.

So, I don't know if I'm answering this right, but I feel like these two models developed here could capture a lot of different scenarios for colloid transport. You just need to parameterize these parameters the right way.

ILLANGASEKARE: So, last question. So, in your model, do you allow for the chemical heterogeneities within the walls, like if your wall is not chemically homogeneous, so if there are points of different surface chemistry.

BOUKHALFA: We don't really, I mean, when we run these equations they do capture that heterogeneity, because all we are looking at is the breakthrough and then assuming that colloids will filter out, so that knowledge, that heterogeneity is captured in the system. But, of course, you will have, that's why you'll have to do site-specific characterizations to get an accurate model.

ILLANGASEKARE: So, basically you are getting is an effective parameter.

BOUKHALFA: Yes.

ILLANGASEKARE: These sort of questions we had (Inaudible) that those effective parameters have to be determined based on experiments, not based on idea.

BOUKHALFA: Correct.

ILLANGASEKARE: Okay.

BRANTLEY: Thank you. That was interesting. So, I'm interested in this, I think it was a model result which says that desorption rate constants increased with time scale. And then you went out of your way to say that's not really what you think is going on. And you interpreted it as a range of sorption sites of different affinities for the sorbate.

So, it strikes me that there are other ways to interpret that. But you asserted that this the way that you are interpreting it. So, what are some of the other ways that you could explain this decrease in the desorption rate constant with the time scale? Because you really only presented one model of how to think about that but no data that convinced me that that was the best model. So, what are some of the other alternative models that could explain it?

BOUKHALFA: You can also consider that in some of these results could be due to the aging.

BRANTLEY: Aging of the colloid?

BOUKHALFA: No, the aging of your radionuclides sorbed to the colloids. And we have done some of these experiments where you prepare your cocktail by adding radionuclide on to the colloidal suspension and you inject them into the column system immediately after you make them and you look at the breakthrough.  And usually you don't get good recovery.

Now, if you prepare that and let it sit for six months and then you inject, you get much more efficient recovery.  And you could interpret that as the systems set, you have radionuclides that diffuse deeper into the colloidal materials and they are slower to come out and that's why you have more efficient transport.

But, again, that's not that different from saying that you have different sites with different…

BRANTLEY:  Are there other models then that you could think of that would explain it?

BOUKHALFA:  I don't know, you put me on the spot, I can't.

BRANTLEY:  What?

BOUKHALFA:  Those are kind of the things that we thought about.  If you have any ideas...

BRANTLEY:  There may be dead ends like couldn't get into dead ends and then come back out or something like that? I'm talking about physical dead ends and pores or something like that.

BOUKHALFA:  You're talking about particulates or solutes, soluble solutes? Because what we have here, these are like for the case of cesium we have cesium that’s sorbed on to a colloidal material in equilibrium between solute and what's on the colloidal material.  The solute does not come out when we inject this through the system.  What comes out is what's associated with the colloidal material.

For the, if the colloids themselves were stuck to the system, we actually capture that in the colloid filtration, not in the radionuclide itself.

BRANTLEY:  Well, but isn't that all model interpretation, I mean, in essence all you're getting is change in something over time and then you have a model that that you're using to interpret that change. And I would think there's alternate ways to think about what the -- even what that desorption rate constant means.

BOUKHALFA: I mean, this is the best attempt from us to find an explanation on why as we go to longer observation times, we see a reduced amount of radionuclides that transport, but it's still there in the model, the only way to account for that is to introduce sites with slower desorption rates.

BRANTLEY: So, let me take a different tack then. So, you used a model and you fit your data and you have an explanation and it's consistent. Do you think it would be useful to try different models with different assumptions and interpret your data in different ways to see if you can find alternate ways of doing this than the basic model that you’ve used?

BOUKHALFA: Absolutely. This is what we came up with. If you have any other possible interpretations, we would love to test them out.

BAHR: Can I?

UNIDENTIFIED PARTICIPANT: Yes, Board.

BAHR: Jean Bahr, Board. A couple of things; one is just a clarification. At the very beginning, you implied that colloids travel faster than the fluid, and I think what you really meant was that they travel faster than the average fluid because the colloids make their way preferentially through the faster fluid paths. They're not actually moving faster than the fluid, is that correct?

BOUKHALFA: Correct.

BAHR: Okay.

BOUKHALFA: It's size exclusion. And when we do the experiments, we always see colloids arrive before the tracer.

BAHR:  Right.  Right.  Just so the people weren't confused about that perhaps being some other mechanism.

But getting back to your -- I'm not clear how you were measuring the -- were you measuring colloids separately from the radionuclides, and is that how you were able to tell that there were radionuclide-free -- more radionuclide-free colloids at the end, and that's what was slowing down or were you -- was it just the radionuclides that you're measuring in your breakthrough curves?

BOUKHALFA:  So, when we do this breakthrough curves, we do count the colloids so that we know our colloid concentration.

BAHR:  You count the colloids.  Okay.

BOUKHALFA:  And we do measure what's on the colloid and what's in solution.

BAHR:  Okay.

BOUKHALFA: We just do centrifugation, ultra-centrifugation so we can separate those and we can characterize both the solute and what's hit the colloids.

BAHR: Yes.

BOUKHALFA: Yes.

BAHR: In your erosion model, you seem to be assuming that when those vials break with the radionuclides in them that the absorption is going to be instantaneous. Is that a realistic assumption?

BOUKHALFA: I wasn't part of the experiments, but from my understanding of the materials from the experiment is that before setting up the field experiments, they did a bunch of tests in the lab where they actually set up the bentonite plugs and put the glass vials in them subject to the formation water to just ensure that the vials will actually break under the pressure.

And my understanding is, yes, they did confirm that, and they looked at that at how radionuclides sorb in that scenario before going to the field experiment.

BAHR: Because one alternative for sort of the lack of visible radionuclide transport might be that it didn't sorb to the colloids, but it actually ended up sorbing to the fracture wall. And so, it was never -- they were never moving with the colloids.

BOUKHALFA: It's possible and the entire setup of the main borehole and the satellite observation holes was cored and sent to the partners in the experiment, and they are doing forensic examination to basically see where the radionuclides went. And they will be able to answer some of those questions. But you are right, we don't know where they went, and we don't know why they never transport beyond the five-six centimeters scale.

BAHR: Okay.

ILLANGASEKARE: The Board staff and consultants.

BISH: David Bish, consultant to the Board. Just a quick question, can you tell me what the flow rates are in your experiments?

BOUKHALFA: So, before the emplacement of the giant packer, those flows were, I believe, somewhere around 600 mils per minute.

BISH: And can you comment on how representative that might be of the natural environment?

BOUKHALFA: That is in one natural environment, one test system, the interesting thing in that fracture system is as you can see these field experiments you don't have the luxury of time. As we try to pick a system that may be is an extreme for what you want to see, so I'm not sure that high flow rate is representative for other systems but it's a nice system that allows you to test extremes.

ILLANGASEKARE: Thank you. Any other?

BAHR: We are at time for lunch. Yes. Well, thanks to all the speakers for an informative morning. We have a one-hour lunch break so we'll be back at 12:45 to start with the final afternoon session of the workshop. Thank you.

(LUNCH)

BAHR: Okay. Welcome back to the afternoon session of our workshop. I'm going to introduce two speakers at this point because they're going to be doing the tag team. So, this is going to be a session talking about the Department of Energy's research on salt.

And the first speaker will be Kris Kuhlman from Sandia National Laboratories. Kris has a PhD from the University of Arizona in hydrology. And he's an expert in a coupled flow and transport in a variety of hydrogeologic settings.

We heard from Kris when we were looking at the deep borehole disposal and a number of other things. And then he's going to be followed Phil Stauffer from Los Alamos National Lab, who has a PhD from UC, Santa Cruz also a hydrogeologist.

And he's the lead at Los Alamos for the salt research and development program. And we heard from Phil several years ago when we had a meeting that was focused on salt in Albuquerque, so take it away.

KUHLMAN: Okay. So, I have a visual aid. This is actually Phil's, so maybe you guys can pass it around, but this is a piece of salt from the Waste Isolation Pilot Plant.

And you can see little fluid inclusions in it, so that's something to look at while talking. Okay. So, this talk is a departure from what we've kind of heard so far because, first of all, this talk is about salt, which has maybe we have mentioned in passing but hasn't been discussed thoroughly yet.

And also, this -- we're talking here about a test which the DOE Office of Nuclear Energy is itself doing rather than simulating somebody else's test. So, this is some work that we're doing and we're in the process of implementing it.

So, we're -- rather than having a test being done already and everybody talking about how we're going to interpret the data, we're kind of at an earlier stage.  And so, we're going to give you -- I'm going to give an overview of the test itself and then Phil is going to get up and talk about some of the preliminary modeling that's been done to refine the test and kind of tie it all together.

So, the team that we have working on this is a pretty large team from Sandia, Los Alamos and Berkeley.  And we also rely heavily on the Waste Isolation Pilot Plant to provide the site and to provide support from their test coordination office, these guys.

They're actually Los Alamos employees but they're in Carlsbad and they work in the underground and really without them none of this could happen.  So, as part of the departure from all the other presentations I have kind of a slide here that talks about why would you want to use salt as a disposal medium?

And so, I'll talk to you about the benefits of salt. We've heard a lot about the benefits of our argillite and crystalline repositories, but now to kind of juxtapose that. So, salt has a lot of benefits, especially from the point of view of long-term performance assessment.

So, we're thinking long time scales and large distances. It has a very low connected porosity and permeability in the far-field. A lot of people would essentially call it impermeable. There is no, really, no flow in far-field.

It has a relatively high thermal conductivity, about double that of dry bentonite. There's really no flowing groundwater, which is probably pretty similar to argillite in the far-field. It’s is kind of a diffusive --- diffusive domain.

One of the things that makes salt beneficial is that the hypersaline brine found in it is, it's not devoid of life but I would say it's biologically simple. There's a very few halophilic species that can survive. I wouldn't even say they can necessarily thrive, but they can survive in salt.

I mean we use salt to preserve food. So, it does a pretty good job. You get the activity of water low enough and nothing can really live. Also, it has less-stable colloids, think back to Hakim's talk. There, a lot of talk about colloid facilitated transport.

Well, when the salinity is really high, a lot of that colloid facilitated transport gets shut down, so that's another benefit of salt as a medium, especially chloride and to a lesser degree boron, the high concentrations of those seen in brines will really reduce criticality concerns because they -- if you have waste packages that get flooded by a really strong chloride brine, the chloride itself will kind of poison any criticality issues.

And the excavations, any damage around the excavations and any fractures associated with excavations themselves will eventually creep closed. And this is similar but maybe to a higher degree than argillite.

Argillite, there is some healing and closing and plastic flow around excavations.  But in salt it's even more so. And to the degree that you can actually take mined salts, you can basically take the gravel and sand-like material that you get from just mining and you could just pile that together and it will all creep and flow back to intact salt.

So usually you don't -- I mean, argillite will heal but you don't backflow with crushed argillite and I think it's going to heal but salt will do that.  And so, in the -- that's typically -- that's how the Germans backfill their repositories.

They backfill it with crushed salt or mine salt and then it's supposed to heal back to intact conditions.  Now, these long-term benefits which are kind of why salt has been considered for so long, dating all the way back to the National Academy of Sciences studies in the 50s, it's tempered by some near-field so short-length scales short times -- near-term complexities.  The hypersaline brine which is biologically simple is also very corrosive.  If you put any metal in it and it's -- especially carbon steel, you're going to get a lot of corrosion.

Salt itself is very soluble in fresh water. So, not such a problem in bedded salt, but sometimes if you have domal salt where you might have an aquifer up against, you could theoretically get some kind of catastrophic dissolution of the salt.

To handle the brine chemistry and understand the actual activity of what's going on of all the species, you need a complex model like Pitzer. Just a simpler approach is just not going to cut it in these brines, so it makes the prediction of chemistry in these salts a little more complicated.

UNIDENTIFIED PARTICIPANT: Pitzer is the brine element model?

KUHLMAN: No. Pitzer is a way of handling activities of water in geochemistry models. It's not…

BAHR: It accounts for the changes in the effective concentration as a function…

KUHLMAN: Yes. It's an approach. It's not, it's not a numerical code. It's an approach. Pitzer is some papers in the 70s by…

UNIDENTIFIED PARTICIPANT: Pitzer.

KUHLMAN: By Mr. Pitzer, yes, Dr. Pitzer. Yes, sorry, I actually don't know his name. And the salt creep which here causes excavation; it causes all the damage to go away, also it requires drift maintenance.

If you open a repository and want to have it standing open for 50, 60 years, the rooms close about the rate your fingernails grow. So, in all the course of weeks and months it's not a big deal, but over decades you end up having to kind of re-mine the rooms out because they just keep getting smaller.

So, these are complexities which they've had to deal with at WIPP, some of the excavations that WIPP were open to about the early ‘80s.  So, it's a complexity, I mean, it's definitely can be dealt with but that's something you have to deal within a salt repository.

So, the talk will be -- I'm going to give the first half here about the brine availability heater test that we'll be conducting at WIPP.  What we're measuring.  Why it's important.  What we expect and international collaboration that's been ongoing.

And Phil will talk about the second half here about what coupled processes are important in numerical modeling.  What constitutive laws are important?  And international collaboration that's happened on previous tests at other locations and then modeling the tests that we're doing at the Waste Isolation Pilot Plant.

So, what are we doing?  We're calling the test The Brine Availability Test in Salt at WIPP or BATS.  And the kind of one sentence description of the test would be we're monitoring the initial brine distribution, brine inflow and brine chemistry that results from heated salt using geophysical methods and direct sampling.

The next few slides will kind of unpack that one sentence. This slide is -- since we have boreholes that are currently being drilled, well, we actually finished drilling last week, so the drilling is complete. Went down to Carlsbad, we brought the core back up to Albuquerque.  We're going to stretch some analyses on the core already.  So, we're in the early stages of this. We've drilled the boreholes. Obviously, there's a lot of work left to be done.  But it still looks like testing will begin in 2019 and will run into 2020.

And we have a shakedown test that's ongoing.  And the shakedown test was a simpler version of just certain aspects of the test, so that we could test certain instruments and things out to refine the design before we get to the actual test.

So, yes, here you can see this is our first core out of the borehole that was on February 7th and the last core was collected I think last Wednesday.  And, yes, here is the drilling of the boreholes at WIPP.  There is Doug Weaver. He's the head of the test coordination office in Carlsbad. I think some of you that went down it last October have met Doug.

UNIDENTIFIED PARTICIPANT:  Yes.

KUHLMAN:  Got to see some of this in person.  Here is the doughnut chart and here is the BATS test over here.  You could see that by the color coding we're mostly interested in near-field perturbations.  And we're kind of in -- we're in near-field.

Salt usually doesn't have -- it's a little different.  We don't have an EBS like maybe argillite does.  It's -- sometimes you backfill with mined salt I guess that could be considered an EBS but this test we’re looking more at the effects of the host rock itself.

So why is brine availability important to the safety case, since brine availability is the focus of the test? Brine availability is the distribution, say, the initial distribution of brine and salt and where is the brine and what types is it. And how does then does it flow to any excavation you make. So, you have to have it there and then you have to be able to get it to the excavation, and that's kind of the essence of what we're calling brine availability.

And why is that important, for these main purposes, the most important being that understanding what happens in the near-field and in the short-term is essentially the initial condition to any long-term performance assessment models.

It tells us about brine migration and brine redistribution around the drifts and also the evolution of the disturbed rock zone and its associated porosity and permeability. The far-field, the permeability and porosity of salt is almost zero.

So, any damage that develops around the excavation, we're very interested in how that evolves and then how it again heals with time.  And so that's part of what we're looking at here, because that porosity and permeability is how the brine is going to flow into our excavation.

Brine itself was already mentioned, causes corrosion of waste packages and waste forms.  It's another long-term performance interest.  Brine is the primary radionuclide transport vector, I mean, if you dissolve radionuclides in brine and then they could be transported.

But in salt, the main example we operate on is WIPP.  And at the Waste Isolation Pilot Plant there is no far-field transport unless you drill through the repository with a human intrusion, but that's still -- that's how it's transported as they drill through and the liquid comes up.

Liquid back pressure, you could imagine if you have enough brine flow into an excavation and then the excavation just keeps getting smaller and smaller, you'll get to a point where the gas is compressible, but if you had liquid brine in there it could actually resist the final closure of that excavation down to nothing.

So that's another thing that can be potentially considered. And these photos on the bottom here show different brine availability tests or they didn't call it brine availability tests but tests from the history of WIPP where they test the different components of things that we're also looking at.

This was a heated brine migration experiment in vertical holes in the floor. These were some canister corrosion tests where they actually dug a trench, filled it with brine, and then put canisters in it.

And then here is a large horizontal drift made with a tunnel boring machine and a little bit of brine flow into that. So, for the BATS test, this is kind of our little cartoon of -- this is an excavation here, showing the different types of damage that are typically experienced.

You have fractures all around the drift. You have clay seams. You have anhydrite layers. You have rock bolts.

You have all these complexities. And our ideal is that we're going to drill a horizontal bore, well, we've already drilled them.

We're drilling horizontal boreholes into the wall so as to avoid these large discrete layers in the floor and in the ceiling. So, we're drilling it into a relatively uniform halite layer horizontally and we're setting a packer and putting the heater beyond the disturbed rock zone associated with the room itself.

So, a little bit more about the test interval itself, this is kind of a cross-section through the heated borehole. You can see the packer there, this gray blob. And on the backside of it, so further behind it is a heater. It's a quartz lamp heater. And we're going to -- there is certain amount of plumbing where we're going to flow nitrogen behind the packer and the dry nitrogen is then going to remove moisture.

And we're going to measure the accumulation of water in the borehole by flowing nitrogen through and measuring the humidity of the nitrogen stream.  We also have a centralizer that's measuring borehole closure with time and gas permeability before and after.

Sorry, I forgot to mention this on the previous slide, but we have -- we basically have two parallel tests running.  We have almost identical tests, about 20 feet apart on the same drift.  One is heated one is unheated.

So, we're collecting all this information and doing this test under ambient conditions and then doing it again, heated to about a 120 C.  So, the point is to compare and contrast what effect the heat has on brine availability, because we'll look at brine availability under ambient conditions and also under heated conditions.

