United States
Nuclear Waste Technical Review Board (NWTRB)

# Transcript

## Summer 2022 Board Meeting

Wednesday
September 14, 2022

## BOARD MEETING – DAY TWO

Arlington, Virginia

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# P R O C E E D I N G S

BAHR: Hello and welcome back to the U.S. Nuclear Waste Technical Review Board summer meeting. I am Jean Bahr, chair of the Board. Yesterday, I described the Board's mission and introduced the other Board members. So to save time today, I'll just direct you to our website, www.nwtrb.gov where you can find formation on our mission, our members, our Board correspondence, reports, testimony, meeting materials. And that includes webcasts of the public meetings. And again, this one will be posted on our website in, you know, a couple of weeks.

So this slide shows yesterday's agenda. William Boyle of the DOE Office of Nuclear Energy gave some opening remarks. And then we heard from National Laboratory researchers who are conducting work for DOE related to geologic disposal, spent nuclear fuel, and high-level radioactive waste in clay-bearing host rocks as well as research and development on clay-based engineered barriers. Today, we are going to start with a presentation by Maria Victoria Villar from the Center for Energy, Environmental and Technological Research in

Spain. And she is going to describe some of the laboratory and modeling studies focused on understanding a couple of processes in clay-based engineering barriers that she's been conducting. Then Chris Neuzil will present some of the technical challenges in characterizing clay formations and identify some key technical gaps that need to be addressed to better understand clay behavior at repository scales.

After a 20-minute break starting at 2:05 p.m. Eastern time, LianGe Zheng will provide details on laboratory experiments, field tests and numerical modeling that focus on understanding coupled processes in the Bentonite Buffer at high temperatures. Yes. Did I ... I ... it did get changed. Somebody did that for me. I think I forgot.

Anyway, and then the last presentation of the meeting will be by Tara LaForce, who will describe how models related to clay-bearing host rocks and engineered barriers integrated into the geological disposal safety assessment framework that she used for performance assessment. As we did yesterday, we'll have a public comment period at the end of the day. As a reminder, those who are attending the meeting in person and who’d like to provide oral comments are encouraged to sign the public comment register at the check-in table near the entrance to the meeting room.

Oral comments will be taken in the order that they signed in. And public comments can also be submitted during the meeting via the online meeting viewing platform using the comment for the record form. Comments via the online meeting platform will be read in the order received by Board Staff Member Bret Leslie.

Time for each comment may be limited depending on the number of comments we receive, but the entirety of any submitted comments will be included as part of the meeting record. And as I mentioned yesterday, these ... these are comments intended for the meeting record. We are very happy to receive them on this ... however, this is not really a question-and-answer period. So if you have questions specifically for any of the presenters, I encourage you to contact them directly.

And we expect the meeting to end at approximately 4:45 p.m. Eastern time. And so Maria Victoria is joining us remotely. And without further ado, we will turn to her for her presentation.

VILLAR: Okay. So thank you for the introduction. Yes, as you say, my name is Maria Victoria Villar. I work in a research center in ... in Spain for Energy, Environment and Technology. And I work for more than 30 years on clay barriers' characterization. So the contents of the talk, I will start by giving some background regarding the processes that take place in buffer. Some of it will be just reminder and talk about the main characteristics of the buffer and what we know about the effect of temperature on each properties.

I will very briefly present the European HITEC Project, and the main part of the talk will be about the different approaches that we have to ... to assess in the laboratory the effect of temperature on buffer materials. And I will use some examples from the HITEC Project. And this is the reason why I will present it briefly.

When I say “buffer,” I mean the material that is, plainly speaking, the waste container and the host rock, normally based on bentonite, can have other aggregates. It’s normally considered to be a bentonite-based material because bentonite is a clay rock that contains high quantity of minerals of the type smectite which have high swelling capacity and high retention capacity.

To put it on ... in the barrier, it can be prepared as compacted blocks. The blocks are compacted with the bentonite with normally ... with its hygroscopic water content. But water may be added before compaction, so we’ll have barrier with a high initial degree of saturation of 60, 70 or 80 percent.

And the bentonite can be also prepared in the form of high-density pellets. You can see some images there. They can be regularly shaped or different sizes or maybe regular. They can be combined with powder. But to prepare the pellets, the material has to be dried. So when we have a barrier with ... composed of pellets or mixtures of powder and pellets, it will be initially quite dry. The degree of separation will be

... will be low.  And in the barrier, we can ... it can be composed, yes, of ... of ... of blocks, pellets or mixture of them.  You can see on the right-hand the Swiss disposal concept in which the waste container is placed on a pedestal of compacted blocks, and then the rest of the gallery is surrounded by ... by granular material, by ... by pellets.

Just a reminder of the processes that take place in the barrier, they are coupled.  They take place because of the combined effect of the thermal gradient and the hydraulic gradient.  We have the hydration of the buffer because of the water coming in from the ... the groundwater coming in from ... from the host rock.  And these will make the bentonite swell, fill voids and gaps, compress air and also trigger mineralogical and mainly geochemical changes.

And then we have a thermal gradient acting ... acting the opposite direction that will cause drying of the bentonite just today ... today in containers, shrinkage, maybe cracking and then vapor movement and also mineralogical and geochemical changes, gas generation.

So as an example of ... of what’s the result of these processes, I ... I ... I have ... and showing here results from an insitu test that is taking place. It’s currently running at the Mont Terri Underground Laboratory in Switzerland.  This laboratory in Opalinus clay, it’s ... in Opalinus clay.  This HE-E experiment, heating experiment, it’s a gallery.  It’s ... in the Opalinus clay with two heaters on ... resting on pedestal of bentonite rocks.  And the rest of the gallery is surrounded by granular material.  And a heater surface is at the temperature of 140.

So you can see on the left-hand side the temperatures as a function of the distance to the axis of the gallery.  So in the part corresponding to ... to the EBS, the ... the engineered barrier system will have these sharp gradient between ... between the 140 degrees of the heater surface and about 60, 50 degrees at the contact between the host rock and the ... and ... and the buffer.

On the right-hand side, we have the relative humidity, the evolution over time at three different positions inside the buffer, the thickness, the total thickness of the buffer is 50 centimeters. So absent 10 cm from the heater, the blue points, and at 25 centimeters in the middle of the barrier, the ... the red points, we can see how the relative humidity decreased very quickly.

So this means that vapor, once the heater is starting to work, vapor escaped to the outside of the barrier. So we had these 7 degrees in relative humidity and these very low recovery. It’s because, well, the Opalinus clay has a low water ... low flow. The water availability is not tight. And this ... and then this water ... this vapor moved towards the external part. And so we can see the ... the ... the green points that correspond to the measurements at the contact between the ... the buffer and the host rock.

So this is a 10-year ... this experiment has been running for 10 years, and we can see that, after 10 years, we still have most of the barrier quite dry, very dry. Okay. So now I wanted to present some major properties of the buffer, thermo-hydro-mechanical properties and how they are affected by temperature, what we know ... what we know about that. So I’ll start by thermal conductivity for most of these properties. These have been studied for many years.

So we know the dependence of ... of these properties on, for example, in this case, mineralogy, water content, dry density. For example, thermal conductivity increases with water content, increases with high density and, in this case, it also increases with temperature. We have an example there, how thermal conductivity changes with temperature for samples of MX-80 bentonite compacted at the dry density of 1.6 for different water contents. In the case, we can see that for the low water content, when the material is very dry, the effect of temperature is irrelevant, whereas, as the water content increases, the effect is more significant.

And with ... as you can see, there are values just up to 90 degrees. And I haven’t found in the literature results for higher temperatures concerning thermal conductivity.

Another property is permeability, also dependent on a series of parameters that are more or less well-known. And it is also well-known that hydraulic conductivity increases with temperature just because the changes of the water properties, particularly the water kinematic viscosity, which increases with temperature. So these ... this is the reason why we have these increase.

But ... there may be other factors because not ... it cannot completely be explained just by considering the changes in water properties. So other factors may be affecting.

Concerning swelling, it’s also known that it depends in many factors such as the particular smectite content, the dry density, the water availability, the salinity of the water. And more or less, we know how it should change with these factors. But for temperature, there is a big uncertainty. There is a work by Pusch et al. in 1990 where it described that ... well, the effect of temperature on swelling will depend on the cation predominant in the interlayer. So you know, smectite has high interlayer cations. So depending on which effect these cations are among monovalent or divalent, the effect of temperature will be different.

However, in the literature, we can find all kinds of ... of results. For example, these two figures, one of them shows results for ... so like bentonite, Chinese bentonite, you can see the black curve correspond to a temperature of 40 degrees and the other one to room temperature. And in this case, the higher temperature, the higher the soil impression. And the other figure shows also results for ... bentonite, the MX-80. And the trend is the ... the ... the other way around. So the test perform at higher temperature. Then in those tests, lower swelling pressure was measured, the black points.