We'll be collecting a lot of samples, cores that have already been collected now.  We're packaging them up to send off to NETL, the national lab in Morgantown, West Virginia where they're going to actually CT scan the cores and we get to see the distribution of all the different non-halitic minerals in there.

And the gas stream, we're going to be monitoring the gas stream in the underground.  We'll have cavity ring-down spectrometer and a quadrupole mass spec hooked up to the gas stream and we'll be measuring compositional real-time, all these -- the isotopes and composition going by.

We'll be collecting the liquid brine samples from grab samples and we'll be analyzing those to look at the natural chemistry and the added tracers we've added.  There's a fair amount of geophysics going on. Yuxin Wu had a poster yesterday and he talked about some of the electrical resistivity tomography work we're doing.  They've already tested a little of that in the underground.  I think it seems to be working pretty well.

We'll also be looking at acoustic emissions from the heating and cooling in the salt and the fracturing and ultrasonic travel time tomography, basically pinging between ultrasonic sensors and measuring the travel time. We'll have a distributed strain sensing and distributed temperature sensing through fiber optics that are being grouted in the boreholes and a mass of thermocouples.

So, from all these instruments, we're going to look at the brine composition of samples and water isotopes to look at how changes in the sources of the brine, where is the brine coming from or where is the water coming from?  What source is it coming from?  And we'll be using the geophysics in 4D, basically, we're taking snapshots and comparing them through time of the saturation porosity and permeability.  How it evolves during the test.  We'll be looking at the temperature distribution in a lot of detail, a lot of measurements because more brine is available at high temperatures than at low temperatures.

And the thermal expansion of brine, Jonny mentioned it yesterday, this thermal pressurization effect you can get. That can happen in salt too.  And that's maybe one of the significant driving forces.

And the temperature may also cause dry-out immediately around the borehole in the hottest regions.  Gas permeability and the borehole closure are going to give us some information about the THM evolution of the test, how is the coupling of the thermal, mechanical and thermal hydrologic occurring right around the heated borehole.

And we're going to be adding tracers so that we can look at both liquid and vapor movement through the salt and try and get an estimate on how effective each one of those is around an excavation.

We'll be doing some post-test overcoring. We're going to overcore so that we can -- we'll have a time distribution of tracer breakthrough in some of the boreholes and then we'll overcore after the test and we'll see the spatial distribution between the source borehole and the final borehole. And that will hopefully be used to help calibrate some of our numerical flow and transport.

So, brine and salt is maybe a little different than other media. So, since brine availability is the focus of the test, I'm going to spend a little bit here just laying out what -- why brine availability is something that you would focus a whole test on because there's really no flowing groundwater in the salt, but it is definitely not dry.

It's less than 5 weight-percent water. But the sources of water ranked here by amount so that the most water in salt is actually associated with hydrous minerals. So, it wouldn't be free water like you would typically, but there's a lot of hydrous minerals in evaporate deposit.

And actually, most of it is associated with clays. So, the little pockets of clays which actually have pore water and hydrous waters incorporated with the clays. You get things like bassanite and gypsum that are different hydrated forms of calcium sulfate.

And you have intragranular brine, which is fluid inclusions like what I passed around. And here's a photo of one. You could see they are sometimes colloquially referred to as negative crystals. So, it's basically it's a hole that looks like a crystal inside the crystal and it's usually filed with brine. But that's kind of a misnomer. But that gives you an idea of what it means.

And then there is intergranular brine which is more or like the type of porosity you would see in like a sandstone, where you have grains and you have porosity between the grains.

Now, the brine content -- total brine content in WIPP salt correlates well with clay content, so essentially means that clay is the most significant form of -- the water associated with clay is the most significant form of water in the salt.

But only intergranular brine which is actually the third most common form of brine, only intergranular brine moves under a pressure gradient. So, if you have a pressure gradient, high pressure in the far-field, atmospheric pressure in the near-field, the only type of brine that's really going to be moving is intergranular.

But the brine that's trapped in these little inclusions in the salt is not going to respond to a pressure gradient unless really -- I mean, that pressure gradient is actually destroying the salt.  But these different types of water actually respond differently to heat.

You'll get -- hydrous minerals will evolve, basically, each hydrous mineral has a different characteristic temperature where it evolves water.  And then that steam may condense and dissolve salt away and flow into the borehole, it might flow right into the borehole as directly as steam.

And you can also have intragranular, so basically fluid inclusions will actually migrate themselves through the crystal if you have a temperature gradient applied across them, it will -- this difference in solubility across the fluid inclusion will cause the fluid inclusion to move in salt.

So that's typically only important at like centimeter scale, but what happens as you have, say, a centimeter crystal and the fluid inclusion moves to the edge of it, it becomes intergranular brine then. So, it's like a temperature gradient dependent source term for brine.

So, all these types of brines have different chemical composition, we had a recent report where we showed that they can be differentiated chemically from each other. And we think that they have a different isotopic composition based on a limited number of samples.  But these are things that we're going to test in the current field test.

And so, the question we hope to answer with the field test is how do these three water types contribute to brine availability?  Because it's true people have looked at how much brine flows into an excavation in salt but they've just said brine is brine or water is water.

Well, these three different types of water, they respond differently to pressure and they respond differently to temperature, so if you want to know exactly how much brine is going to flow into an excavation and what timing it has, you need to understand how those three different types contribute to it.

It's kind of maybe an open question which our field test is addressing that has never been looked at before, so maybe it's a detail, but I think it's an important detail if you want to make a physics-based prediction going forward.

So, a little bit more about the conceptual model, we have heated and unheated versions of the same test.  Salt like many rocks, it’s been mentioned already that the hot side of things is maybe where things are more complicated.  Salt is especially, I'm going to say maybe thermally activated because salt creeps but hot salt creeps much faster than cold salt.  And there is more brine available in hot salt because now all of a sudden you have hydrous minerals, you might be dehydrating those depending on the temperature you get to.

These fluid inclusions might migrate to the edge of a crystal, so there's more brine potentially available.  And salt itself is more -- it's temperature dependent solubility.  So, there’s just more things going on in hot salt than there are in cold salt.

And high temperatures can lead to dry-out of the salt around the heater.  And this little diagram down here shows what's kind of often referred to as heat pipe, but you basically have the hot waste package here in red and your water is driven off as vapor and it deposits a crust.

And you can see this is one of those vertical boreholes at WIPP.  This is a heater.  They drilled a 36-inch hole and they -- they drilled a 36-inch hole, set the heater and it heated.  The borehole closed shut and it actually deposit -- evaporated enough to deposit salt on there and caused the heater to stick to the borehole wall, that when they pulled it out it came out as one unit.

And so that's what happens here.  The steam goes away.  Salt is deposited, and your near-package permeability is reduced because of that.  And brine is corrosive, but dry salt is not necessarily corrosive.  So, if you have a dry salt environment around the steel waste package it might not actually be as -- not as corrosive as a wet brine environment.

And so, trying to consider these in coupled models is complicated. You have to consider creep, damage and healing and the effects those have on porosity and permeability, so that's a complex coupling.  We have to look at precipitation and dissolution of the minerals, so as you're precipitating salt around the heater, vapor flows out until it gets to the point where it condenses.

Well, now you have de-ionized water in the far-field and it dissolves in salt it cools in.  So, you can actually have the creation of porosity in the far-field and a destruction of porosity in the near-field.

And then you also have relative permeability effects.  You have the migration of brine in areas that are vapor saturated or liquid saturated can exchange.

So, what do we expect from this test? In the unheated array, we're going to look at -- we're going to have a peak in brine inflow and it's going to decay with time.  When you turn the heater on, you're going to have a new peak associated with turning the heater on.  You're going to get dry-out around the heater and you're going to have decreased permeability and porosity.

When you turn the heater off, you're going to have increased permeability because now there's a contraction and all of a sudden, the permeability and porosity are increased.  So, you'll get another peak of brine inflow when you turn the heater off.

And I think these geophysical methods that we're proposing are hopefully going to help us see that, and we're adding natural and man-made tracers to help us understand the actual advection and dispersion of these through the field.

So just a bit here about integration with GDSA, which Emily is going to talk about more, we actually have a seal component and that relates us back to the engineered barrier system.  We're going to put a cement seal on a borehole and look at how it interacts with the salt.

We think that the improvements we make to our models, what Phil is going to talk about, feed back to the models we used to predict tens of thousands of years into the future.  And future tests may have, be hotter and considered buoyance issues for dual-purpose canister disposal.

So, one last point about ongoing international collaboration, we already have a pretty strong international collaboration with several parties. And around the world, there are different kinds of salt. I think I hinted at this that we get bedded salt that at WIPP. There is also domal salt which is dryer but more complicated geometry. And there's pillow salt is what the Germans call it which is maybe halfway in between.

We have an international collaboration every year called the U.S.-German workshop. But now it has contributions from several countries. This year it's in Rapid City, South Dakota. It's in May. And then we also have NEA Salt Club meeting at the same meeting that will be coming up.

And we have several model validation experiments going on with some German colleagues. And as Jens already mentioned, there's a possibility that those tests will be a DECOVALEX 2023 task.

So now I'm going to pass this off to Phil. He's going to answer all your questions.

STAUFFER: All right, thank you.

Okay. Good afternoon, everyone. And I'm going to be discussing the modeling as Kris said. And these are some of the goals of the modeling that you can read up there. One of the big things that we try to do in our efforts is to have a constant loop back and forth between the data and the modeling, always looking for new data sources to help us improve our modeling, and, figuring out ways to design the model so that we can take advantage of data coming out of the field. It's not always that easy.

So, what we're looking at is trying to understand these repository processes, gain confidence in the long-term predictions. And we don't have a hundred years or a thousand years to sit and watch what happens in a heated salt test.

So, we have to figure out ways of doing these things in decades. So, we're also exploring uncertain processes and inputs. That's really where this loop comes in, and then integrating the process physics into the GDSA performance assessment.

And I'm going to try to point out some examples of where we've recently had simulation results that are backed up by experiments that are guiding parameters that are going to go into the safety analysis.

Clicking the button. The bottom button. This one? Oh wait, hold on. Okay. So, with the thermal hydro mechanical chemical process level modeling, we have certain tools that we have been using.

TOUGH-FLAC is what Jonny Rutqvist has been talking about, developed by the Berkeley team in collaboration with the Europeans. And TOUGH-FLAC can do large-scale deformations where you're looking at entire rooms closing.

FEHM designed at Los Alamos the finite volume code. We can do THMC but only on small deformations. So, we don't recompute the numerical mesh and allow for those larger deformations.

When we're doing these simulations, we don't always include all of the physical processes. It just becomes too overwhelming, and to get at individual pieces of the puzzle, you need to be able to see what's going on.

So, in some of these experiments and simulations, we try to isolate individual processes and validate the models using thermal hydrologic, thermal mechanical, combinations of the different processes.

And this takes some planning to be able to design an experiment where you preclude some of the processes from happening. But it makes the interpretation a heck of a lot easier than having everything all going on all at once, which is what our current field test will have.

And in the bottom, you can see from some of our previous work, looking at canisters buried under a pile of salt. This is an image from the shakedown test where we had an existing borehole that had been drilled in 2013.

And we were able to use that borehole and some surrounding boreholes to collect thermal data. And this shakedown testing really helped in our -- the evolution of our current test plan. We were able to learn a lot from that. And this just shows a two foot by two foot by two-foot cube that we have in the laboratory for testing -- running mined salt.

All right, so Kris talked about some of the couplings that are going on. In deformation, we've got strain as a function of stress, time, saturation and temperature. And I've color-coded these. So, you see temperature crops up in many of these feedbacks to the physical processes. Porosity is in green. So, porosity can change by dissolution and precipitation, stress and strain.

Thermal conductivity is a really interesting one because the thermal conductivity is a function of porosity, saturation and temperature.  And all those things are evolving through time, especially in the granular salt.  Anyhow, lots of couplings going on.  An interesting one I'll be talking about a little bit later here is the water vapor diffusion and capillary pressures.

We mentioned clay dehydration earlier.  And we have a paper with Hakim in Environmental Science and Technology where Hakim ran experiments, looking at how much water comes out of the salt as a function of temperature, and then we coded that up in FEHM and ran some simulations, showing how the increased availability of brine would impact the system through that multi-phase heat pipe that Kris mentioned earlier.

Someone previously had asked, well, what do you do when the porosity changes?  Shouldn't the retention curves also change?  And while we were exploring these processes in the FEHM simulation tool, I had a PhD student who got interested in that exact point.

And if you look at this plot, I know it's hard to see but one of the axes is porosity and another axis is saturation. And the capillary suction is a function of both the porosity and the saturation.  So that as the porosity goes to one, so a completely void space, there is no capillary suctions. It's just a flat line, no matter what the saturation is. That'll be like your glass of water.

And so, with a simple functioning we're able to show that as things dissolve, the capillary suction should drop to zero and the model behaves a lot differently than having a hard-wired function that has a minimum saturation regardless of porosity.

Okay.  And so the importance of some of these processes in a larger scheme is in the performance assessments especially, figuring out the damaged rock zone or the EDZ, it's also called, because that's a potential pathway for transport if you have the drifts that are hundreds of meters long, and they're backfilled with the run of mine salt, if the permeability and the porosity of that don't close in as fast as we think then you have a permeable pathway that can last longer.

And so, for the safety case that feeds in, the same ideas in the damaged rock zone and then just understanding these processes as the short-term decade-long tests are done, if we have the ability to simulate what happened, explaining it through physics, then we have enhanced our confidence.

We have the roadmap that was talked about from the 2010, 2011 timeframe.  And we recently revised that in January of this year.  We have a report coming out on that.  We learned that maybe we were missing some things.

One of the experiments we had done in our laboratory produced a significant amount of hydrochloric acid.  And so, we added a task to our analysis, trying to understand where the hydrochloric acid is coming from and will that be an issue for the long-term performance, and then, of course, in the international community.

So, this is just an example of one of the -- constitutive model issues that we have, which is the deviatoric strain as a function of stress is not a flat line. And so, a lot of the laboratory experiments are done up here at very high rates of strain and large deviatoric stresses in the upper right.

And if you project the data from the lab conditions down to low deviatoric stress, you would expect to see very low strains. However, we are fortunate to have some in situ data that suggests that there's a band in this constitutive law which allows creep to happen much more rapidly than we thought.

So, strain at low deviatoric stress is something that we're trying to get a handle on, and then also granular salt reconsolidation, granular salt when it's wet and at high temperature will reconsolidate quickly. But if we're boiling all the water off the granular salt, it might be wet for a while after we heat it up.

Okay. So, this is an example of data from the heater test at the Asse Mine and it really pulls out the influence of temperature and moisture. We have a heated area in red and a non-heated area in green. And this is showing the change in porosity as a function of time up to almost a decade. So, this is not a short test. And so, in the heated area, you have a much faster decrease in porosity.

And plasticity is higher at temperature than the non-heated regime. And you can see this is also a code comparison between the TOUGH-FLAC and FLAC-TOUGH which are two versions of the codes coupled in different ways by different research teams.

Is that correct, Jonny? Yes. So, the Germans have coupled TOUGH-FLAC and they call it FLAC-TOUGH because they are the FLAC people. And at Berkeley they've coupled TOUGH and FLAC and so they call it TOUGH-FLAC because they are the TOUGH people.

Anyhow, really good results on that, and then we've also got matches to the temperature as a function of time in the two cases. And this is getting at how long does it take to complete compaction and sealing in the backfill.

So, the next slide -- at least it's working. The next slide shows how we've used the validated model over the eight-year timeframe, which is going 0, 1, 10 years. So, we have data up to about here that we feel that the models are reproducing fairly well.

And then this is marching us forward on a recent paper, Jonny and his post doc who's now a staff member, right? Yes, ran a bunch of simulations, looking at the long-term evolution. And this goes out to 100,000 years.

And one of the take home messages from these sets of simulations was that even at a thousand years some of the salt has been packed around the canister only gets down to about a 10 percent porosity at a thousand years corresponding a 10 to the minus 15 meter squared permeability, which is six orders of magnitude, seven orders of magnitude, higher than the intact salt permeability.

So, we're hoping now to feed these types of results back into the GDSA safety analysis, because the safety analysis currently uses some simplifying assumptions from the WIPP program that are -- were not for, using this level of calculation.

Okay. So now, we're going to jump to an experiment we did before the heater testing, trying to get a handle on the evaporation of water and water migrating into a pile of salt that's sitting in the humid air in the WIPP facility.

So, for this, we had pans of salt sitting on very sensitive scales, so we're able to measure the change in weight of that pile of salt as the humidity in the drift air flowing over it changed. So, at low humidity, the salt would give off water and at high humidity the salt would pull water in.

And so, this allowed us to use FEHM. We implemented a new time-dependent relative humidity boundary condition. And we were able to run a simulation. And without any tuning parameters, just using the measured humidity in the drift air in the mine ventilation, we got the following match between the simulation and the data for the percent change in mass of a pile of salt.

And that was really encouraging that our relative humidity functions where the vapor pressure is impacted by capillarity and the dissolved salt concentration.  And so, now, we're moving into the thermal hydro chemical model of the shakedown test.

So, this image shows the drift face, so we're looking in to the wall of the drift in WIPP.  We've got a borehole gridded at very high resolution in the center of the red dot.  This is a three meter by three-meter chunk and then looking at a cross section into the rock salt, you can see the packer and the heater. And that's going in seven meters from this face. And this is just to zoom into the mesh where the heater is. And you can see the high resolution that we've got, the total heater is 0.3 meters long.

And we found in previous simulations that capture the chemical side of things, the front, we needed resolution on the sub-meter scale.  So, this is showing an initial blind prediction where we just used properties of salt we had and what we knew the temperature where heater block was going to be to predict temperatures near the borehole. And you can see our prediction was quite high up here, nearly 55 degrees.

We'd stuck our heater in and we at data at 0.3 meters away where we're getting this very low temperature. So, we scratched our heads and we said, "Well, our model is not behaving like our data. So, we know the data is right, what could be wrong with the model."

And it turns out that we had used a block, a stainless-steel block heater. And upon thinking about this, we realized that the heater was not coupling completely to the wall of the borehole. And so, we set up the simulation where the heater was just touching along the bottom of the borehole so that the heat could propagate through the high thermal conductivity below the heater but not so much through the air, the air gap, like a one-inch gap surrounding that heater block.