And finally, another important pH and property of the buffer is its water retention capacity, which is normally expressed as the water retention curve that relates suction or relative humidity to water content. And it is known that it decreases with temperature simply because of the changes in water surface tension. But again, the reason they ... there may be other factors that have not been studied so deeply that also affect the condition for how temperature changes the water retention capacity. And again, there are not many results on the water retention capacity of bentonite so temperatures higher than 80, 90 degrees or at least I don't know them.

Okay. So this is ... this was the introduction. This is what we know or what is more or less well-known about the properties of the buffer and how they change with temperature. And so... with this ... in this framework, the HITEC project is studying the influence of temperature on clay-based material behavior but of elevated temperature, considering elevated those beyond 100 degrees, which is more or less the limit of what the studies have mostly treated temperatures below 100.

So this is part of the EURAD Joint Programme, which is a financed activity that is financed by the European Commission on Nuclear Radioactive Waste Management and include as many different topics from the waste itself, the container, the interaction between the different components of the system, gas generation and transport and knowledge management. And also this HITEC work package, which is for each work ... work package are ... is, in itself, a project.

And these HITEC, its aim was to ... or is to provide and resolve that there are useful to different national waste management programs. So the conditions in which ... that we are studying or in which we are working are very different because the disposal concepts are different. But for the clay host rock, participants are working with temperatures lower than 100 degrees and for the buffer, temperatures mostly lower than 150 degrees C.

So it was considered relevant to study the effect of temperature for ... for temperatures higher than those that have been considered so far or normally considered because while the effect of temperature on the clay host rock may be relevant, mainly because of the difference in the thermal expansion coefficient of water and solid rock that may cause stresses that can reactivate fractures or cause a propagation of factures and increase permeability both in the far field and in the near field, in the excavated disturbed zone. And then for the buffer, going to higher temperatures, it’s known that a repository in which the cannisters are in place at higher ... at the higher surface temperature with ... with the lower cooling time will be more efficient. But also, even if finally the agencies decide not to go beyond that temperature, knowing or assessing the performance of the buffer at higher temperature will increase confidence on the ... on ... on give greater credibility to the ... to the design.

So ... so I'm now ... I will start with the main part of the talk, the concerns ... the ... the approaches to ... to analyze effect of temperature in the laboratory. There are two main ways of tackling this. One is determine the properties of high temperature. And the other one is preheating the samples in conditions that can be more or less relevant or similar to those in a repository and then testing the properties at room temperature and see if they have change ... if they have been altered because of the preheating.

So let's just start with the first one, which is ... so the determination of properties at high temperature. I presented results in the introduction about this way of testing. So normally, they use samples that are compacted at relevant high densities. And these ... this way of testing is used to assess the thermo-hydro-mechanical properties and mostly introduce saturated conditions, although it is also possible to produce unsaturated ones. And they are important because they provide representative parameters for the models.

So I will show an example of the determination of two of the most important properties of the buffer, such as the hydraulic conductivity of permeability and the swelling pressure. They are ... although they are ... there are equipments to determine them separately, more or less standard equipments, it’s very ... it’s becoming more and more frequent that its laboratory developed its own... its vessels or cells where the two properties can be developed at the same time and in the same cell, the same material also at room temperature.

So normally, they are ... they are thick-walled cells, and they have to withstand high pressures. And when we work at high temperature, if ... it’s ... ideally, they ... they can be constructed in ... in ... in materials with low thermal expansion coefficients.

To perform the test at elevated temperature, the ... the cells can be put in an oven or in a thermal bath or can be wrapped in heating mats and then insulated ... wrapped in insulated material around. And in this kind of test, injections and ... and backpressures are applied, then the permeability, for example. But when the tests are performed at high temperature, we have to take into account the water phase diagram to apply the adequate pressures. Also, this kind of designs also measure ... we measure inflow and outflow. Some technical aspects of testing at high temperature ... so right ... sorry. Because it doesn’t seem to be working. I cannot move the slide. Hello?

BAHR: Can you back up her slides? We’re working on it. Can you move forward now?

VILLAR: Yes. I see the slide, but everything is frozen so I ... no.

BAHR: Maybe ...

VILLAR: I cannot ...

BAHR: Maybe ...

VILLAR: Doesn’t work.

BAHR: ... you can ask them to advance the slides for you if you can see the slides that they are displaying. It looks like we need to go back.

VILLAR: Yes, someone ... you can hear me?

BAHR: We can hear you, yes. Can you hear us?

VOICE: I think she's frozen.

VOICE: She can't ...

BAHR: Oh, on her end. Okay.

VOICE: Give us a ... give us one ...

VILLAR: Okay.

[Pause.]

BAHR: So we see you. I don't know if you hear us.