And when we ran simulations with this example, we got much closer to the data. And that caused us to rethink the stainless-steel heater block and we replaced it with an infrared quartz heater that was able -- oh, you'll see later. It's a much better choice though for the experiment.

And we're really glad we didn't do this in the real experiment where we had 14 boreholes and we'd spent all this time and money. We did this in an existing borehole at a much lower cost and we were able to learn other things too, but today for time, I'm just showing a couple of things.

And so, one of my post docs actually went into the code and said, oh, if we have that air gap, so what I showed before was just the initial single temperature. Here we ramp the temperature up, the gray curves are the data, this is temperature going up to 44 degrees and time out to 45 days.

As we did a step test in heating, of course, the model without with an air gap just acting as a single conductivity gave this result, but when we put in an effective radiative transport conductivity term based on the temperature to the fourth power, we ended up with results that looked better. Of course, we're not having the air gap anymore. We've got an infrared heater. But this was a good test for post doc to add some code to FEHM.

So, moving on to the real heater test with our new 750-watt infrared heater, we initially had the metal block heater at 120 C. And you can see that the radius of influence of the thermal energy is very small. The maximum temperature is still 120 C but we're only getting a very short distance into the rock.

We ordered a 260-watt heater and took it into the shakedown test hall, put it in and confirmed that it was getting much better energy coupling. And then we've taken a 750 watt now and put it into that shakedown test. And we're getting a region of influence where out to 4 meters you're still getting over a degree of temperature change, so that's what we're looking for in this test. We want to get a strong amount of heating into the salt, so we can see some of these processes going on.

And this is showing a one-meter slice through the 750, looking into the heater.  And you can see that out to one meter, we're getting a 40 degree temperature contour.  So, we're much more confident now that this experiment is going to give us what we want.

And in these images, the drift face is along where I’m moving the green line up, so they're not symmetric.  There are 3D calculations but you're just looking at a slice. And, of course, we had to skew this temperature bar dramatically to be able to see any of this.

Okay.  And so now we're moving into some of the calculations done with TOUGH-FLAC that Jonny Rutqvist did at LBL using a thermal hydro mechanical model in the Lux-Wolters constitutive of relationships developed for domal salt.

So that's one of the issues, are the parameters for domal salt going to work for our bedded salt in WIPP. And so, Jonny set up this calculation, I know it's a little hard to see but starting at time zero, we march along until the borehole heater is turned on.

And you could see temperatures rising, temperatures on this axis going 30 to a 120. Pressures on the left axis and as the temperature rises to the 120 degrees, you can see that the fluid pressure, the blue dashed line peaks here at about 20 megapascals. The in situ stress in WIPP in the unperturbed rock is on the order of 12 to 15 megapascals.

But of course, in the drift air and in these boreholes, 0.1 megapascals atmospheric, so we have this huge pressure gradients over short distances. And they're maintained because the fluid pressures are so high.

And you can see that as the -- once the heater is turned off at this point, the temperature drops dramatically, that the pressures dropped but you also get -- this is the amount of water, flow rate in grams per day. When that heater is turned off, the thermal relaxation as the water that expanded thermally is contracting, allows permeability to open up and you get a major drainage event.

So, our five-year plan for the salt project in terms of the experiment is to finish up these borehole heater tests over the next one to two years. And 2015, we developed a level two milestone, a significant milestone outlining this plan. So, if there's interest you can look that up.  And in that milestone, we outlined a phased approach to the testing -- thermal testing of salt where we would start with small borehole experiments, move to single canister experiments and then eventually get to larger scale tests of multiple canisters at different heat loads. And these are just pictures from that report.

And so, the summary of our progress here moving forward will be -- and then we've got that boreholes drilled.  We've got most of our equipment, the packers, the 150 to 200 thermocouples that are going to be installed.  And we've got the ERT probes ready to go.  And so in the next few months, we're going to be installing all of that in the underground. Once it's all installed, we can turn the heater on and start collecting data.

And so, of course, we're piping this back into DECOVALEX. We should know by this summer whether or not we've been invited into that club. I'm hoping we do get to go to that. I guess that's November, right? November in Switzerland, they'll make the decision.

And then the whole time that we're working on the experiment, we're also trying to figure out ways that we can improve our THMC codes by cycling that image where the data and the model go round and round. And so, as we move forward we'll be -- there should be a loop between the experiment and the modeling at all times. So, if there are any questions.

BAHR: Thanks, Phil. Maybe we can get Kris and Phil both up in front for questions. This is Jean Bahr from the Board. I'll start out. You have some baseline information about the total water that's in the background salt, correct?

So, I guess I'm wondering what kind of, sort of bracketing if all of that were to mobilize, what would that mean in terms of brine coming in contact with canisters or -- can you do some sort of,…

KUHLMAN:  Yes, there is a…

BAHR:  … background PA kind of -- what's the worst case scenario or the best case scenario in terms of repository performance?

KUHLMAN:  Right.  So as was mentioned in one of the slides that -- it varies from borehole to borehole, but kind of a WIPP wide average.  It's less than five percent, weight-percent -- but it's typically highly correlated with clay.

So, if you drill a borehole, you might drill into clay or you might not.  And so, you might get one percent, two percent, five percent.  So, you could -- yes, you can bound it by assuming the worst case and assuming kind of this five percent discount of the max they see, and you got to apply that everywhere and you could see how much brine is going to inflow to the drifts.  But it's highly variable in space and time.

BAHR: And what would be the consequence of all of that brine being mobilized and available in terms of repository performance?

KUHLMAN: I don't think -- for the, like the WIPP performance assessment which is not heated. It's just unheated waste, obviously that's -- the amount of brine is a small amount of that, because it's just the hydrous minerals don't dehydrate into the borehole, so, yes, for the WIPP performance assessment, it's a smaller amount of that and it was totally fine.

I think a little more brine would be available in a hot repository, but I don't think that it would -- I mean, it wouldn't break the concept. The concept is still going to work and the salt repository is still a great idea but just getting a -- rather than just taking the conservative approach and saying, "However much brine flows in, we can handle it," we're actually trying to predict a little more resolution what that is.

BAHR:  Yes, I guess I'm trying to get back to some of the ideas that we heard at the beginning about building the safety case and where does this fall into the safety case. How important is this phenomenon for a high-level waste spent fuel repository in salt?

KUHLMAN:  So, it was -- as was stated, the brine availability and looking at near-field and short-term perturbations is the initial condition for a performance assessment simulation.  And so, getting this right is a lot of details, but it's kind of the initial condition for what you have going into the far-field. So, I guess, hard to say like what the exact impact will be but it's not…

STAUFFER:  I could see a case where the water that is available precludes the porosity from completely closing.

KUHLMAN:  Right.

STAUFFER:  And then when you get your inadvertent intruder which is the only way WIPP fails, then you've got…

BAHR:  But we're not talking about WIPP, we're talking about…

STAUFFER:  Yes, yes.

KUHLMAN:  Right, right, right.

BAHR:  …high level waste repository.

STAUFFER:  But still it's a similar safety case where we think that the far-field is going to be so impermeable that this water will not get out unless there is a way that you can punch through it like an inadvertent intruder putting a borehole into it and if you've got a pressurized pocket of water that's dissolved through the canister, it could carry some dose.

KUHLMAN:  Since we're doing generic research, we don't…

STAUFFER:  So that's the -- we don't…

KUHLMAN:  … we don't look at…

STAUFFER: … intruders.

KUHLMAN: Yes, yes.

STAUFFER: Yes, so, but looking forward to a real PA CA.

BAHR: Okay. Are there questions from other Board members? Tissa.

ILLANGASEKARE: (Inaudible) the Board. So, I like your goals of your modeling because modeling is not for prediction. You are also looking at insights and I also like the idea of isolation of specific processes, so you mentioned that one of the tests was ambient condition, the other one was real conditions, so in the real condition what were you kind of counting on and what are the parameters you found sensitive in the ambient condition data analysis?

STAUFFER: Well, the ambient case will be highly controlled by the damaged zone that's set up by drilling the borehole and also, the type of material that we're drilling through.

So, we said earlier that we targeted a region that had very little clay content.

However, the clay content is gradational and as we got towards the top of our pattern of drilling, we encountered higher clay content and that small -- one of the smallest boreholes had the highest immediate inflow rate that we think is related to the material that we drilled into.

ILLANGASEKARE:  Yes.  The second question, so in your -- I'm assuming some multi-phase field formulation because you are looking at the intergranular brine flow.  Is that correct?

STAUFFER:  Yes.

ILLANGASEKARE:  So that means that you are looking at still very low water saturations.

STAUFFER:  High water saturations but low water contents.

ILLANGASEKARE:  High water saturation…

KUHLMAN:  Yes.  So, the salt in the far-field is 100 percent brine saturated.  And as you approach the excavation, you have increasing porosity and increasing absolute permeability.

ILLANGASEKARE:  Yes.  Yes.

KUHLMAN:  But you can imagine it takes a rock with one percent porosity and you add five percent porosity that's damaged, well, no brine flows into that, it’s air filled.

UNIDENTIFIED PARTICIPANT:  Yes.  Yes.

KUHLMAN:  So, all of a sudden you go to mostly air-filled porosity near the excavation, so the absolute permeability goes up, but the relative permeability of brine actually goes down because it's the permeability of that phase actually.  So, there's interplay of those things going on around the excavation.

ILLANGASEKARE:  Yes.  Yes, so in those extreme conditions in your constitutive models, like relative permeability model, do you -- what type of relative permeability model did you use?

STAUFFER: Well, we've been experimenting with that, and that's what this image was. This is the case where as the porosities drop -- as the porosity is increasing, the capillary function goes to zero.

ILLANGASEKARE: Yes.

STAUFFER: And so, as the porosity is evolving, we're looking at different representations to capture how the retention curves are changing…

ILLANGASEKARE: Yes, so you are not fitting…

STAUFFER: We don't have data, so…

KUHLMAN: But that's some of the core -- we're going to take sub-cores of the cores we've already collected and have mercury injection capillarity tests done to characterize the fracture porosity distribution of the damaged salt.

ILLANGASEKARE:  And my point is that when you try to fit these permeability functions to the range of saturation, sometimes you may predict one part of the retention function, but then the accuracy to that especially low water content then the formula, then the functions become really…

STAUFFER:  This is something we've been struggling with for years.  We got samples and sent them off at one point.  And our contractor reported back that the salt was dissolving too quickly to really find out what's happening.

KUHLMAN:  Yes, so you can inject mercury, or you can inject air, but you start dealing with brine, and a lot of times you will start dissolving the salt away…

STAUFFER:  Yes, you're precipitating.

KUHLMAN:  Yes, we're precipitating the salts. It modifies itself during the test.

STAUFFER: That's one of the parameters that we would love to have more data on.

ILLANGASEKARE: Okay, thank you.

BAHR: I think I saw a question from Lee?

PEDDICORD: Yes, Lee Peddicord, from the Board. I think I need the brine 101 lecture here to get to the first slide.

So, on slide 15 you talked about the different types of salt, bedded, domal, pillow, and so on. And then within those categories are there distinctions of characteristics of salt in each of those or are they, when you talk about bedded salt would you find them more or less the same?

KUHLMAN: So obviously each formation can be different, just like every sandstone aquifer can be different or every clay stone. But salt tends to, I mean the way it works geologically, salt is typically deposited in a Bedded you basically have something evaporating, deposit over a large area, and then it's deformed into a dome or into a pillow, that is if it doesn't make it all the way to a dome.

And typically, the process of deforming it, it's kind of like kneading dough and you churn it all up and the water gets kind of excised from it by the process of domal salt, creating the salt dome. So, you could imagine that there is various amounts of deformation that occur, and you might, it's a spectrum. So, you can get a wide range of behaviors. But typically, domal salt tends to have about a factor of 10 less brine in it than in bedded salt.

But there's variability across the world, but it's not as variable as, say, sandstones or limestones.

PEDDICORD: Stand over here.

KUHLMAN: I'm sorry. Okay.

PEDDICORD: Further.

KUHLMAN: Further.

PEDDICORD: Okay, thank you. Okay, so I think I get that. And then you also on slide 11 you are showing the distinction because of the three types of water, really talked about brine availability. Yes, this one.

So that was very good. But then I guess as I say for brine I conceptually envision this kind of slurry or something…

KUHLMAN: I'm sorry, kind of…?

PEDDICORD: A slurry, you know…

STAUFFER: It's just saltwater. Like the ocean.

KUHLMAN: Yes, very salty. So, the seawater is about 35 grams per liter, yes, and this is about 350. So, it's about 10 times as salty. Yes, as seawater.

You can go back there, there's a salt core, I mean, you could see that little pockets that are left over, that used to have brine in them or in between the grains. The salt itself is, it holds in excavations, it’s not like you mine and it just flows, but you can walk through the excavations and the underground at WIPP, they are relatively intact. But the brine itself it looks like liquid water.

PEDDICORD: Okay, so then finally on slide 9, Dr. Turinsky and I were muttering to one another, this is the brine availability test in salt. And then in your picture up there, there is no brine. It doesn't say anything about brine. Where is the brine in this slide?

KUHLMAN: So, where the brine flows into the borehole, we're flowing dry nitrogen in and that will evaporate so the salt will be precipitated into the borehole, and the water vapor will leave the borehole. And then we are measuring the humidity of the gas stream as a function of time. It's also passing through a cavity ring down spectrometer. You're actually going to measure the concentration of different water isotopes in the output stream. And then it's passing through a quadrupole mass spec. And we're going to measure how much CO2 and helium, and all these other things are in there too.

So, we are basically passing a gas stream through there and analyzing the kind of real time. And that's how we analyze the water.

PEDDICORD: So next time I get to see this slide I want something on here that says brine.

STAUFFER: Yes. That's what we are going to do. It will be out here in the wall.

PEDDICORD: Okay.

KUHLMAN: And there are actually going to be liquid brine samples in other boreholes. Sorry. The brine is really everywhere, but, yes.

PEDDICORD: Well, Okay, put a big thing on there that says brine, then I don't know what brine is.

KUHLMAN: Okay.

TURINSKY:  So, are you measuring the salt deposits also?

KUHLMAN:  Yes.  So, after the test is done when we pull the heat we will essentially scrape the borehole out to get all of the precipitated…

TURINSKY:  And you're not measuring in real time?

KUHLMAN:  No.  We looked into the different ways of doing that and we tried things like having like an access tube while it's heating, and it was just too difficult to get a good sample or to not interfere with the heat.  So, we moved it to another borehole.

TURINSKY:  It's really being (Inaudible).

KUHLMAN:  Well I think the way you could do it is you could heat to different degrees, like have one borehole that you heat for six weeks and you collect the sample.  You have another borehole that you heat for nine, and it's difficult to like interrupt the test and you get the solid samples off.

TURINSKY: So, assuming the boreholes are exactly in the same environment?

KUHLMAN: Exactly.

STAUFFER: And they are not because the gradation of the clay, so we pick the best spot that we -- well, there's logistics so you can't just go anywhere you want in WIPP. It's an operating facility, so…

TURINSKY: So, these, sort of like a level sensitive conductivity gauge or anything for the salt?

KUHLMAN: I think we could theoretically, maybe the next design we might be able to come up with some real clever way of going in there and sampling the solids as the test is passing along. But honestly, we wanted to come up with a test that was simple enough that we think it will succeed, but interesting enough that we think we are going to get some results that will be useful.

STAUFFER:  And as part of the phased approach, any ideas that you guys have will be, get them to us because we could be doing another pattern next year and incorporate new ideas into it.

And one of the big things is we are not getting samples of the solids for sure, but we're also not getting samples of the liquid, we are getting samples of the evaporated liquid which means…

KUHLMAN:  Well, we are getting liquid samples in another borehole but not in the heated borehole.

STAUFFER:  Not in the heated borehole, so.

KUHLMAN:  Because like I said in the shakedown test, we attempted to collect liquid samples like while it’s running and logistically it's difficult, and we just thought let's leave this part out.  And once the test is refined a little bit, we might spend some more time and try to do that better.  But it seemed like a part that was destined to fail, so we left it at that.

PEDDICORD: So, would you run this or is this type of experiment being run in the other two types of salt that you identified as well too?

KUHLMAN: These tests have been run in the past. So, this procedure of flowing dry nitrogen through to measure the brine it's been done at the Asse mine in Germany which is domal salt. It's been done at WIPP, but in vertical boreholes that crossed these anhydrite layers and they produced orders of magnitude of more brine than they expected because in the salt formation the clay is the permeable stuff. So, you cross these layers and they produce a lot of brine.

So, we are trying to redo the test in an interval that's largely halite, so as to come up with the results that we hope is more generic and applicable to other sites rather than specific of this one interval we happened to cross in our tests that kind of dominates the results.

BAHR: Paul Turinsky?

TURINSKY:  Yes.  What would be the advantage if this thing gets accepted into this international other than perhaps some money?

KUHLMAN:  So, it's in kind.  We participate, DOE pays for us to participate.

TURINSKY:  Yes, but would they then be doing modeling also and you can compare models?

KUHLMAN:  Correct.

STAUFFER:  Yes.

KUHLMAN:  Just like what Jens already talked about, it's a collaborative effort.  People bring together different conceptual models to explain the data.  And in the end, it's an interesting way of showing, well, gosh, people used three different models and they've got about the same answer or maybe not.

STAUFFER:  And our experimentation like I mentioned before in salt stopped in the late '80s, early '90s.  And so, neither of us were around when that was going on, so we're just learning about this stuff, so anything we can pick the brains of people that were in the field, even if in the Asse mine in Germany then that information is extremely valuable to us as just learning how to do these experiments.

BAHR:  Are there other questions from members of the Board? I see Sue, no?  From Staff, Nigel?

MOTE:  Nigel Mote, Board staff.  To the two-part question about temperature.  On your slide 12 you've got high temperatures that lead to dry-out and the third sub-bullet is less corrosion in a dry atmosphere, and I understand you were talking there about the implications of the salt temperature, but in traditional material science you expect the corrosion rates to increase with temperature.  So, you will have one effect which is increasing and one effect which is decreasing, which one wins?