VILLAR: Yes. Okay. So now it works. Okay. Thank you. Fine. And so people is ... can hear me now. Okay. So I don't know which moment you stopped listening to me. But when I went ... moved to the ... to the next slide just to comment on some technical aspects of testing at high temperature, in these cells that I described in the previous slide in which you can determine permeability and swelling pressure at the same time, it is very frequent to measure both axial and radial pressures and very interesting both at room temperature and at elevated temperature. But when we work at high temperature, we have to use sensors that are able to withstand these temperatures for a long period of time, not just for peak temperature. And also, they have to be able to withstand high temperature and corrosion, which is something that ... well, bentonite for water can be quite saline. And with heat, this is enhanced. So, corrosion is also an issue. And the other possibility is using sensors that are installed outside the cell. Of course, this will depend on the cell design. You have an example there where the load cell is placed outside the cell and then they use heat dissipaters to avoid the ... the ... the heat transmission to the sensors.

Cables also have to be temperature-resistant to hold leaks and also the insertion of the ... the inlets where the sensors enter into the cell have to be perfectly sealed with upper ... materials. But the most thing when ... when testing at high temperature in these kind ... kinds of cells is the calibration of the stresses and strengths in the same conditions as ... as the test ... tests are going to be performed because it has to be possible to tell apart which part of the ... deformation and obvious stresses we are measuring correspond to ... to the equipment and which ones correspond to the ... to the bentonite.

Okay. This is some ... just some example of results obtained in HITEC. You can see changes of intrinsic permeability and swelling pressure with temperature. In this case, they have up to 200 degrees, but it is not so common.

And I also wanted to present some kind of testing, which is more innovative, let's say, although it has been already done for several years. But now it's becoming more systematic, let's say. This is also performing different work of HITEC. But in Finland. So we have ... you can see the cell on your left. We have the sample. Water comes from ... from the top, and there is drainage at ... at the bottom. And they used x-ray imaging or tomographic method to analyze both the transport and swelling.

So the cell has to be transparent to x-ray and to work at high temperature, they simply put the cell in an oven. And they take it out at different moments, put in an insulation box to ... to do the imaging that takes a short time. And with this kind of testing, they ... they will get information similar to ... to the one we get with more conventional equipment, such as you see on ... on the right, the evolution of water content with time for three tests performed at different temperatures. But the advantage or the particularity of these kind of testing or where we have imaging is that we can have distribution of water content inside the bentonite over time. You have the example, the color figure shows three tests performed at three different temperatures, and we have the images at three different times. So the blue colors mean higher water content. Red color is lower water content. And you can see that, for each test and each period of time, we ... we are able to see how the water has distributed inside the bentonite. And on the right, you have similar image for the displacement, the displacement, the ... the strain. When the bentonite, when it gets wet, it swells. So whenever we have an increase in water content, we have degrees in ... in that dry density, displacement. And this is what we can see on the right. So this is very useful. But the accuracy of the results rely absolutely on the accuracy of the calibration, which, in this case, is quite complicated and has to take into account many, many different technical aspects.

And finally, for kind of testing at high temperature that I said is ... is mostly used to obtain parameters under relevant condition, it can also be used to understand processes. This is also research performing different work of ... of ... of HITEC in France. They are working with the homonized smectite. So they have taken just the ... the clay fraction of the bentonite and homonized it with different cations. And they are testing it in miniature oedometer put ... this is placed in an oven. And so you have the bottom results of swelling pressure test at different temperatures. The red curve corresponds to 100 degrees. And the right figure shows results for a sample ... for samples homonized in calcium. And you can see that there is no influence of temperature on the swelling pressure measures.

Whereas the other two figure corresponds to samples, to material homonized in sodium. And in this case, we do have the influence of temperature. And it’s different depending on the dry density, one and the other. The left-hand figure corresponds to the dry density of 1.4, and the other ... the other, middle one, 1.6. So we ... we can see that, in this case, the effect of temperature is higher for the higher density.

Okay. So we’ll move to ... onto the other ... the second group of ... of ... of ... the second approach, which is the preheating of samples and then testing of how the properties of the material have changed. So the simplest way is to heat the bentonite in the open, dry conditions. This can be representative or ... of repositories that remain dry for very long, as we saw in the HE-E example at the beginning. After 10 years, we still have the ... the ... the contact or half ... almost half of the barrier very dry. So these can also be the ... the situation in a repository with immediate water availability or where vapor can escape. And then the other way of heating these material will be in wet ... wet state.