KUHLMAN: You know, I am not a material scientist, so I am not a specialist, but I think the corrosion from like a humid briny environment is pretty extreme. And so, if we can eliminate the water part, I guess I am not sure about the increase in corrosion with temperature like you say, but in my naïve understanding of it would be that the corrosion due to the intense chloride environment, if all of a sudden you don't have any chloride in solution because you don't have any water, that that removes one of the kind of the significant directions to get corrosion.

MOTE: When you were going through it, I was thinking I can understand that, thinking only about the salt and then I started thinking about material. And so, the second part is if I start with Yucca Mountain as a concept the emplacement pattern for the fuel and the high-level waste was intended to even out the thermal load, thermal source, in other environments thinking crystalline or clay shale types, there is a focus on spreading out the heat level more because of the lower conductivity, the lower ability to absorb the heat.

So, in this case if you take it that the corrosion is reduced at higher temperature, if that wins, which was the implication as I was thinking, then you'd be trying to devise a loading pattern that maintained higher temperatures in the interest of reducing package corrosion?

KUHLMAN:  That could be one strategy.  Yes, there is I think a lot of engineering considerations that would have to go into how you space your waste packages, probably some of them are from an operational point of view, which are not really our specialty to look at.  But I think from the point of view of just maintaining the temperature between the canisters and trying to drive the moisture out of that near-package environment, I think you're right hotter to a certain degree is better.

You know, I didn't really talk about it too much, but if you get above 250 C you actually get decrepitation of the salt, so there's little fluid inclusions, they actually shatter because they will like explode due to the thermal expansion. And we don't want to get that definitely because you basically have like popcorn going off in the underground.

MOTE: You may have just side stepped the question because you said you haven't thought about it, but my sort of sequel to that, the endpoint was, so what are the implications for a repository. I mean, if I go back to a statement, Kris, you said the salt is still a good repository. So in terms of technical analysis of the temperatures and the implications of the water content, I can see that there's some reason for that. But I don't know what the operational implications are because it might make things difficult in terms of loading pattern.

Okay, thanks.

BAHR: Okay, we have Bret and then Bob Einziger.

LESLIE: Okay, and maybe Emily can answer this in her presentation.

Did the GDSA base-case for the salt include brine inflow or buoyancy and you can just work that into your talk. Second, will the salt test be able to assess your hypotheses for where the chloride is coming?

KUHLMAN:  For where the brine…?

LESLIE:  Or the HCl gas is coming from?

STAUFFER:  It could have some bearing on that because the, what is it, manganese chloride that is in some of the brines, there's a constituent that's dissolved in the fluid inclusions?

KUHLMAN:  Yes.  There are a couple of working hypotheses.

STAUFFER:  If we see that showing up then that -- at 120 we don't expect -- that's one of the reasons we kept this below 150 C is because at 150C is where the HCL really started to show up.

LESLIE:  So, my last little question is when you did your reprioritization this year, how much influence did you think about in terms of the DPCs and the buoyancies which is kind of a fundamentally different conceptual model rather than a FEP?

KUHLMAN: There definitely was a component of what effect would DPCs have on salt. I know a lot of work has been done on DPCs and it's thought that for DPCs salt is maybe the easiest environment to dispose of DPCs in, because of the chloride which maybe helps with criticality. But you're right, package buoyancy it's kind of an open question. It's a difficult thing to test in the field because it either involves emplacing enormous canisters or somehow getting the jack and kind of pushing them into the floor, we’re thinking about it.

But, yes, I think that right now it's something that's handled with numerical modeling and hopefully we can improve the constitutive law so that the predictions from the numerical models are more relevant.

BAHR: Okay. Bob Einziger?

EINZIGER: Yes. This question is -- Bob Einziger, Board staff. This question is with respect to the salt repository for spent fuel. I’m having a hard time determining whether you are looking at a primary effect or whether you are looking at a secondary effect because spent fuel is going to have a high radiation field, a high gamma field and to a lesser extent a much lower neutron field.

I presume somebody is looking in that and determining what the effects are with respect to the ionization of the salt, the ionization of the water, the interaction of the two and the interaction of the products with the primary waste form and the canister. How will you take the results of the people who were doing the work with ionizing effects and integrate them into your model?

KUHLMAN: So that's a good question and there are two things there. So first, most of the waste packages are going to come into the repository in some self-shielding kind of manner so that the radiation and all the effects of the waste are combined in the inside of the waste package until you have a breach or something.

And also, there was a fair amount of work done on the effects of radiation on salt back in the '60s at Oak Ridge National Lab as part of project Salt Vault. They irradiated salt in different manners and they found that irradiating salt it makes it a little bit, it changes the stiffness just a little bit, maybe five, ten percent, and brittles it just a little bit. But it's not a dramatic like the oh, the salt is completely ruined.

So, it was found that, it was like within the uncertainties about everything else we know about salt. And so, honestly, not a lot of work has been done on that topic since that work was done back in the '60s, but some people have looked at it.

EINZIGER: Thank you.

BAHR: Okay. We have time for one more question if there is a quick one from anyone in the Board or the staff? Okay, hearing none, I thank our speakers and move on to the final speaker of the day before our concluding panel discussion.

ZOBACK: Okay, Mary Lou Zoback, Board, and our final speaker is Emily Stein. She is currently the acting manager for the Applied Systems Analysis and Research Group at Sandia National Lab.

She has been the lead modeler for the Safety Assessment Toolkit that she'll be describing today. And she earned her PhD in Earth Sciences from the University of California Santa Cruz.

Thank you, Emily.

STEIN: So Geologic Disposal Safety Assessment or GDSA which I will probably say many times throughout this talk is the name for a portfolio of projects that are all related to developing and demonstrating a next-generation software toolkit for probabilistic post-closure performance assessment.

And the GDSA project is definitely a multi-disciplinary and multi-lab collaboration involving a core team of developers at Sandia, and a process modeling teams at Los Alamos, Berkeley, Livermore Argonne and Pacific Northwest National Labs, as well as at Sandia itself.

You have seen the blue half of this slide before and this is the disposal research work scope of DOE’s Spent Fuel and Waste Science and Technology Campaign.  All of the components of this work are interrelated and they all feed into Geologic Disposal Safety Assessment in one way or another.

And then on the right side in green I have broken out the work scope that falls underneath GDSA, and that includes development of GDSA framework which is that software toolkit for repository performance assessment or PA.

Model development, so developing process models, implementing subsystem process models into the framework, development and testing of uncertainty and sensitivity analysis methods.

Repository systems analysis is development of generic reference case repositories and simulation of those reference cases. And then geologic framework modeling is three-dimensional models of geologic systems, and that provides information feeds to their repository systems analysis and the reference cases.

So today we'll be talking particularly about how some of these international collaborations that you've just heard about feed into the GDSA work scope, and we'll focus then on the framework development, the uncertainty and sensitivity analysis methods we'll hit on, and I will talk some about the repository systems analysis too.

I have to do both of these in my right hand, keep switching back and forth. GDSA benefits from international collaboration in three main ways and the first is that we use international data sets and concepts to create the technical bases for our reference cases. So, we look to the international community to characterize our generic natural barrier systems, the disturbed rock zone and the engineered barrier systems.

GDSA also benefits through direct contributions to the models we use in post closure performance assessment and by identifying through the international community relevant features, events and processes that need to be included in those performance assessment models.

And the third way we benefit is via confidence enhancement. So, the more we can collaborate, we can make sure that we are conducting PA in accordance with international standards of practice. We can improve confidence in our software through benchmarking, debugging and demonstration on diverse problems. Sometimes because we have open source software, we benefit from functionality contributed by other users, and of course we stay up-to-date with state-of-the-art developments in other countries.

So GDSA framework is this software toolkit for post closure performance assessment. And it's built around PFLOTRAN, a sub-surface, multi-phase flow and reactive transport code that can run on your laptop or on a supercomputer. And PFLOTRAN is the platform into which we are going to couple our process models describing source terms, heat and radionuclide source terms, the evolution of the engineered barrier system, flow and transport processes, and also, we can couple biosphere models into that, but I won't be discussing that today.

Other pieces of the framework include a software toolkit called DAKOTA that we use for uncertainty sampling and sensitivity analysis.  And we have several on pre and post processing codes.  We rely heavily on Python scripting.  We use dfnWorks that Hari introduced you to earlier in his talk and we use ParaView for virtualization.

So, some of the work scope in GDSA framework development, and this slide mostly focuses on what we are working on this year, is ensuring a robust multi-phase and high temperature capability.

Coupling subsystem process models, this is ongoing.  And the subsystem process models that of course we are interested in coupling into GDSA framework fall into those same key R&D topics that Jens introduced yesterday, including engineered barrier processes, processes resulting from near-field perturbations, and flow in radionuclide transport processes.

We are also working this year on adding to our software verification test suite. We are always keeping regression and unit tests up to date and we are working on documentation related to quality assurance.

We also have international visibility and promotion explicitly as part of our work scope. And we are committed to that through the open-source software development by offering PFLOTRAN short courses around the world and participating in a variety of international venues. So, this is just to tell you that you have heard about all of these things already in these past two days.

Repository systems analysis then ends up being mostly about developing references and applying our software framework to them. And each reference case is going to have some description of the heat and radionuclide source terms. It will include a description of the engineered barrier systems, so including things like the fuel, the form of the fuel itself, the waste package, any buffers or backfills, fields, shafts, repository lay-outs.

The DRZ might be included in here. I think I have included it when I list it later as part of the engineered barrier system. And then a description of the natural barrier systems, so including the repository host rock and any units lying above or below that, as well as any significant geologic features.

PFLOTRAN of course is used to simulate all of these pieces interacting numerically, and the DAKOTA is used to sample on uncertain parameters and create multiple realizations.

Within the repository systems analysis work package our work scope is mostly about reference case concepts, so identifying features, events and processes that should be included in a particular reference case. Looking at repository designs and layouts, we have started to look at disposal contents for dual-purpose canisters just this year.

And of course, we are always developing the technical bases, the descriptions that characterize the engineered and natural systems.  So, we do do total systems simulations as shown on the previous slide, and we are also working on near-field simulations designed to facilitate process model coupling.  And we do rely rather heavily for many of these reference cases on international data sets.

So, these are four host media for which we have multiple reference cases I think for each one of these, listed in order of reliance on international data.  So, the crystalline reference case, fractured crystalline rock relies most heavily on international data sets, particularly from Forsmark, Sweden.

The shale set of reference cases rely to some extent on the French safety case.  The salt reference cases benefit from the collaborations with Germany.  And we do, have recently added to our list of reference cases an unsaturated alluvium reference case and that one is entirely homegrown.

In the uncertainty quantification and sensitivity analysis work scope we are concerned largely with identifying, implementing and applying uncertainty and sensitivity analysis methods that are effective for computationally expensive problems.  This work package also gives us an opportunity to provide feedback to research and development in the other work packages because we can identify which uncertain inputs contribute the most to the uncertainty in the output.  And this might be a place where you would like to go do more research.  And also, we can identify which uncertain inputs have little to no influence on the output uncertainty.

Again, international collaboration is explicitly stated in this work scope.  And here it's primarily focused on exchanging knowledge, to some extent comparing software and methods and guiding the discussion on what standard of practice should be for probabilistic performances.  And we'll come back to that too later in the talk.

This slide is a diagram of the components of a safety case. And starting at the top, a safety case would have some sort of introduction.  It would discuss the safety strategy and that would include management, operations, siting and design, and then the safety assessment strategy.  It would include a discussion of the technical bases and that will include pre-closure technical bases and also post closure technical bases.

There will be the safety evaluation itself, including both pre-closure and post-closure safety assessments.  And there will also be this piece about confidence enhancement, where you might go look to URLs or natural analogs to learn more about the system that you are trying to model.  And then finally there will some kind of synthesis and conclusions.

So, the work scope inside of GDSA framework development overlaps with the safety case in three main places, and that's in this definition of the post-closure technical bases, in the post-closure safety assessment, and then in the confidence enhancement field.  And the rest of this talk will basically go through those three different components of the safety case and point out where international collaboration really benefits the safety case and GDSA framework.

So, first looking at the post-closure technical bases, international data sets contribute here. And they contribute to our description and characterization of both waste forms and waste packages, buffers and backfills, shafts and seals, and uncertainty in all of the parameters that describe these things. International data sets also contribute in some cases to our host rock and disturbed rock zone characterization, and again, to uncertainties in parameters describing these things.

On this slide you are looking at a list of some of the features and processes that are included in the crystalline reference case. And they are listed here also with the countries that we borrowed data from. So, the reference case, the site concept itself, let's go put a repository in a sparsely fractured crystalline rock with an unconfined water table. That concept is based on the Forsmark site in Sweden. As are the various statistical distributions describing the fracture network, that also comes from Forsmark.

Matrix permeability and porosity came from work at the Grimsel Test Site, the Lac du Bonnet, URL in Canada and the Korean underground research tunnel.

I grabbed an effective diffusion coefficient from some work done at the Grimsel Test Site.  The disturbed rock zone permeability and the extent of it as well come from work again at the Lac du Bonnet URL and the Korean underground research tunnel.

And then pore water chemistry, assumptions about pore water chemistry and the geochemical environment come from a variety of studies in Sweden, Finland and Canada.

The engineered barrier system also benefits from international data sets.  So, for instance, we have relied on a set of data from Sweden to describe spent nuclear fuel dissolution rates.  Bentonite buffer concepts came from a paper out of Korea which also referenced several other countries’ bentonite buffer concepts. Bentonite properties, thermal conductivity, porosity, permeability, sorption coefficient came from around the world.

Okay.  So, moving on to this post-closure safety assessment, we benefit in two ways here.  And the first is that international collaboration like you've learned about over the past two days has the potential to directly contribute to the subsystem process models and concepts that are included in performance assessment.  And international collaboration also can increase confidence in the tools and software that we are using for performance assessment.

So, I've got this pointed out here where international collaboration contributes directly would be in analysis of relevant features, events and processes, also in numerical descriptions and conceptual model descriptions of subsystem processes.  And then increases in confidence would largely be in comparing our software and models to other places through the knowledge exchange component of that international uncertainty and sensitivity analysis collaboration.  And we are going to look at some of these yellow things first and then move on to the green.

You've seen this slide already many times over the past two days, and I've outlined in red all of the different URL work that you have learned about recently.  And all of this work has the potential to contribute to our post-closure technical bases, to help identify features, events and processes that need to be included in performance assessment, and also to directly contribute to the process models that are implemented in GDSA framework.

So, we'll just step through those one at a time.  This is a little bit of a review at this point.  And I've got them organized by reference case.  So, when we look at the crystalline reference case, we are largely looking at URL work that seeks to better characterize flow and radionuclide transport processes.  And the colloid formation and migration experiments at Grimsel Test Site helped in that respect.  They both identified kinetic and equilibrium regimes that could result in significant colloid facilitated transport over the long time and distance scales relevant to a repository.

And also, the researchers at LANL were able to create a generalized colloidal transport model that is ready for integration into PFLOTRAN.

Let's see, we heard about two different sites, looking at flow and transport in fractured rock.  And I have to say that there have been many -- there has been much work in fractured rock URLs around the world besides just this that has helped the U.S. program develop efficient, good, accurate methods for modeling flow and transport in fractures.  And you heard a lot about that from Hari earlier today.

And these two experiments in particular, we're looking more at the near-field and benefit conceptual models for bentonite re-saturation and in fractured rock, and diffusive transport in the DRZ.

For the clay shale reference case, we've learned a lot about the effects of near-field perturbations on both the bentonite buffer and the disturbed rock zone of a shale repository.

So, you heard from Jonny about heater tests, both at Mont Terri and at Bure.  And these result in a conceptual model that describes the mutual evolution of the DRZ and the buffer, and the interactions between those two, and may result in, I mean Jonny has got the numerical models, but we may be able to integrate an emulator for those coupled thermal, hydrological and mechanical processes into PFLOTRAN that would then describe the evolution of porosity and permeability in the buffer and the DRZ.

For the salt reference case, URL work is also focusing on near-field perturbation.  And you heard about some older tests, heater tests in the Asse Mine that Phil and Jonny have both been involved in modeling.  And the very brand new brine availability test in salt at the Waste Isolation Pilot Plant.  And all of this work contributes to conceptual models for salt creep for the evolution of the porosity and permeability of the DRZ and of a crushed salt backfill. They also help us learn more about gas and brine migration in the near-field, especially under the influence of heat-generating waste.

And eventually, again, like the clay backfill and DRZ work, we may be able to integrate some kind of emulator for this coupled THMC, in this case is chemical processes that affect the evolution primarily of the porosity and permeability of the backfill and the DRZ.

So now we are looking specifically at engineered barriers system, and when we look at this we are talking about Bentonite barrier, really, so these experiments could be relevant to a crystalline reference case or to a shale reference case. And Liange and Carlos both told you about the FEBEX dismantling project and Liange mentioned HotBENT which has not yet started yet.

Both of these are heater tests in bentonite at the Grimsel Test Site that served the purpose of identifying the processes the affect the evolution of the engineered barrier.  And that evolution would include evolutions in swelling, porosity, permeability and chemical properties like adsorption.

These tests will also help establish thermal limits for buffer integrity and eventually may result in some kind of integration into GDSA framework that describes the changes in buffer properties with time.

So, this gas migration experiment which so far has been lab scale experiment is also related to the integrity of the bentonite barrier.  So as Jonny pointed out we are still working on or they are still working on conceptual models for how does gas migrate in bentonite and what is the effect of that migration on the permeability of the bentonite?  Is it reversible?  Does it create permanent damage?  And eventually this type of work can lead to some kind of function for permeability of the bentonite as a function of gas pressure.

Okay.  So finally, confidence enhancement, international collaboration increases confidence in the tools and methods that we use in performance assessment by providing opportunities for peer review, for a verification and validation of models, and also for transparency.

So GDSA participates in international collaboration very deliberately. And one of the things that we collaborate in is this U.S.-German salt collaboration which Kris and Phil are also involved in. For GDSA this has involved development of a comprehensive database that features events and processes relevant to salt repositories, and we're also working on a performance assessment software benchmark comparison.

This International Uncertainty Quantification and Sensitivity Analysis collaboration is an informal group of at least half a dozen countries that has grown recently, and it's mostly about knowledge exchange, but this is an opportunity where the U.S. really has an opportunity to contribute expertise to the international discussion because we have a very well-developed approach to probabilistic performance assessment.