They ... they are using this kind of vessels or that are hermetic where the material is put in wet conditions or mixed with water and completely filled to ... to avoid boiling. And this could be representative of the ... of a repository where the buffer is placed with a high initial degree of saturation or where ... or in which the water availability is high or vapor cannot escape.

In any case, what the ... after these treatment that can be for different periods of time, different temperatures, the material is ground, stabilized or not, given relative humidity. And then it can be used for different mineralogical/geochemical characterization and also for determination of thermal hydromechanical properties. And for that, material has to be remolded and compacted.

And then what they do is, for example, on the ... on ... on the left, we have values of hydraulic conductivity as a function of dry density in grade. We have results for untreated bentonite. And then in red and orange for bentonite that was heated and dry conditions and in blue, bentonite that was heated under wet conditions. So this allows to check if the properties have significantly changed. In the other figure, we have, for the same samples, different property, this ... the water retention curve for samples untreated and those that were heated and then dried wet condition to different periods of time. So this allows us to evaluate if heating has changed their properties.

And then in particular way of heating is the steam heating. So the ... the heating that takes place under normally low solid liquid ratio in autoclaves and when there are well-known studies such as the Couture one in ... in 1985. Normally these studies are performed under conditions that are ... that say extreme. So the treatment has to be performed, high-pressure vessels, the autoclaves. You have to be ... normally are manufactured from ... from special materials. The temperatures used are much higher than 150 so much higher than those that are currently considered in most repository concepts. And these are studies designed mostly to analyze mineralogical and geochemical changes, illitisations over the transformation of montmorillonite into illite. That’s known to take place at high temperature, require high temperatures and high-capacity contents. So, well, normally they work with purified so just the clay fraction and frequently homonized in different cations.

So we have in the figure an example of results obtained after steam heating that have the cationic exchange capacity of untreated material against the cationic exchange capacity of material that has been treated at 200 degrees in this ... in this case. But the smectite was homonized in different cations that we can see in the legend. And we can see that the effect is different depending on ... on the cation.

So in general, the results are dependent on the solid-liquid ratio on the contact time, the temperature, the potassium concentration in pore water and then on the ... on the characteristics of the smectite, of interlayer cations. So it is maybe for these reasons that there are no ... as far as I know, this is not my ... my topic. But for what I’ve been able to read, there is not a general agreement on the effect of steam on bentonite. But it seems that the

... the new ... I mean new ... those after the Couture work do not point to drastic changes but to slow changes in the smectite character. That means the montmorillonite is transformed into a beidellite, which is another kind of smectite.

Okay. And finally, this kind of ... of test that are ... in which the bentonite or the buffer is heated under conditions that are representative of those in ... representative of those in the repository so this kind of testing is performed in thermal hydraulic cells where we put the ... the material prepared as it is in the barriers so compacted at the same dry density and the same water content.

And if we want to simulate a barrier made out of pellets or we want ... put pellets in the cell. Yhe cells are instrumented. And so they provide online results. And then when they are dismantled, they also provide postmortem results. So they are very useful to validate models.

And I will show you an example of a particular testing in which we used one of these thermal hydraulic cells to reproduce the conditions of the barriers in the HE-E experiment that I already mentioned.

So the material used are ... is a mixture of pellets of MX-80 bentonite as the one that is used in the in situ test. The thickness of the barrier, as I said, is 50 centimeters. So the length of the ... of the column is 50 centimeters. We have the heater at the bottom of the cell set at 140 degrees, such as in the in situ test, the heater surface temperature. And then we inject water on top that simulates the water ... the groundwater in the ... of the Opalinus clay.

So it’s a synthetic water that is called Pearson water that we produce is the composition of the ... of the natural water. So the ... so here you have a cartoon of the ... of the whole experiment of the tap. You can see the ... the hydration vessel where the water is ... is contained. We used a very low injection pressure, just the water column. But this is what ... we realized this is different hydraulic condition that the one we have in situ where the ... what we have is the very low flow. So the ... the water availability is not as high as ... as in the ... in the laboratory test.

But you can see in the middle the cell, which is made out of Teflon but surrounded by stainless steel cylinders to restrain swelling. And then on the ... on the right, the cell wrapped in insulated material to avoid heat dissipation. But we were not able to avoid heat dissipation completely. So the temperatures that we had inside the bentonite were lower than those in situ.

And you can see the ... on the ... on the left the evolution of temperature during the 10 years that they ... that the test lasted. And you can see that it is quite constant. So ... at the bottom on the right, you ... you can see these temperatures as a function of the distance to the heater and the sharp thermal gradient that we have close to the heater where the temperatures go very quickly from 140 at the heater contact to 60 degrees at 10 centimeters from the heater.