In November we will be attending the DECOVALEX meeting to propose a PA benchmark comparison that would involve comparing both the physics simulators used in repository simulation and sensitivity analysis and uncertainty methods.

Some international agreements allow us to provide PFLOTRAN support for repository programs in other countries, and we are actively involved with both Taiwan and Australia repository programs.

And then, open-source development is one of the hallmarks of the GDSA framework and this creates transparency, encourages collaboration and sometimes leads to expanded functionality.

So, to summarize, I return to this slide. GDSA benefits from international collaboration in three main ways and the first is that we borrow a lot of data sets and concepts from the international community.  The second, all of that URL and other laboratory collaborations help us to identify relevant features to include in our models, help us develop subsystem process models, and then the opportunity to exchange knowledge, to test software on a variety of problems, and to promote transparency in the international community helps with confidence enhancement.

So, questions?

ZOBACK: Thank you, Emily, that was a nice synthesis of all the pieces that we've heard over the past day, day and a half.

Does anyone on the Board, Jean?

BAHR: Yes. All right, I think that was a very nice presentation and you showed us very nicely how a lot of this research program feeds into the GDSA.

Are your reference case models at the point where you can also use the GDSA to feed back into priorities for research, and asking these questions what are the processes for which a great uncertainty is going to make a difference in the eventual outcome, and which ones might be, should be able to constrain to the point where it's not necessary to have more detailed process level information?

STEIN: So, I would say that our reference case simulations are not quite yet to that point. As we start exploring the hotter waste package, the dual-purpose canisters, we begin to get into temperature and also pressure ranges that our simulations have not gone before. That begins to raise questions about what are appropriate engineered barrier materials for that type of a system? So, I would say that's one place where performance assessment may provide feedback to research and development.

But a lot of this stuff that happens in the near-field doesn't have a huge effect on radionuclide releases when you look in the undisturbed case five kilometers down gradient in an aquifer. And at this time, we have only modeled the undisturbed case in all of these reference cases.

When you start going to disturbed cases, and you consider human intrusion then the near-field properties and behaviors are going to become a lot more important to the safety case. And since we haven't done that yet, we cannot at this point identify which of these near-field processes or features are important to that.

BAHR: Thanks. Paul?

TURINSKY: Paul Turinsky, Board. I wonder are any of these activities coordinated through NEA? They have so many of these benchmark, blind benchmark tests, big codes in different areas of physics. And I wondered in performance assessment there is a similar thing like there is a system to a phase flow codes, their transport codes?

STEIN: Yes, so I am not aware of any. I mean in the past, actually Peter, I almost wonder if you should answer this question because you could speak more from the history of it.

SWIFT: Peter Swift, Sandia National Laboratories.

In the 1990s the U.S. program was active in NEA-sponsored performance assessment working groups. Programs have diverged enough since then that the level that you are thinking of has not been kept up to the best of my knowledge. The U.S. went down a different path, a more detailed and probabilistic path than most of the other programs.

And the European Community, NEA may be going on on its own, but we have not been engaged with that, we have engaged in other NEA programs certainly, the topical areas in crystalline rock and salt, and argillite, we are engaged in that.

ILLANGSEKARE: Tissa Illangasekare, Board. So, I was looking at your slide number five, basically a GDSA framework, so I think I know the answer, but I will ask.

STEIN: Okay.

ILLANGSEKARE: So, this is just a framework, a PFLOTRAN program has a whole bunch of inputs and you are expecting outputs. It's not like a big program code, and you put all inputs and expect outputs. It basically is a model that you put together using Python and basically small modules talking to each other, or is it a big…?

STEIN: No. PFLOTRAN is a big program. And all of the subsystem process models that we use to date are coded inside of PFLOTRAN. So, where Python comes in is that we use it for -- for instance, I use it a lot for setting up initial and boundary conditions that I then hand to PFLOTRAN.

It's also essential in coupling PFLOTRAN to DAKOTA. And in the future this GDSA framework will become a system for run control. And at that point there will be something like Python scripts or some other interface that pulls all the pieces together and automates the flow from beginning to end.

ILLANGSEKARE: Yes, this brings to the question, so PFLOTRAN is a model with all these processes built into it. So, some of these individual processes has been validated, tested, or calibrated, so you are enough confident that the model can capture these processes at all relevant scales?

STEIN:  So, we definitely have a QA test suite which is analytical solutions to various 1D, 2D, 3D problems.  And we compare PFLOTRAN solutions to those.

In terms of calibrating to data sets, we haven't done that because we are working in this generic space, right?  But in the future when you start looking at a specific place, you would want to calibrate the data and it would be the process modelers who would do that, who would say this is the model that works here, the parameters that are right for this system.  Maybe here is an uncertainty distribution that goes with these parameters.

But by the time we get here to the performance assessment modeling, we are doing predictive modeling.

ILLANGASEKARE:  Yes, so this brings to another question, so that means, let's say that the process models capture the process quite well.  But then now when you’ve got this, the integrated simulations then some of these processes are basically getting coupled, they are affecting each other.

So, the question is that is there any hope in validating that type of models because the processes, let's say you capture well, but then again when you, the processes interact with each other, they are much, can be quite complex.

A good example is that if you have a porosity change because of heat, for example so that type of things that, would it ever be validated or any type of…?

STEIN:  So, when you begin to couple things, how you couple things does matter to the answer that you get.  And that does need to be a thing you consider as you are moving forward.  So, for instance if we take a process model and couple it into PFLOTRAN, we would definitely compare our PFLOTRAN results back to for instance Jonny's original process model.

ILLANGASEKARE:  But there are no place where you validate the model for the interaction cycle?  Like in a certain process is done well, another process is done well, but when they come together sometimes it's not trivial how they are coupled.

STEIN:  Yes, no, it's true, it's not trivial how they are coupled, yes.

UNIDENTIFIED PARTICIPANT:  (Inaudible).

ILLANGASEKARE:  Yes, yes, and one of the factors, but…

TURINSKY:  I mean if you cross one process model as its part of its model inputs from another process model.

ILLANGSEKARE:  Yes, and so, they are coupling.

TURINSKY:  There you've got you do have the coupling and you can validate that, so that model let's say something in function or temperature, or porosity you can validate that separately if you have the experimental data…

ILLANGSEKARE:  Yes, my question is all these processes coming together in a real field setting come together, not two or three and a number of these processes are getting coupled and if not in the systems.

BAHR: Jean Bahr, and I think the other issue is that the time scales, and the spatial scales of many of these processes aren’t the same, and so, do you couple things sequentially or do you have to iterate, in reactive transport the classic problem is do you split the reaction part from the transport or do you solve in one fully coupled set of equations, and it can make a big difference in what the model spits out if you don't do that correctly.

STEIN: Yes, yes.

BAHR: And I'm sure you are worrying about that.

STEIN: Yes, that's definitely true. And one way you can address that is simply to compare the different methods, right? If I couple sequentially and take such and such a time step, then I get the same answers as when I solve the full system of equations. And if the time step is too long then I do not get the same answer.

I think there are multiple ways of addressing that problem, it's definitely a problem that needs to be addressed.

BAHR:  Thank you.  Any more Board, staff?  Bret?

LESLIE:  Bret Leslie, Board staff, Emily, very good talk summarizing a number of things.  And I think you guys have made progress in terms of the generic reference cases in terms of leveraging the international contributions on what I would consider kind of site areas.

Can you explain how you've leveraged the different behaviors of the waste forms from the different countries into the GDSA framework?  So what type of waste form dissolution model do you have?  Do you have one model that is just modeling commercial spent fuel?  What are you changing in your base cases?

STEIN:  Okay, Okay.  So most of our reference cases do assume commercial spent nuclear fuel.  And we have one model, which is just a fractional rate dissolution model, to model dissolution of uranium oxide fuel.

There was a time however where we were funded to work on defense-related spent nuclear fuel and high-level waste. And at that time, we developed models for other types of waste dissolution and degradation.  And so, that we have a couple of forms of dissolution model for glass dissolution. And you can have the option of having an instantaneous dissolution of your fuel which would be appropriate for metallic fuel.

And PFLOTRAN is object-oriented and very modular, so when you arrive at a new waste form that you would like to be able to model the dissolution of, if you can numerically describe how that dissolution occurs there is a place in the code where you can just go plunk that in.

LESLIE:  So, a kind of a follow-on, I mean, again, I think Simon said something about, well, they worry about the diversity of their waste forms in the sense of does it induce processes that are different than commercial spent fuel? And uranium metal is well known to be a strong gas generator for instance. So, you've taken kind of, and I'm not trying to undermine your progress, but a solution or a safety case has to think about what all you are going to dispose and develop a safety case for the system?

Do you know at what point do you plan to go back to getting further resolution on the things that could actually change the behavior of how the whole system would behave?

STEIN: Do you mean when we do back to considering other waste forms?

LESLIE: Yes, or DPCs which could include buoyancy effects in for instance in salt that the other countries don't have. So, to get from a big picture I think you've mined very well what's out there, and you've come to a certain point, but have you stepped back and said, Okay, so how are we different from this other things and how would we move forward?

And again, I am putting you on the spot but I think it might be Okay in the salt discussion that someone else is addressing, but it's an observation.

STEIN: Yes, I think that would be a good question to address in the facilitated discussion and I will tell you that DPCs has entered our consciousness only really in the past year or so, but I think that that is, will become an active area probably in all of these, hold on, let me go back, so direct as opposed to dual-purpose canisters, I said there were interrelationships between all of the topics listed in this blue thing, and I think that addressing the differences to the system created by disposal of those large hot waste packages does need to be addressed. Yes.

LESLIE: Jean can I ask one more?

So, and I think the transparency that comes with open source is great and I see you are working on quality assurance. Do you ever, if you had to use this and take it from a generic to actually applied, would you have difficulty with it being an open source code to meet the requirements of the regulation for nuclear quality assurance?

STEIN: Yes, I am not sure that I can answer that question, partly because I don't know what the requirement will be in the future. Having said that, it is always possible to freeze a version of the code wherever you need to freeze it, yes.

ZOBACK: Are there any other questions? Well, that's what I thought. Thank you, Emily, we are really way ahead of schedule.

STEIN: No, we are exactly, your discussion was supposed to go, Okay.

BAHR: Do we want to just give people a half-hour break instead of…?

UNIDENTIFIED PARTICIPANT: And have a longer discussion?

BAHR: Well, we can have a little bit longer closing panel…

ZOBACK: If we want to do that. Why don't we give everybody, what is it?

UNIDENTIFIED PARTICIPANT: 2:45.

BAHR: We were supposed to start up again at 3:15. Maybe we could start at 3:05?

ZOBACK: 3:05, 20 minutes to get outdoors and enjoy the sunshine.

BAHR: Enjoy the sun. Yes, so again, thanks to all of the speakers. And also, before we take this break I wanted to acknowledge Bret Leslie who just asked some of the last question, but who also was the staff member who was very instrumental in putting all of this together, and recruiting the international speakers.

Yes, so we'll come back, and we'll have a closing panel discussion.

ZOBACK:  At 3:05.

(BREAK)

ZOBACK:  Okay, welcome back.  It looks like most folks have made it back.  We're going to be closing off the workshop with a panel discussion.  The panel includes our distinguished international speakers and our distinguished American speaker representing all the international programs, and as well as two representatives from the DOE -- distinguished representatives from the DOE program, yes.

And just as a recap, Mick Apted, I want to kind of go down the panel just to remind everybody, Mick is the person that gave the overview of all of the underground facilities and labs.  Irina Gaus represents NAGRA, the Swiss implementer. Patrik represents SKB, the Swedish implementer.  Daniel represents Andra, the French implementer and Simon represents Waste Management which is the U.K. implementer. And I just want to point out at this point, they're all here representing programs making a good deal of progress and they all represent a single purpose organization, purpose being to get to dispose of waste.

And then we have Bill Boyle who spoke earlier and introduced the program and -- from DOE. And finally, we have Peter Swift and Peter has not been a speaker yet. He's added some valuable comments, so I wanted to give him a bit of an introduction. He's currently the National Technical Director of DOE's office of, let's see, now, it's the Office of Nuclear Energy Spent Fuel and Waste Science and Technology, that's a long acronym. Their R&D program and he's got several decades, you work for him, he's got several decades of experience in evaluating the technical basis for radioactive waste isolation.

He's worked at WIPP and he also worked a great deal at Yucca Mountain. He's got a PhD in Geosciences from the University of Arizona. He did his undergraduate work at University of Wyoming and a very distinguishing characteristic is that he has a Bachelor of Arts in English from Yale University. So, we'll all have to be on our Ps and Qs today.

And in fact, Peter, since you haven't had your time on stage, I thought we'd let you begin by posing a question for the panel.

PETER SWIFT:  Thank you, Mary Lou and actually let me go off script just really briefly.

ZOBACK:  That's fine.

SWIFT:  I want to thank all of the presenters both poster and oral sessions with DOE team, thank you very much for coming here and making these presentations.  And particularly, I want to thank Jens, Jens Birkholzer, thank you for years of leadership on our international collaborations, it's because of you, so thank you.

ZOBACK:  Thank you.  And Peter, I'm going to also go off script and I should have mentioned this myself.  I thought we have really outstanding talks over the past few days both from our international visitors and the DOE speakers, and I really appreciate we gave you long lists of questions and for the most part, you were very good at addressing them and that's appreciated. We appreciated the cartoons for -- you can see from some of our questions, most of us were back at a freshman level in your particular area of expertise, so I thank you for that. Okay, Peter, now go back to the script.

SWIFT: Sure, so I want to start this discussion with a question for our colleagues here from other national programs, not from the U.S. program, and the U.S. program has come to international collaborations with a very specific list of things we were interested in, that we were picking and choosing, we were taking advantage of a lot of other people's work, we still are, thank you. So, my question is from the perspective of the other national programs, is what we're doing useful? Is it useful to you? Is it useful to us too if you can comment on that, but are we helping internationally with the collaborations that we've chosen to engage in?

ZOBACK: And let me just add to that, as you all make your comments, if you have suggestions on how the program could be more useful, I think they and we would like to hear that.

GAUS: Okay, so I'll start, I think the first answer to your question is yes. I think this has been a real benefit for our programs that we had an additional group of excellent scientists working and co-working with our experts on several topics.

I just want to reflect a bit on the experiments, we saw the involvement in the FEBEX-DP experiment where really this additional aspect of temperature which serves not only our program, but also the U.S. program has been carved out by the people from the U.S. Their interactions have been much appreciated, also the next step now where they will take an even bigger role in trying to bring in the goals and the actual design of the next experiment. So, we're actually building up a kind of a series of experiments there together with the U.S. partner, so this is really a huge step forward next to of course the other partners.

And also, in terms of the gas issue, where we saw some excellent modeling work today, this is really state of the art. There are few people in the world who have reached that level of being capable of describing these experiments although -- and this is although, the experts are also associated with the regulator, but we are very happy if our regulator has excellent experts as well. So, I think this is another area, especially this gas evolving where there are very little experts in the world who can contribute to this problem and the contribution from the U.S. there has been exceptional.

Also, the other experiments, you can really see there's an added value, there's a huge potential of scientific state of the art available in the U.S. and the choice actually to use this potential to the benefit of the European programs partly has probably been a wise choice given the situation.

ZOBACK: Thanks. Patrik?

VIDSTRAND: Can I continue on the line?

ZOBACK: Yes, this time, we'll go down the row, yes.

VIDSTRAND: Yes, I would like to follow Irina's path here and I would like to exemplify with Hari which is my field of fracture network modeling and I also think it's very important to get new people in.  I would say that in Europe and the entire world, the people that are able to work with us are relatively few, and they are developed and educated together and have a basically the same conceptual ideas and having new thoughts that come in is very important.  And that gives help and debate that is fruitful.

Also, the U.S. is very good at publish which is also very important to get the results out in the academic world and the last, but maybe not the least, you are also extremely good at developing software and especially high computing, high performance computing, and that is also something that has come in and helped the development a lot.

ZOBACK:  Okay, thank you, Patrik.  Daniel?

DELORT:  Well I'm very embarrassed, most of things have been said already.  Well, anyhow, in France, well I can assure you that most of the progress we have made during this like short period of time in fact has benefited a lot from international cooperation.  So, I don’t have a specific example where in our case U.S.A has helped more than the other, the French program, but there was contribution in international groups and I'm sure it was very important for us.

ZOBACK: And Simon, do you have any personal…?

NORRIS: Well I'll just emphasize that I fully agree with what the others have said before, participation of the U.S. organizations in international studies was bringing significant benefit to the studies. It's the best way forward to work collaboratively, to pool our resources, to pool our intellect, also to pool finances and working on problems of common interest, and the colleagues from American programs I work with are very knowledgeable, very professional and enjoyable colleagues to work with.

So, I find it a good contribution to a number of different projects, a number of different fora. Other fora exist of course and so if there is thoughts to be more expansive and to participate in other international programs, I'm sure they would also be welcoming of U.S. input.

ZOBACK: Thank you. Bill?

WILLIAM BOYLE: Yes, I would like to address, start too first by thanking my colleagues from outside the United States for their remarks. But as I showed in my slides and Peter just mentioned a moment ago, we, the DOE and the U.S. we had our own objectives for entering into this. One was further development of staff capability and tool capability, and I think it's been money well spent based on the last two days, based on the talks you heard, and we also had another objective of contributing to the state of knowledge.

And again, I think the talks you've heard over the last two days is evidence that it has been money well spent, by U.S. taxpayers’ money that was well spent.

ILLANGASEKARE: So, I have, Tissa Illangasekare, Board, I have a follow-up basically expanding on what Irina said and Patrik said, you were finally talking in the context of fundamental science and process understanding, you were talking more about in the context of software models. So do you have a -- can you comment on the value of both of those in a way in building because science will be still going on, at the same time, we also have to focus on the products, decision tools, how they convert into software, do you have any comments in relation that we may be able to separate them in a different emphasis?

GAUS: So, if I understand it correctly, you kind of want to hear about how the progress and the process description sort of phenomena has contributed to our program.

ILLANGASEKARE: And the tools would end up in that (Inaudible).