And we were also measuring relative humidity, which is the ... the middle figure, where you can see the blue on the green curve correspond to the measurements in the upper and middle part of the column you can see that, at the end of the experiment, the two sensors were measuring relative humidities higher or close to 100 percent, whereas the bottom sensor, we had a very strong drying at the beginning and had not recovered the initial values.

So after 10 years, we dismantled the cell. We extracted the sensors. We were able to see that the bottom one was broken, completely corroded. This is what I ... I mentioned about the salinity effects. Saline ... we know that ... that salinity concentrates towards the heater, and this is enhanced by the high temperature. Then we also extracted the material inside the bentonite, inside the column. You can see on the ... on the right-hand the upper part of the column, which presents wet aspect. It is dark ... consistent. We were not able to see the ... the pellets to tell them apart. The middle part of the column, with lighter columns at ... then ... and then at the bottom close to the heater. We had the material very dry, completely disaggregated, almost as it was put inside the cell at the ... at the beginning. So this is the way in which we have some of the material.

It’s an interesting information for ... for the dismantling of the in situ test. So the ... and they know now that they are going to find the material, which is very dry, close to the heater so it’s going to be completely disaggregated. This is not easy to sample. So they aren’t really looking ... looking for ways of dismantling these large-scale in situ test. It is still running.

So this is ... in the upper part, you have, more or less, reconstruction of the column from ... on the left where hydration ... on the top of the column. And on ... on the right where the heater ... heater was, we cut the ... the ... the ... the column in ... in 25 sections. And in each of these sections, we ... sample to obtain material for different determinations. So now, we are going to perform a complete postmortem characterization, and we are going to know about the changes in mineralogy, porosity, geochemistry. And of course we determine water content. This is the green curve there. And water content as a function of the distance to the heater, so close to the heater, the 5 centimeters closest to the heater. We have material, which is completely dry. We have 0 percent water content and then a sharp increase. The upper part of the column was ... was saturated.

And finally, of course, based more representative are examples that come from large-scale in situ test that have been dismantled. Some of them, more ... at least three of them at the Aspo Hard Rock Laboratory in Sweden. There have been at least three tests in which they have used temperatures higher than 100 degrees, the LOT, the Prototype and the ABM. And there is also mock-up test performing in Belgium where they used a heater temperature of 170 degrees C.

So just to conclude or summarize what I've said, the effect of temperature for temperatures lower than 100 degrees have ... has been studied for many years. It is more or less well-known. But at least I think there is a general agreement that the changes ... there are changes in the properties at least that do not compromise the safety, function or functions of the barrier. There are aspects that ... that are well-known. For example, some ... mention some of the properties change because there are changes in the water properties, although we cannot always explain totally the changes we observe, because of the changes in water properties. But more or less, we can. However, there are other properties in which we do not know which are the mechanisms that cause the changes. For example, in the swelling, we have seen that there ... we have very different results for different bentonites. And there is not a consistent trend.

The ... apart from that, there are ... some of the properties are affected when the bentonite is compacted to a high density but not when it is a low density or the other way around. And, well, just mention that most of the ... of the work on particular ... has been performed in compacted samples that ... now there are many disposal concepts that are also considered the use of pellets, and these have been less studied. And there ... there are some properties that may be affected by the fabric of the ... but ... of the buffer by the way in which it is ... it is manufactured, blocks or pellets, at least for the unsaturated condition.

However, for temperature higher than 100 and

... 100 degrees, there are not many ... many results concerning pH and properties. There ... there are a lot of results maybe concerning mineralogical or ... and geochemical changes. But maybe they ... they have been obtained, and there are extreme conditions. And the ... why we do not have many results for high temperatures, probably an important reason is that it is difficult to test for temperatures above these limit because of the technical issues, the sensors, that not all of them are appropriate, vapor leaks, the calibration issues that are very important.

And there are also less studies in unsaturated materials than in saturated materials. And finally, what I ... we have seen, we can approach these studies in different ways. And they ... they are complimentary because they may have produced different phases or concepts of repository. And in fact, the testing approach would depend on what we are looking for if we want to know parameters for the models or if we want to understand processes maybe. So this is ... this is all. Thank you for ... for your attention.

BAHR: Thank you very much, Maria Victoria.

Do we have any questions from online? Okay. Are there questions from the Board members at the table? Paul Turinsky?

TURINSKY: Your figures, none of them had uncertainty bands on them. Could you talk a little bit about uncertainties, whether ... the experimental uncertainties, whether they are in the reports and how you go about determining the uncertainties. Do you do ... repeat experiments to get some idea of what the distributions are?

VILLAR: Yes. Uncertainties is important because many of these properties ... maybe not all, but many of them are very dependent, for example, on the density. So if we have a slight difference in the ... in ... if we compare the hydraulic conductivity of a sample at different temperatures and there is slight difference in dry density between one temperature and the other, maybe the differences that we are finding are also due to the difference in dry density. And these ... these kind of determinations, swelling pressure, hydraulic conductivity, we rarely find ... we cannot ... we have to perform a lot of determinations to have ... for example, here, you have the variation of hydraulic conductivity with ... with dry density.

The gray points correspond to samples that ... that are untreated. And you can see that there is a scatter. There is a dispersion. This is very ... this is the normal thing because there is a natural viability of the material. And then you can see here that there is an exponential relation between hydraulic conductivity upon dry density.

So if ... if ... if we have a change in ... that we are not aware of, a small change in dry density may cause some change in hydraulic conductivity. So normally in these kinds of determinations, we cannot say exactly what's the uncertainty of the determination. What we have to do is perform many tests ... many tests and then determine these empirical relations between properties, the property and the dry density.

I don't know if this answers your ... your question. But it is true that in some cases, the effect of temperature is in ... in the range of the uncertainty that we have for the determination of this property in some cases. I wanted to show, for example, this. This is hydraulic conductivity for three different dry densities and ... and three different ... and ... and different temperatures. You can see that the scatter for ... for ... for the same dry density is very high.

We have ... we have interpolated the line. But it's just an empirical relation, but there is a lot of scatter. So there are trends, but it is difficult to give exact values. So I think we ... we mostly work with this kind of empirical relations between a property and dry density or a property and temperature. It's mostly dry density that conditions most of these properties. The major factor is dry density.

BAHR: Tissa?

ILLANGASEKARE: Yeah. Tissa Illangasekare, Board. Actually a lot of material to absorb but I ... when you look at Slide No. 16, if you look at the hydraulic conductivity where it's just temperature ... so when I saw this slide, I had a question. But in your conclusion, you basically answered that. So normally, you expect the hydraulic conductivity to vary with temperature in a granular material because of the viscosity effects. But you mentioned there are some other mechanisms.

So if you look at this figure, not this one, the Slide No. 16 ... so if you look at that, the hydraulic conductivity and temperature that points are just sort of going all over the place. So do you have some sort of explanation why that is the case, or you don’t know?

VILLAR: No. Because, well, these are ... I forgot ... forgot to say these are preliminary results. They ...

ILLANGASEKARE: Yeah.

VILLAR: These are ... have been obtained in HITEC. They are not yet published. These are results taken for ... for reports that are still in draft. So I was ... I just wanted to show you that it is possible to measure these properties for temperatures of up to 200 degrees. But it is true that the values are ... yeah, are strange.

ILLANGASEKARE: Yeah.

VILLAR: I … we... So I cannot say ...

ILLANGASEKARE: In fact ...

VILLAR: ... why.

ILLANGASEKARE: ... do you have some sort of hypotheses that you mentioned that some of the ... the post-scale processes may be some chemical processes maybe contribute. So do you have some hypotheses or just doing the testing now and try to figure out what's going on?

VILLAR: Yes. Well, there are ... there can be geochemical changes, maybe some cementation.

ILLANGASEKARE: Yeah.

VILLAR: This is ... I think this is what the ... the authors of these results say. There can also be microstructural changes, changes in the porosity.

ILLANGASEKARE: Yeah.

VILLAR: And porosity is essential for ... for hydraulic conductivity. So if there are some irreversible changes in porosity caused by temperature, of course the ... this would affect hydraulic conductivity.

ILLANGASEKARE: Yeah.

VILLAR: Mineralogical changes, I ... I don't think. Well, maybe we consider cementation is mineralogical change. There might be consolidation of the sample because of the ... so ... so, yes, there is several possible factors that may affect the hydraulic conductivity at these high temperatures in addition to the changes in water properties.

ILLANGASEKARE: Yeah, my second question sort of leads from that one. So when you simulate all these experiments, you are not using triaxial cells. You are obviously using vertical compression and the stress within the sample is created by the walls of the container. So what did ... do you have some sort of a, again, hypothesis or question when you interpret this column data, the in situ data where the stress field can be different because the compaction ... do you have some idea whether it’s going to be underestimating or ... or overestimating these numbers under in situ conditions in the column ... the type of constraint you have in the experiment when you tried to sort of upscale to the real 3D scenarios?