GAUS: Well I think there are a few, I mean in a safety case and then the performance safety assessment, there are a few areas where you always -- well you identified it, the process understanding is insufficient. And when there's a real need to progress the fundamental science within this area, and the areas which are being touched upon this is the whole internal aspects when you go to high temperature, do you have boiling, if can you exclude boiling, how much is the whole system affected by the thermal gradient.

And you clearly feel that if you want to move towards that, there is just the lack of databases not only but also a lack of confidence that the constitutive models we have that they are capturing the main phenomena.

And I think this is an area where we work together and progress with the thermal one.  The other one is the behavior of gas, the low permeability of rock.  We have a new Euratom project starting now in June, so another 5 million will be spent with about 15 or 20 partners to progress this fundamental understanding of how gas moves through low permeability rock, what happens in it if in case it's fractured, if there's self-sealing or not.

So, these are areas where we say, Okay, the uncertainties are still there.  We can probably reduce the uncertainties by improving the process understanding.  Now on the smaller areas, I think one of them is the emerging topic of microbiology, the first EU project will finish now in May, lessons will come from that and what are the next issues to look for. So, these are these fundamental process and understanding is still relevant in certain areas. Other areas we can cover by taking larger bandwidth in the safety assessment or by engineering measures.

VIDSTRAND: I totally agree, both fields are very important. Although I don't think you can really go to engineering without science, and you need to have some kind of basic understanding about the features before you start to simplify. And on what level you simplify, kind of also developing quite fast now with the last presentations we heard here about PFLOTRAN running on supercomputer machines and everything.

Nowadays, you can do the entire performance assessment in one code. That wasn't possible just five years ago. We mixed everything, and we moved information from one code to another code and all that has improved the knowledge I would say, and minimizing or optimizing, I don't know what word to say, the uncertainties.

ZOBACK:  Simon?

NORRIS:  I'll go.  I showed yesterday a sort of a pyramidal structure to a safety case where the safety case which is underpinned by assessments and underpinned by knowledge base, URLs and what we talk about now provides a lot of input into the knowledge base and into sort of the research and the know-how.  And I think when you talk to regulators and when they make decisions, they want to have confidence in your understanding of the situation, your understanding of various processes.

So I think you need to do basic science to give you the understanding and then abstracting it into a model that you might want to put in to a performance assessment is kind of part of the whole process, but until you’ve got the science adequately fleshed out, adequately bounded and you can understand the uncertainties, we can understand how the uncertainties might affect other aspects of this system, until you have that sort of ring fenced and covered off to an extent, the assessments, you can't really proceed with any great deal of underpin, so I think we do need to keep working on the sort of processes that -- of concern, revisit things that we think we might have boxed up in previous years because things do come back, revisit it on the basis of perhaps when we're looking at new waste and new suggestion of how we package waste or we have new waste we didn't have a few years previously.

I think it's an iterative process, you never -- I can't say that we’ve sort of bottomed out anything to it, we won't ever revisit again, so it's a live process that we need to keep thinking are we on top of this situation, do we need to go back to it.

BOYLE: Great. I do think it's a common approach across all the countries here and the countries that aren't here and it tends to lead to questions like Professor Turinsky asked earlier today that I'll paraphrase as how are you going to get all that detail into your safety assessment? Well, as Simon just mentioned, it’s very commonly by abstraction, but as you even indicated this morning, in your question, sometimes it actually leads to the exclusion of a process that people thought, well this might be an important thing, let's do a test and then they find out, "Well it's not as important as we thought."

And if there were any way to avoid all this detailed science, I know from my decades on this, the people that would particularly like to avoid it if possible are the people that are actually paying for it, which is typically the generators of the power or that sort of thing.  And yet, even with that pressure if you will by the people who are funding the bills, in the United States, it was very commonly NEI, why is this taking so long and so expensive and the other countries, their similar groups, it's just -- it's proven to be necessary.

If there were a faster, easier way to do this, short of doing this detailed science to provide a sufficient understanding, one of the countries somewhere in the world would have done it.

ZOBACK:  Thank you.  Okay, I have a question and based on the program we've heard here, what opportunities do you think we might be missing in the U.S. program, and I think I'll go to Daniel first.

DELORT: Well I heard for quite a lot of time that today you have a concept already, you want to have this direct disposal of this fuel, the post canister and today, most of the experiments you are doing around this are performed in the European laboratories more or less, but with the limitation that well, the test that are performed are performed on the basis of our concept which will be completely different because we don't have the same disposal package, the geometry is different, the composition is different, we don't have while we try to have a very simple cask as we can to limit uncertainties.

And then I think maybe somewhere there is a gap today in your R&D programs, what would be the impact of this dual canister on the EBS, on the host rock and maybe there is something specific to define here and maybe to come up with new ideas of experiments that you can launch in foreign laboratories just to test, because the facility can be available and you can find an interest in other countries to contribute to this experiment.

So, I think that with your concept and your idea, you can generate new ideas to test new things and to help the others also to progress on the understanding of positive phenomena that's mostly specific to your case, but certainly interesting for the scientific community.

ZOBACK: Thank you. Anyone else on opportunities being missed? Irina?

GAUS: This is a very difficult question I think to answer, because for the people here on the table, they have a case to defend.

ZOBACK: Right.

GAUS: So if you have a case to defend, you settle the arguments, and then you check when the arguments might be not so reliable or whether there might still be uncertainties in the arguments. And when there are these uncertainties, these are the RD&D topics. So, I feel that this hat, this umbrella for currently is not fully present apart from the dual-purpose canisters which have been mentioned. So, this makes it really difficult to say, "Well, where is the gap now," because if one has to identify all gaps in science, one ends up with a program for the next million years.

So, weighting what is important now, then we can say, "Okay, let's look at the priorities from other programs, the European programs," then one aid might be that within Europe, there is going to be published a strategic research agenda which brings together the research institutes and the implementers in Europe.

So, this might be a document to look at where there's being ranked as high priority there and up to the moment where you will have your own case to defend and can focus on the specific issues because in general, the RD&D addresses very specific issues in the safety case.

ZOBACK: Okay, anybody else? Simon?

NORRIS: You have a certain type of spent fuel, it’s probably different from what we have, part of our waste -- part of our own research program in the U.K. is understanding how that spent fuel may evolve when it's under repository conditions, longer term how it behaves, it's something you'll -- I'm sure there are experimental techniques that you may wish to look at and consider using, but I think that is something that you can start thinking about now, how does your waste package behave under repository conditions, how does that waste itself behave if the canister’s ever breached.

ZOBACK: I think Bill or Peter, do you want to comment. I think that it started -- things get siloed into separate departments.

BOYLE: I'll just address the dual-purpose canister disposal issue. It's just an alternative that's being looked at by the United States. We're also looking at smaller waste packages and that sort of thing, and as I said yesterday, it actually came out of a discussion at a Board meeting, and although the United States, based on that discussion, well, even prior to the discussion at the Board meeting, the U.S. had looked at this historically all the way back when TRW was the M&O contractor in the Yucca Mountain in the '90s and then Bechtel SAIC looked at it for the department. So, the U.S. had looked at the disposal of DPCs specifically at Yucca Mountain in the past and now we're looking at it for other geologies, but we have been contacted by the Spanish disposal organization. They're interested in it.

And as time goes by, other countries may be interested in it as well because the use of dual-purpose canisters for storage is a commercial worldwide phenomenon. A lot of countries do it and I don't keep track of what their disposal plans are, but I do know that if they're not going to dispose of them as is, it's going to cost them time and money to repackage it into something else. So, there is a natural momentum of what the heck, if we can dispose of them as is, isn't that a good thing.

So as time goes by, maybe other countries will be interested in it as well.

ZOBACK: Bill, can you remind us how many roughly dual-purpose canisters are currently, Peter?

SWIFT: I can do it. Yes, there are about 3,000 deployed now in this country, and by mid-century, assuming we aren't operating a repository and we're continuing to load them, they'll be on the order of 10,000 of them. And just for those who aren’t tracking that, the large ones now hold 37 pressurized water reactor assemblies. Most of the world's repository concepts use disposal packages that would hold four such assemblies at a time. So that's -- it's a very different way of looking at a disposal problem, if you want to try and take a package that big, it's -- primarily it's the thermal load that you have to deal with.

There are criticality control issues in the long term in them, yes, there are criticality control questions that have not been answered and issue might be too strong a word, but it need to be addressed.

And there are straightforward engineering problems, can you get something that big and heavy underground. Existing hoists in mine shafts, they could be made big enough, but they aren't right now.

ZOBACK: And is there a chance they'll get bigger and heavier?

SWIFT: Somewhat, but I think you're probably reaching handling limits or close to it anyway. They've got to be moved around by gantry cranes and transporters on site, they’re got to get them onto a rail car to be shipped.

ZOBACK: I think that's sort of something on the scale of the space shuttle mobile transporter.

SWIFT: I think the space shuttle is bigger, I don't know.

ZOBACK: Maybe not as heavy though.

SWIFT: The loaded -- they’ll weigh on the order of 50 tons and with shielding for transportation more than double that probably.

ZOBACK: Okay, Daniel?

DELORT: Yes, the type of payloads we are moving in situ we'll be moving in situ using a funicular because we have to move a cask over the -- a round package and the cask is quite heavy, so.

ZOBACK: Okay, so anyone else want to comment about things that the U.S. program might be missing that they could be taking advantage of the URLs for? Patrik?

VIDSTRAND: I'm not sure, maybe you are doing things because we haven't talked about that, but we talked a little bit about demonstration when we were having our things and much of the demonstration we have been doing has focused on how to get things done in the ground, how to retrieve it and things like that. But one thing that we haven't really thought of so much is the IT structures, information systems, it's quite a lot of monitoring and surveillance and some -- and safeguard issues that needs to be handled and all these things that needs to work in one system and it's a system that typically IT department hasn't really thought of.

And so it's kind of a recommendation if you haven't start to thought to that, start early.

BOYLE:  Well on this topic, I know that this is a real topic of concern, IT and things digital, right, people remember floppy disks and that sort of thing, that it really moves quickly with respect to the timeframes of a repository, and the NEA more than once in the past couple of years has had discussions and the group that they typically invite in is CERN from Switzerland, because they generate so much data and are going to be looking at it for so long, they run into the same kind of problem.

So, there are other organizations in the world that realized due to their long timeframes, they have this IT problem of how do we keep the data secure, we're not changing bits and bytes as time goes by as we switch from floppies to optical and that sort of thing. So, it is a well-known -- it a known challenge already.

SWIFT: And it's not just a data challenge, it's a human challenge too, this is a multi-generational process currently. And I don't speak for anybody else, but my generation is aging out and what does that mean? In this week, we talk to some of this on a break that this is actually one side benefit, it's not the primary goal of underground research laboratory, but it does provide a focal point for continuity in a focused community, a community that has a mission and it's a place to recruit younger people into, it's a place to transfer knowledge from one generation to another.

Frankly, I'm envious of the European programs that have a URL specific for that purpose and that's one of the reasons you'll notice that some of our speakers were younger, that's a great thing. And part of why they're here in our program is because they have the opportunity to work in your URLs, so thank you.

ZOBACK: Before we leave this point, Mick, you've been uncharacteristically quiet, so I wanted to see if you had any comments about things you think that might be missing in the U.S. program in which they are taking advantage of being able to work in the underground labs.

APTED: I mean, first I'd like to congratulate all the speakers, they did a great job. It was especially pleasing to me from a geochemical background to see, especially sort of the turning on now of the THMC type of modeling. I think it's certainly long been needed and good to see. And just echoing earlier comments, I mean the talented staff of DOE is self-evident, it was really pleasing.

I broke my questions down or responses into sort of the obvious yes that there is an advantage certainly both international and to DOE itself for these sort of collaborations, just echoing some of the topics that I touched on in my presentation, and I heard especially from Emily's talk and she smoothed out a lot of my concerns quite frankly in terms of her talk. I thought that was excellent, this idea of focusing in safety significant issues and so on and not just everything and I've heard Bill mention the same aspect that you can't get around to working on everything, so that's good.

What else was it in terms of is it useful? I think and again, we've talked about it, that it's -- yes, it's useful, but noting that different programs are in different stages and they are evolving stages type of things, so that some of the -- let's say the U.K, or the Spanish program which are really nascent and just beginning are going to have some interest and you'll probably try to connect with those. Others are going to have much more focus, they're going to be mature, they're going to say we have here's really the top three issues and if you can work on them, great, and if now, then we'll be working on them ourselves.

But the other, in terms of the, again, Emily’s talk on the GDSA and emphasizes FEPs and of course that's been big in the U.S., I mean Sandia has sort of invented FEPs, so I think in terms of our business.

ZOBACK:  Features, events and process.

APTED:  Process, yes Okay, I thought it’s been said enough that everybody got it.

ZOBACK:  Yes, but someone new tuned in.

APTED:  Okay.  But I think it's also been mentioned by a number of people here that really the safety function approach was useful, top down complementary approach.  I guess I'd like to see that maybe sort of brought in to that thinking as well.  I think that would bolster sort of you're able to communicate and connect with some, again, more mature program.

Lastly, I've been around here for even, and probably as long as Peter, maybe longer.  I started in the '80s, early '80s and at that time, there was actually a program here, the basalt program and in some ways it has the most contact in connection with the existing European programs because it was in a saturated rock, it was reducing conditions, it was looking at bentonite and mild steel and copper as barrier materials and a lot of -- DOE paid for a lot of development of testing protocols and analytic methods and so on.

And that seems to be forgotten and I guess it would be nice you know in a sort of -- all that sort of pre-internet, pre-Google search type of area in terms of documentation, but there's a lot of useful information that talk about scaponite forming and that was no one back in the early '80s and stuff.

So I worry that we're in a position now that some of the results that seem to becoming forward are great, but in some ways it's sort of being rediscovered and it would be nice to look back a little bit to see at least on stuff related to buffer and some of the canister materials, some of the work that DOE did in the '80s and everything.  So that would be something that in terms of some of the experiments I saw in terms of it could be a benefit from what's been going on before.

ZOBACK:  Great, good point.

BOYLE:  And there is a chance that DOE still has those records.

APTED:  No, I have those records.

BOYLE:  Yes, please send them then.

APTED:  Are you sending the check as well?

BOYLE:  When the waste fund and the waste fund was paying for this work in Hanford and also the salt site in Texas. Those records ended up in the possession of the Office of Civilian Radioactive Waste Management which then went away in 2010, but the DOE at that time when the appropriations stopped for Office of Civilian Radioactive Waste Management, the task of maintaining all the records fell on the Office of Legacy Management which has them in Morgantown, West Virginia, some in salt mines, it's actually in a building.

But they're not available to the general public, but Peter and I and other people who have need to ask legacy management, hey, can you get me a record on this, that or the other, they're actually very good at it if you know the acquisition number.

APTED: Just to add in, I mean I was kidding about the check, I mean I talked to I think it was Len last night at the poster, we talked about trying to get him some of this information that's published and I remember these old materials research society symposiums and stuff. There's a lot of information that we've talked about in terms of being sort of pulling them all and sending that kind of information to them.

ILLANGASEKARE: Yes, I'd love to pick up on another issue which came up in the presentation and some of the discussions we had. So the URLs can play another role which has been the training and so training and I want to divide it into three topics, training in the context of training a new generation of scientists and engineers starting from college to the advanced research, and we saw a little bit of that because some of the presenters are fairly young, so they are into, they’re bringing.

And the second one which came out was the public confidence, how do we use the URLs to gain public confidence, so there are different models we heard about demonstration field sites is happening here, is happening in other countries. And also, the third one is so important that we talked about knowledge transfer in the context of science, we probably write papers and people read these papers. But another knowledge transfer that comes from experience we have in working these sites for the next generation of people, people whose expert systems that of ideas, but there are a lot of expert system within us. We are working on these problems.

So, I like to explore this question of what is the role of the URL in this training, public confidence and knowledge transfer may be a good place to start given the U.S. view and which are happening now, at the same time maybe going back to the issues of opportunities – are there opportunities which exist for -- I'm thinking of something like can you do training where joint training programs, people visiting URLs, young guys visiting URLs, that type of programs.

SWIFT:  I don't have an answer.  Does anyone else want?

APTED:  Yes.  You're asking for what sort of structure it would look like or can it be done, what ...

ILLANGASEKARE:  I mean, I'm just giving an idea about the role of URLs in training and public confidence and knowledge transfer, that sort of thing.

APTED:  Certainly ...

ILLANGASEKARE:  Can you comment on those, so you can give an idea?

APTED:  Well, you see, one example of course that's offered for the GDSA and stuff like that, that's sort of an outreach to -- and it's open basically to other -- everyone basically.

PEDDICORD:  So, this is Peddicord from the Board, I want to build on Tissa's observation.  So, I'm in nuclear engineering at Texas A&M University. I'm going to switch hats a little bit here and I would have to say we don't exactly have students clamoring to enter into the waste field in our department.

But -- and again, I want to express appreciation to NAGRA. Last May, we did a special topics course on the backend of the nuclear fuel cycle and radioactive waste management, storage and disposition. And as part of this, we were able to make a trip to Europe and visit a couple of key facilities at the Grimsel Test Site and Mont Terri. And from that we have had several students that participated in that become excited about the waste mission and express interest and actually make plans to pursue careers in this.

These facilities you all have can be very compelling in engaging the younger generation. So, now, I want to toss out a suggestion to DOE, and that is you have a number of good programs. You work primarily through INL and so on with various kinds of fellowships and scholarships. And the suggestion might be as Tissa suggests is to use these facilities as part of kind of an integrated approach on training but attracting younger students maybe through a fellowship program that would include some time visiting what they have in Europe.

But there is a capability to interest and inform and attract students into this field. In all due respect to the references to the younger folks here, they're actually not that young ...

UNIDENTIFIED PARTICIPANT: Yes, we are.

UNIDENTIFIED PARTICIPANT: They look young to me.

PEDDICORD: 18-year-olds and 19-year-olds that are in college, so, I would suggest we could do a little bit of good strategic thinking here, because these are, as we say in Texas, a bird's nest on the ground in terms of bringing along, again, younger people. And I think we could collectively do something very creative and effective.

ZOBACK: Okay. Irina, I think has a point to make.

GAUS: Yes. I just want to acknowledge that that the Grimsel Test Site because this is very much an international laboratory. They're actually working towards organizing more training courses.

I think last year, we had one on bentonite behavior and integration in the long-term assessment. And these are topics you don't get at the university. So, these are very specific waste disposal topics. What it also has to say that you have to rely on a couple of, a few experts you have to get together in a week to be able to give the course. So, there's quite a bit of planning and organization there to do so, but there is definitely an interest in that. That's what we see. I think SKB is undertaking similar initiatives.

So, the location is there. The interest is there. How -- it depends a bit on the demand also if there's an expressed demand that say, "This is something we want to see happening more," then we can definitely look at it and trying to organize training courses together.

ZOBACK: Irina, you might want to mention what you told us about -- there may be alternative paths for people interested in working on this problem based on the people you’ve hired recently.

GAUS: What we see -- yes. What we see is that this has also to do with the nuclear phase out which has been decided in Switzerland, that the image of waste disposal has been changing. I mean, we have -- we're actually recruiting people who say, "Well, I'm not necessarily in favor of nuclear energy, but I want to contribute to something which is of relevance to society which is providing a solution for the waste management or contributing to the solution" and we had several people already coming with this intention.

So, you see we basically -- the waste disposal is also being seen as solving an environmental issue for the planet in order for us to be able to move on to more, taller issues. So, it's smaller. It's taking place, but there's a change in image of our business. Yes.

ZOBACK:  And, Peter, I know you -- thank you.  I know you ...

SWIFT:  I would just offer the observation.  I think all of the speakers here came from backgrounds other than nuclear engineering.

ZOBACK:  That's true.

SWIFT:  I think that most of them came out of the earth sciences in one way or another and that is one of the issues we found in trying to recruit from universities is that the -- to put together a team to work on disposal problem, a repository science team.  You need geochemists.  You need chemical engineers.  You need mathematicians.  You need software people, earth scientists.  You don't exactly need nuclear engineers except for various specific issues around the fuel form or criticality control issues.  And yet, there are no academic departments of repository science.  This is truly an interdisciplinary field.

And so, trying to -- yes, there are individual departments, often in nuclear engineering, sometimes in earth sciences where in fact a member will get excited and recruit good students and build a small program. But it's because of its interdisciplinary nature, it's not a good fit for academia. And so, I like the model of trying to recruit people who are just sort of there to solve the waste problem. It's a good way to do it.

BAHR: Mary Lou, can I comment on this?

ZOBACK: Sure. I just want to -- no one else -- Okay.

BAHR: I was just going to mention that the Department of Energy did back in late 1980s through the 1990s have a fellowship program related to the environmental management program and that was very attractive to a number of students from the University of Wisconsin and elsewhere, many of whom ended up with jobs at national labs.

So, it was provided both support during their academic programs but it also involved internships at national labs and something like that that would provide an internship experience at one of these underground research laboratories I think could be very attractive, and it provides -- it wouldn't be a focus in a particular academic department but I think it would be a powerful incentive for students to pursue topics within their discipline that relate to this problem.

ILLANGASEKARE: I want to actually follow up on Irina's experience. So, I'm a teacher at Colorado School of Mines. So, we have a pretty good engineering schools. We have nuclear engineering programs.

So, in my department in environmental science and engineering used to be, we have more female students that used to than men. So, I have a feeling that if I told a student and say that "You are going to be working on waste -- nuclear waste", they may be like thinking like you're nuclear anti, but I think that's a good opportunity. These students will probably be getting into this field with the goal of serving. A lot of students we get, they come and say "I want to work in international programs. I work on humanitarian engineering."

Similarly, if you can package this in a way there's opportunity for you and especially if you say to the student that you can work in a lab in Switzerland, and then, I mean, this is very attractive to recruit students to our program.

ZOBACK: Anybody else?

VIDSTRAND: Going on a little bit on what Jean said, I think not only on a student basis but also by the employees our different organizations would gain on actually visiting and doing work at each other's locations or work with safety assessment in another country or -- we typically -- not so many from Europe or U.S., but quite a few Asian people are visiting for a year or half a year doing work for us, not for themselves.

And we have had people at Los Alamos for a couple of months to just learn and get new ideas and I think that is one way of exchanging information that is also helping.

DELORT: Yes. I just want to come back on a previous question about the disciplines needed for our program. We work here mainly between scientists. We have engineers, but it is not only hard science, this kind of project.

And then part of our activities is to serve sciences, I mean, social sciences, memory keeping, how to transmit messages for future generations, we don’t know if they will still speak French or another language.

ZOBACK: Or speak Chinese.

DELORT: Maybe. And it is a very interesting field of research. I mean, for example, the transmission of important messages from the past have been conveyed by non-technological matter. It was religions. It was heart. It was a thing like this.

So, we are going to explore to go through this soft sciences because some of the answers to the questions we have today cannot be solved only by technologies or pure science, and we have to rely to understand human society, the evolutions, how can we transmit these messages, can we keep the memory of this, how to manage our knowledge today to next generation that comes, for much further generation. And this is also very interesting, and it is maybe something to explore as well.

ZOBACK: Yes. No. I think that a lot of problems have been generated by communication -- poor communication or communication problems, but -- yes.

I'm a little -- I'm vacillating. Peter, you had another question that you thought you might throw out. I also wanted to -- let me just check. Does anybody on the Board -- I'll hold your questions for after Peter's, but does anybody on the staff, any questions you like -- I was looking for Steve Becker.

Paul, you have one.

TURINSKY: Yes.

ZOBACK:  Okay.

TURINSKY:  It's not directed directly at underground research laboratories.  On the science side, we seek collaboration, Okay?  On the regulation side, is there a similar thing?

With reactors, there is.  I mean, and some of that is historical where the U.S. was a dominant player very early on and much of our technology including our regulatory approaches were basically exported, and we all have -- everyone's using a similar product.  That product is marketed internationally by different -- from different countries on that and there's a real incentive there for it to have some uniformity in regulations.  And the regulators routinely get together from different countries.

Here, we have national programs.  There isn’t a vendor out there marketing a repository for another country at that point.  So, I'm just wondering.  It's a question I have.  Do the regulators collaborate also so there's some commonality, because if there's commonality there, there could be more commonality in the R&D and engineering required to basically make a repository a reality.

BOYLE:  Yes.  I'll take a crack at it based on my experience through DOE.  The NEA, Nuclear Energy Agency has a RWMC, Radioactive Waste Management Committee.  A specific subgroup of that committee is the regulator's forum.

So, as the regulators -- and believe me, the Radioactive Waste Management Committee historically -- it's only changed recently -- had dealt with disposal of spent fuel and high-level waste.  So, yes, the regulators for spent fuel and high-level waste do get together on a regular basis by themselves independent of the implementers, but also with the implementers.

TURINSKY:  And what's the result of the activity?

BOYLE:  Here's my general take on it.  Each country for various reasons does things a little bit differently there in terms of regulation and implementation.  There's customs. There's laws.  They're all generally speaking in the same direction in part thanks to the IAEA, which gives broad overarching guidelines for how you should do these things.

And then along come Germany and the United States. There's always outliers in terms of the IAEA. What I'm referring to is the International Atomic Energy Agency has guidelines on how you should classify waste as high, low, very low, and that sort of thing, and there really -- two are anomalous outliers that get to the same end result, but in a strange way and it's Germany and the United States.

It's like -- in the United States, if an atom of plutonium 239 was in a building for one purpose and an equivalent atom of plutonium 239 is in a tank at Hanford, they're treated as different types of waste even though they're both plutonium 239. And Germany's way of classifying waste is inherently -- it has a lot to do with how much heat output and that sort of thing, but in the end, it works for both countries.

But there are -- I would say the regulators getting together, there's always differences, but broadly speaking, they're in sync.

ZOBACK: Okay. Mick, did you want to add in?

APTED: Yes. I mean, I worked in the last 10 years for both the Finnish regulators, STUK, and Swedish SSM regulator, and again because there was this really strong shared concept there of the KBS-3 -- strong interaction between those two regulatory groups, but I will say that STUK in Finland as it was leading towards its review of the construction license application, we convened a committee that I chaired which had someone from the U.K., Health and Safety something -- French regulators, someone from ENSI from Switzerland.

So, they had built a team basically around them to advise them as they went in terms of some of their decisions. And again, as Bill said, they all have sometimes different perspectives on retrievability or timescale, but they are also at the bottom, regulators. And so, they really contributed to each other in terms of trying to guide their thinking, especially for the first of its kind, STUK was really facing some difficulties in how do we evaluate this construction license application?

So, the answer is yes.  There's been some really strong interactions.

ZOBACK:  Bret?

LESLIE:  Bret Leslie, Board staff, and I'll follow up on Paul's kind of comment.  We've had some conversations in the breaks.

Broadly speaking, Bill's right, that everyone's country can point to the IAEA, International Atomic Energy Agency guidelines, but each country implements it slightly differently.  So, in the U.S., we -- the Nuclear Regulatory Commission use a risk-informed performance-based standard which allows a lot of flexibility to the implementer and a phased licensing report or application which has no specific level of design detail required at time of construction authorization.

Now, if you were to ask the same question of Switzerland, Sweden, and France, they might be at very different technological levels of readiness, because they have constraints in their regulations that require them to be further along, the U.S. leaves it totally up to the implementer. And so, I think maybe one of the things I heard was the focus of the Europeans on demonstrating their technology is somewhat driven by their regulations, whereas the U.S. hasn't focused so much on demonstration of technology because they're not required, they could have advanced their design, but they weren't required to.

Did I characterize our conversations correctly?

APTED: I've been wondering what the question is.

LESLIE: Well, the question -- I mean, we started the first day off hearing about how important demonstrating technology was, right? And I would say the next day and a half, we heard how important it was to demonstrate through science.

And so, the point I'm trying to get across is just because they're different, it might not be -- I think part of the difference is because their requirements are different at the time of construction authorization or application.

Peter, did I kind of get that right?

SWIFT:  I would agree with that.  I would say having been an applicant in the U.S. to, or worked for an applicant in the U.S. to both EPA on WIPP and Yucca Mountain to the NRC, applicants read those regulations very, very carefully. They do define what we do.

And so, if the NRC regulation says they want a fully probabilistic performance assessment, considers uncertainty from all causes, and they don't say we want a detailed design, guess what they're going to get?  They're going to get the probabilistic performance assessment and the preliminary design.  And this is not a surprise.

The good news is I think that in all regulatory systems, they were working towards the same common goal of deep isolation, get the stuff underground and get it there safely.

BOYLE: And in a word, "safety".

SWIFT: Yes. Thank you.

ZOBACK: Thank you.

APTED: Let me just add a bit around that again in terms of -- I'm very much agreeing with your point, I think, Bret.

For example, in Finland, they built this Onkalo facility even before they had a construction license application. So, it's three miles of ramps and underground and doing demonstrations and so on, probably not allowed. I mean, it was going to eventually be the repository. So, they were sort of pre-building it and the answer of no probably, given how invested they were at this site long before the construction license application sort of came to the fore. So, that type of approach probably wouldn't work in some other countries based again as you said by their laws and precedents.

ZOBACK: I'd like to get us back to the workshop topic of underground labs. And, Peter, you posed a question at lunchtime that you were hoping you could get some input from the international community.

SWIFT: I think the one you're referring to was the question about how URLs have moved their programs forward toward the decision point.

ZOBACK: Exactly.

SWIFT: And I'll preface that by saying I'm hopelessly goal oriented. I want decisions on repository programs one way or another.

So, I'm curious and I understand there are many ways in which a URL advances a program towards that decision point. It builds confidence. It may answer very specific questions that have to be done. It may serve as a technology development site and demonstration site. But I'm curious as to -- for those programs that had URLs and currently do operate offer URLs, some discussion of how they have actually move your program forward.

ZOBACK:  Who would like to start on that?

APTED:  We'll go from Patrik this way.

UNIDENTIFIED PARTICIPANT:  Yes.

UNIDENTIFIED PARTICIPANT:  You start.

UNIDENTIFIED PARTICIPANT:  Okay.

UNIDENTIFIED PARTICIPANT:  One of you start.

DELORT:  Well, I think we would never reach to the point we are today in France without Bure laboratory.  There is no direct link between the decision taken by the parliament with laboratory and laboratory is a tool that feeds our program and a safety demonstration in certain cases to obtain a decision from the parliament, from the government.

So, there is no direct link. I mean, the link is through safety assessment or through studies and things like this, integrations. But, well, today, we can be sure that we have to -- well, to be convinced and we have to propose -- consolidate analysis to have such kind of decisions. And without the laboratory, well, we wouldn't be at that step today.

By the way, the laboratory was in the law -- we got to construct the laboratory in the first law launching our program. The laboratory was since the beginning inside our program.

VIDSTRAND: Yes. I'm not sure it has evolved in relation to the applications, but in one way, it has because the present application, the one we handed in in 2011 was focusing on the site. And when we started the planning for the Äspö laboratory, it was very much focused on what's needed to do investigations from the surface, while we were constructing, we kind of checked if we could predict and if it worked.

And all that learning then went into the methodologies we used in the site investigation programs.

But after that, I would say it's more experiment driven. You do an experiment. You get results and sometimes, unexpected results, that creates new experiment. Something happens that you need to investigate. You change your mind about how to extract the rock from drill and blasting to mobile miner. And so, it's more driven by needs that occurs I’d say than…

ZOBACK: Can you see that your program could have advanced to the point that it's at today which is in a decision mode without having -- can you envision that would have happened without having the Äspö?

VIDSTRAND: No. I don't think. Some of experiments, of course, we could have done somewhere else.

ZOBACK: Yes.

VIDSTRAND:  We have participated at Grimsel in some tests, in some ways, similar properties.

ZOBACK:  Right.

VIDSTRAND:  But at the same time, we also need to have an underground environment that is as close as possible to our expected repository site and in that sense, we couldn't have done that without our repository.

I think understanding chemistry for instance had some crucial parts, but we need to be as site specific as possible, I would say.

ZOBACK:  Irina?  You guys have two labs.

GAUS:  But I will focus on the Mont Terri URL.  I think the time when we -- the decision was taken to construct the Mont Terri URL, this was really at the beginning of exploring how you would put or plan a repository into clay host rock.

ZOBACK:  Right.

GAUS: It was the election time of how to characterize clay host rock, how to measure low permeability in this type of rock. It was a unique opportunity. And a lot of this experience -- first experience was built up together with Andra who was very present at that time in the Mont Terri underground research laboratory.

Now, gradually, this evolves, of course. And now, for us, this is essential for demonstration experiments, one-to-one demonstration actually showing that the plans you have in your papers and on your computer, how they look like in reality that people can touch part of the experiment and see how does the rock look, how are the processes being measured, how does our equipment look, is it all being credible and defendable and this is the role it plays now.

In the future, it will diminish as we go to this next site where we have to do the characterization on the site. But also there, the answer is would we have been able to put in our license which we are going to put it in 2024 without Mont Terri. I think if we would have a couple of galleries from the Bure side, some of the issues -- launch part of the issues could have been solved. But however, it would still -- it would be very difficult to rely on a URL in another country -- in France in that case to be able to make a safety case.

I think the fact that they had access to the Opalinus clay in Mont Terri has been a critical element here.

ZOBACK: And, Simon, you're sort -- Daniel, you want to say something.

DELORT: Yes. I just want to add just one point for clay repository. I mean, the host rock is our main contributor to the long-term safety. So, this is an answer -- an elemental answer. It is part of our demonstration because ...

ZOBACK: Yes.

DELORT: ... it is linked to our understanding and knowledge of this clay layer which is one more time we need it. And we don't rely too much on ideas. This is really in the French culture what is technology solutions that we are not really confident in long term because we are generating uncertainties. We have difficulties to manage but this is in our culture. So, we prefer to rely on geology.

So, it was really of apparent importance to be able to demonstrate that we understand quite well our host rock. So, the laboratory was mandatory.

ZOBACK: And I'd like to ask Simon, your sort of ...

NORRIS: Well, our program is we're still moving forward. We haven't chosen a geology. We haven't chosen a site.

ZOBACK: Right.

NORRIS: So, we're making good progress internally on our own program by working internationally and collaboratively in a number of different URLs as I went through yesterday. Some of the geologies that we're working with, the Opalinus clay, the Callovo-Oxfordian clay, they have their units in the U.K., geological units in the U.K. which are very, very similar.

So, it makes perfect sense given where we are at the minute to engage with such URLs.  And also, high strength rock, Äspö for example or Grimsel, again, analogues to what we may find in the U.K.  It makes sense given where we are to working those as well and it's good to the opportunities there.  The sister organizations are very welcoming of our engagement.  It's a very effective way of working, sharing knowledge.  It's also good for the financial leverage angle that we don't have to fund everything ourselves, that we can do a bit of cost sharing as well, which helps everyone make progress.

ZOBACK:  So, given that, when you find through your consent process a site, do you envision that beginning with a URL will be part of the program, or can you not make that judgment now?

NORRIS:  So, when we do have a community, there is so much we can do from the surface.

ZOBACK:  Yes.

NORRIS:  Geophysical approaches, so much to be learned from boreholes as well and that may give you confidence to go underground.  But I think when you go underground, you would also still need to do some additional research, confirmatory testing just to make sure that your knowledge base that you applied when you were on the surface is actually -- it comes true when you go underground that it still holds true.

So, I don't think we'd ever build two facilities.  I suspect we'll build a small research gallery to start with, once we've eventually moved to depth.  Do some initial work, do some research, probably, set up some long-term experiments to confirm the rock properties or chemistry and to be able to understand it.  But also, as part of the process, we'll also start constructing part of the galleries as well, a staged approach once you’re underground.  I don't see us having a standalone URL.

ZOBACK:  Okay.

NORRIS: I think we'd have to go through a separate siting process even for that and it wouldn't serve anything, because we're getting knowledge and the experiments we need at the minute by working internationally.

ZOBACK: Sure, good, good, good to hear that.

Mick, do you have any comments?

APTED: No. I just wonder what happens in the U.K. if the answer is yes to all three geologies will you -- I mean, in terms of volunteers. It sounds like you said volunteers start first and you do ...

NORRIS: Yes.

APTED: ... you do surface basic exploration there. And so, there'd be a process winnowing it down to some final site.

NORRIS: Yes. Yes.

APTED: And at that point, it ...

NORRIS: But, we might do surface based investigations at a number of sites including boreholing which is in itself quite expensive, but we will have to make a decision about where to go in terms of locating the GDF.

APTED: No. I think to your question, I mean, clearly these URLs and your surface test facilities have been important for these mature programs, but a lot of them were don't when they weren't mature programs and I think they did their own learning and so on. It was a benefit and social acceptance. There are a lot -- all those listed early advantages I think came into play.

And I think now you start seeing the URLs of more mature programs moving into some of the engineering, constructability. We see a lot of -- we all put together these beautiful diagrams and cross sections and there's no gap between barriers and stuff. I can tell you now that it's a real problem with bentonite, for example, getting tight fits of those emplacements.

So, those are some of the future challenges of how is it going to look as emplaced and what are the subsequent issues about that.

ZOBACK: But it is good to be able to be underground and be able to start working on these at full scale which we've seen. And I guess what's sort of underlying everyone's comments is there is this more fuzzy, but very real idea of building confidence in the public.

And I was really struck by what Mick began with in his talk about how the public’s view the underground and many of us in the room are earth scientists and we know what the underground looks like. We think we do and yet, I think of ads for pesticides and things and they have some cross-section with grass growing and then there's some dirt with some bugs crawling through and then there's something underneath, and people have felt like when you talk about an aquifer that there's something -- water tank underground or something.

So, the chance in Sweden, we went down in Äspö and they have a circular ramp, so the tour buses can drive down there and get out and look. And as I think you told us, it's in the top 20 tourist attractions for visitors to Sweden or Swedish visitors.

VIDSTRAND: Yes.

ZOBACK: So, there you go.

Do you want to second -- serious question.

ILLANGASEKARE: Yes. I think -- so, we had not a lot of time actually. Eventually, we had to start writing our reports. I'm trying to tie a few things together there. This is not a question, but the issue of new technologies, monitoring, and modeling were discussed at different levels and different reasons.

So -- but, I’d like to explore the idea of URL opportunities in this context of new technology. For example, Patrik mentioned that it's nice to have the software models developed here and it is very useful for you. Similarly, I can think of some of the experiments I saw, some of the technologies using this experiment. So, maybe are there opportunities for us to this -- to get together and develop new technologies, monitoring technologies as part of the URL more joint effort.

And similarly, the modeling now, there is something already going on in DECOVALEX project where we look at data sets and develop models that we run. So, can you comment that at least can you have a vision that someday we'll have these models which can be sort of used on the different countries, different places, under different conditions but there are some sort of not normalized, some standardized models. Is it possible it can happen in the long term?

I'll just question this. I want your thoughts on this.

UNIDENTIFIED PARTICIPANT: Go ahead.

VIDSTRAND: I think Bill said something about the people that pays us. I know from SKB’s point of view that sometimes the people that pays says exactly this, couldn’t you just have one model.  It's much cheaper but have you pay all the licenses for it.

To me, I don't really like that concept.  And so, I think numerical models are built on conceptual models.  Numerical models are run by people and all people are doing different stuff.  You can actually have the same numerical model, the same conceptual background, two teams producing different results, and that is part of what we need to do.

So, I hope that we are not getting to the situation where everyone is wanting one big super model to solve all the questions because I don't think we will capture all uncertainties.  I like the ones Irina is now employing.  I started this an environmental fighter.  I'm not someone who's really -- I'm getting older nowadays.  I think nuclear power maybe one of the best things, but I didn’t do that when I was young and rad and whatever you say.

ZOBACK:  Rad has two contexts these days.

VIDSTRAND: So -- but, of course, it's possible, but I don't think it's a good way to go.

ILLANGASEKARE: Yes. Yes. I was just asking the question.

BOYLE: I want to emphasize the people aspect that Patrick mentioned and extend it to organizations. I showed a slide where we have nine national labs participating today. And historically, on Yucca Mountain we had multiple national labs and even over these last two days, you heard reference to certain numerical codes like FEHM out of Los Alamos.

Did the scientists at Berkeley use FEHM? Not on your life. Did the scientists at Los Alamos use TOUGH? No way. And did Sandia use PNNL codes? No. It's ...

ILLANGASEKARE: I use all three.

BOYLE: Yes. Yes. And so, I've got comfortable with it. If I hire a carpenter to come to my house, do I make him use my hammer? No. I leave it up for yours. They bring the tools they need to get the job done.

And a consequence is it's a proliferation of tools and that sort of thing, but I think I'm with Patrik. I think it would be difficult to change to something else.

ILLANGASEKARE: To me it’s not a strange concept, I was in workshop committee in DOE several years ago, we had a workshop in D.C. that we actually talked about developing a common modeling framework for DOE activities. Like you said, it didn't go very far exactly like you mentioned and the NSF, they were trying to do the same thing, develop more of a community model like (Inaudible) atmospheric models.

So, I was just thinking that context that we can come out in more community models. We have people who can bring their modules into that and then you can -- models can develop, but any other comments?

BOYLE: One further comment, I will say from a DOE point of view, having multiple participants able to do the same thing ...

ILLANGASEKARE: Yes.

BOYLE: ... it does provide the flexibility if for whatever reason under the sun you're not happy with participant A, well, I can always go get B or C to do it, right? So ...

ILLANGASEKARE: Any other?

GAUS: Yes. Two small comments, I think as long as models have uncertainties in it, we should not stick to one because we might not be certain what causes the uncertainties. And if it's a completely deterministic thing and it's all defined and set, then, we can agree on as a practicality.

But you also mentioned the technology development and I think there are two domains there which are being looked at also quite a bit in Europe, which is the fiber optic technology.

ILLANGASEKARE: Yes. Yes.

GAUS: Which is also being used by Andra and which provides instrumentation which has a very long life which is easy to emplace, which doesn't perturb. And the other aspect in terms of monitoring is also the remote sensing.

Battery, there's a huge development in batteries now. So, trying to -- this has not reached our community yet. So, there might be opportunities to develop generic, not generic, but specific technology which might be applicable to multiple URLs. Yes.

ILLANGASEKARE: Yes, I’m spending my sabbatical with Bill's old school, actually I'm working with the group. This is exactly looking at the fiber optics for infrastructure monitoring and a lot of -- we will do a lot of work in this area.

ZOBACK: Yes.

ILLANGASEKARE: Also, can you comment anything you can about monitoring, any opportunities or new knowledge can be generated in the URLs in the context of developing new methods?

NORRIS: So, the European Commission has just recently completed a project called Modern2020 which is all about monitoring that can be undertaken in the GDF during its operational period, pre-closure, to drive information that can then be used to bolster the safety case for the post-closure long term evolution.

So, this is, again -- it's a European Commission project and numerous partners, 30-plus partners. So, part of it was to do with the strategies and monitoring strategies, how do go about monitoring GDFs and using information during the program, during the operational period of the program. There's also a module on new technology.

So, they have been developing some of the fiber optics, some of the sort of the long and battery powered monitoring devices that you may put in a vault -- seal and close the vault, but it still gives you a signal. So, you can still gain information about the repository as it's evolving in the operational phase. So, it's in the concept where you close vaults incrementally.

So, even when you're emplacing waste, you've closed another vault. You're understanding how that vault is evolving whilst you're still putting in more waste, then you can again use this information iteratively.

It also involved a stakeholder angle. So, some communities, some national programs that have communities, stakeholder communities that are interested in monitoring, what they can derive from monitoring, they were able to participate as well. So, it had its symposium a couple of weeks ago.

So, again, the European Commission projects in general, they were obviously built by the European Commission, but they’re not closed. So, they're open to nations outside of Europe as well. So, it could be something that some of the U.S. programs might wish to participate in at some point.

So, our Modern2020, the presentations from the final symposium are now available, everyone can have a look at them and reporting’s in progress.  There's a lot of new knowledge there that could be available for anyone to come and have a look at and upskill.  It's a useful project.

DELORT:  And they're looking at that in English. (Inaudible) there was a closure meeting on this second semester 2020.  There are eight working groups -- working packages and I think there were about 200 people who had contributed to the other sites, so a lot of people from all over -- all around Europe and outside Europe.  I don’t remember, but I think that there was Chinese or Korean.  So, it's open.

ILLANGASEKARE:  And Bill or Peter, can you think in terms of generic sites, the monitoring, any strategies I think DOE will look at the generic sites in the long term.  Are there any program where you're thinking in terms of not Yucca Mountain but other generic site, monitoring, this is monitoring?

SWIFT:  It's not a research focus for us right now.  That's the simplest answer.

ILLANGASEKARE: Yes.

SWIFT: If we had a site-specific location, yes, it would be.

BOYLE: Yes. And my input on this question is looking historically at Yucca Mountain with all the measurements we made, the most challenging were related to the heater test, that it was easy enough to find instrumentation that could take high temperatures, absent the presence of water, or it was easy enough to find instrumentation that would work in the presence of water absent heat.

But to find instrumentation that will work with heat and water even with steam present was more challenging. And so, it's a rougher environment, given that many of these countries are looking at not as hot repositories, that may be less challenging.

APTED: Could I ask Daniel and Patrick, or I mean, Simon sort of what monitoring -- what's to be monitored, what was discussed in the sort of decision or this -- I mean, is it pressure, temperature, what moisture content, what type of monitoring, everything?

DELORT: Yes, almost everything. Well, we are expecting something back from the evolution of the system. And so, we are quite able to identify some parameters that we would like to monitor. So, this is for technical aspect. But it is not also that.

I mean, also to consider monitoring the environment involving the local communities in the monitoring, because we are living with them and also, they are contributor to the memory preservation of the system. So, it was a really very wide programming, and I think it's very difficult for me. Maybe you know more, to make that in a nutshell because it was three or four years work, more than 300 participants, researchers on many aspects of monitoring and probes, data management, knowledge management.

It was a very wide program. So, as Simon said, well, everything is available on the Web, you just have to type

Modern2020 and you have an access -- direct access to all these data, it’s very easy, and in English.

ZOBACK: Well, and I would think that, Bill, you talked about the experience for Yucca Mountain and sensor, microsensor evolution is just exploding and I think it's going to be the generation today are going to expect to have all that information on what you guys have stuck underground and how it's evolving and they want to be able to see it on their iPhone.

So, you may have additional requirements that maybe aren't, weren’t written into statute in the '70s, but there may be public expectations that may drive some of that.

ILLANGASEKARE: I want to comment on that. And so, one of the projects I'm working at Berkeley that is my collaborator, he is looking at plants. When plants go, they generate electricity. So, they are using that power fiber optics, so, basic idea is to put fiber optics network in plants and some of the power. It's not enough to transmit that signal, but enough to register that. So, they're basically showing how (Inaudible).

ZOBACK: Yes. Redwood forests are monitored to see how the trees on the periphery grow with respect -- how they take up moisture -- I mean, it's just incredible and a lot has been driven from Berkeley.

Lee has a question. We are getting ready to close down. It's been a long day.

PEDDICORD: It's a commendation. Whoever came up with the Donut or Daisy or whatever you characterize it of the international programs, URLs, the various media and so on that you all in the DOE programs labs use I thought was superb and it was extraordinarily helpful at least for me to understand where things fit together and what we're doing and so on.

So, who did that?

SWIFT: Jens did that.

ZOBACK:  That was Jens.  Yes.

PEDDICORD:  Well, again, well done.  Think bonus at the end of the year, right?

SWIFT:  He’ll have to talk to himself about that.

ZOBACK:  Actually, I have to say Tissa, myself, and Jean and Bret and Bobby were in Las Vegas a few months ago and Jens put that figure up, we go "Yes.  That's what we want.  We want to see that in every talk" and it was in every talk. So, thank you very much.

Anyway, I, too, want to -- I'm going to give the panelists a chance for a final word or a final sentence.  But -- and it's not required, but I'm giving you a moment to think about that while I want to extend our thanks to, the entire Board’s thanks to Bret Leslie and to Bobby.  They both were the ones behind organizing this, but I especially want to call out Bret because I know he even worked on some people's presentations.

I tried to get the organizational diagram out of one, but it didn't work, but anyway.  Bret, we really appreciate all the hard work and you're also coordinating us to get to the dinners and everything else.  You kept us going.  So, thank you, and I hope you can crash very shortly.

And now, everyone has a chance for a final word -- one bullet.  Yes.  There you go.

APTED:  Just one last point and it's I think just to honor some of the questions that came up from your advisory staff and so on.  To be very careful about comparing models to experimental data if what is the control, what were the operation conditions.  I mean those are very important constraint to get something useful in those sort of comparisons.

So, going forward with sort of other URL experiments and further DECOVALEX, be careful in terms of the design of experiments and the design of technique for measuring what's important.

ZOBACK: Irina, would you like to ...

GAUS: I hope -- I sincerely hope that the U.S. program will pick up and be in a position to provide a clear goal for the research to be addressed. In the meantime, I would say please take good care of your excellent people and send them to us. You're welcome to ...

ZOBACK: Thank you. Thank you.

Patrik?

VIDSTRAND: I can just fill in exactly what Irina said and say thank you for letting me be here and I actually learned quite a lot, not only on U.S., also by my European colleagues. So -- yes.

ZOBACK: Excellent. It's always good to get together in person. Yes.

Daniel?

DELORT: Well, same, thank you very much for inviting me. It was a pleasure. I really enjoyed the presentations -- the technical presentation of your fans ...

ZOBACK: Great.

DELORT: ... and young researchers. It was very interesting. If you by chance come to France, don't hesitate to come to Bure. It is our -- one of our missions. It is legally, it is in the law. We have to receive the people to explain what we are doing from anywhere. So, well, if by chance you can visit Bure, you are always welcome.

ZOBACK: Thank you. And I have to say we had a lovely lunch in the nearby village. It was just great.

DELORT: Yes. It is a little bit in the middle of nowhere.

ZOBACK: But that's good. It's a lovely spot.

DELORT:  The wine is good, but the water ...

ZOBACK:  Simon?

NORRIS:  So, thank you very much for the opportunity to come and thank you for the invitation from the Board.  Thank you also for the speakers today.  So, they're very informative, I learned a lot that I can take back.

I appreciate the American colleagues working on the projects together, with Andra.  I would encourage more such interaction going forward.  So, we welcome very smart people, very nice people.  They're very engaging.  I think the projects benefit from having an added group now.

ZOBACK:  Great.

Bill?

BOYLE:  Yes.  I would like to offer thanks as well.  This was very beneficial for me personally in U.S. program.  And two last specific points, the point that Chairwoman Bahr and

Professor Peddicord brought up about fellowships. I'll check into it. I've got a note here.

But it's my impression that either OMB and/or the appropriators don't like DOE in directly giving money like that. They do that as basic energy science in NSF. I'll check into it, because it's a good idea.

And then, it was the exchange between Bret and Emily and Emily's talk about why have we focused on commercial spent fuel rather than the -- well, look at the amounts of spent fuel versus the other waste streams. It was just -- that was the only driving reason.

ZOBACK: Peter?

SWIFT: So, I want to say again what I think I tried to say at the beginning, which was to thank the other programs in the world that have developed underground research laboratories for doing that and for being willing to share their knowledge with us.

I mean, this program had a long ways to come starting in 2010 in catching back up with the rest of the world, and of disposal concepts other than Yucca Mountain. And so -- and that isn't just the people here. There are other programs that we've borrowed heavily from who weren't here. But, the goals that we set out in our international collaboration concept starting 2011, 2012, we're happy with where we've gotten with them.

ZOBACK: Great.

SWIFT: So, thank you.

ZOBACK: You're welcome.

And I want to also invite Jens Birkholzer who is the coordinator of this program. I think he's the leader, but somehow, he shied away from that moniker.

BIRKHOLZER: If I was leading, I'd have budget control, but I don't.

ZOBACK: I get it.

BIRKHOLZER: But the only thing I wanted to say, two things real quick, one is echoing Peter that it was super exciting for me in 2012, 2013 to kind of tour the world and then go to Mont Terri meetings and go to SKB meetings and see how -- what's done, but also be sort of so warmly invited back into international research space. So, thank you for that.

And the other thing is I'm a geoscientist. I work across applications. I'm not a nuclear waste person, per se. I do a lot of that, but not all. And what wasn't discussed today I think is the value of some of the work done in our research labs beyond nuclear waste science, if you think Stripa or other works at the time, fracture patterns, migration flow. It really started that field, I think.

You think Yucca Mountain deep unsaturated flow and transport and the URL that we built, we learned so much and then clay science started probably with Mont Terri in some respect at least. And I think now we sort of see that this history of underground research labs for nuclear waste, it's sort of now starting to be used in other disciplines, right? We see fault slip induced seismicity tests creeping up at Mont Terri and we see Äspö being used for other studies that have nothing to do with nuclear waste.

So, I think this idea of being down there, being able to do stuff, having access to other codes and measurements from all three sides and putting fiber optics in there and it's not expensive to drill two kilometers. It's really taking off. That's very exciting. So, thank you for that.

ZOBACK: Thank you. Yes. And a final -- a thank you to all the speakers represented here, those of you in the audience, and the audience members that have stayed with us. So, thank you all.

And I'm going to throw the program back to Jean because it's time for public comments.

BAHR: I understand that we don't have anyone signed up for public comments.

ZOBACK:  Okay.

BAHR:  So, I think that brings us to the end of the formal program.  But again, I'd like to thank everyone for coming and participating and listening, and Mary Lou and Tissa again for their role in organizing this.  They put a lot of thought into -- in the questions for the speakers.

ZOBACK:  He wants you to say his last name.

BAHR:  Illangasekare, Tissa Illangasekare.  Yes.  So, thank you all.  I think it's been a really interesting meeting, and we have our work cut out for us now in trying to synthesize some of what we've heard in a brief report.

So, anyway, thank you all and we'll ...

ZOBACK:  And again, I forgot to mention our consultants that work here ...

BAHR:  Yes.  Thanks also to our ...

ZOBACK: ... and provide us expertise, greatly needed for filling gaps in our expertise. So, thank you guys and all of the staff, thank you so much for all the support and we've got a group of women outside. We got these wonderful AV people.

Everything you said and all the things I said are recorded. They'll be turned into a transcript. They're on video. So, you can't run and hide. So, anyway ...

BAHR: Thank you. Thank you, guys.

ZOBACK: ... thank you, everybody. Thank you.

END