VILLAR: Well, if you mean the ... the last column I show ...

ILLANGASEKARE: Yeah.

VILLAR: ... we ... just to measure axial pressure but in ... in ... in this particular column. But now in the test that we are running now and also other laboratories, they are more and more aware that there are changes along the length of the ... of the samples in ... in stress. So that’s why we are also measuring radial stresses, not just axial stresses but radial stresses.

And ... and they are different and ... from the axial ones. And they are also different along the column, even when a steady state has been reached because it will have different water contents because hydration ...

ILLANGASEKARE: Yeah, yes.

VILLAR: ... goes from one side to the other. We have expansion where the water content is higher. So there we will have the first increase of ... of radial stress. But as the rest of the ... of the column becomes wet, there will be, like, material redistribution, changes in dry density.

So we may have additional changes in ... in

... in stresses. So this is something that ... that it's ... it's important. And it's being studied by many laboratories. Yes. This is an important topic. And it's ... it's taking it into account. We did not ... this column I mentioned was mounted in ... 11 years ago. So at the time, we didn't think of measuring radial stresses. But in all the tests that we have mounted now, we measure also ...

ILLANGASEKARE: Okay.

VILLAR: ... radial stress.

ILLANGASEKARE: And also, looking at the ... looking at the retention function that you are measuring up to 25 percent ... but it's quite different. The retention be quite different from granular results. So my question is that, eventually, you need to use this information to do some sort of multiphase flow modeling. So then you need to have relative permeability type of ... so you ... are you ... do you have any plan? Because normally in granular material, you can get the retention function. Then you can use ... get the relative permeability using the retention function. But seems like those theories won't work here. So do you have plans to measure the relative permeability using the same approaches because you are basically looking at saturated hydraulic conductivity. Is that correct?

VILLAR: Yes. There are ... there are ... normally, the unsaturated permeability in these kind ... kind of material is ... is ... I'm not an expert on that. But it's computed by back analysis of infiltration test. So they ... they are ... so it's not possible to measure it directly.

ILLANGASEKARE: Yeah.

VILLAR: So they apply a model and they back-analyze results of ... of infiltration tests where they have measured the water intake and maybe suction at different locations. And so these allows to compute and ... it's normally ... I think it's normally, as in other materials. It's related to the degree of saturation with an exponent close to three. I know there is some tests of these kind performed at high temperature, not ... not many but some tests. So this ... yes. This is something that ... this is ... I think this is an area where more work needs to be done.

ILLANGASEKARE: Thank you very much.

VILLAR: Thank you.

PEDDICORD: Lee Peddicord from the Board. So it was very interesting for EURAD or EURAD or whatever it’s called, the project. And in your presentation, it was very interesting. The breadth of the participants in the project and the number of organizations and countries, including universities from, I think, the Czech Republic, in Finland and in other national organizations.

The question is how ... how is the management of the project organized? How are you sharing information from the various organizations and how often do you, for example, get together to discuss results?

VILLAR: So, well, the project is ... as I said, it’s called a work package, but it’s more a project. And inside the project, there is task. And each ... each task has a leader that coordinates not ... coordinates the reports because the work of the participants ... each participant has decided around ... well, they wanted ... normally participants work for their national agencies. So if I’m a Spanish participant, I will try to use the material that is interesting for my agency because it’s the material that they would use in ... in a ... in a ... in the future, in the repository. So these ... the work of each participant is very much conditioned by ... by the agency for which they ... they work, the national agency.

But there is a coordination of the reports. There is ... there are meetings every six months. There are some participants that get together or exchange material. For example, for performing the same determination but in different laboratories, simple determinations in ... in ... in this case.

And then while the project has been very much affected by the pandemic because we couldn’t ... were able to meet in person for ... for many months. In fact, I think there has been just one in-person meeting and with very few participants. So there is a project coordinator that is mostly done in ... in task. So those that work with a host rock, those that work with the buffer materials, and then it’s mostly coordination in terms of reports. And, well, we have meetings every six months.

PEDDICORD: Thank you very ... hey, well, I guess the follow-on, because you do involve at least two universities that showed up in your slides, is opportunities for students to participate, get involved, perhaps look at doing this from their professional careers. That is, looking at the waste-handling issues. So has that come out as part of the ... part of the tasks or projects, too, that a student participation ...

VILLAR: There are ... the ... the EURAD joint program in which these work package HITEC is included is very conscious of ... of ... of knowledge transfer. So there are many initiatives to ... for the exchange of students. Doctoral theses are ... are encouraged. So the movement of people among organization speaks also, promoted. So at least among the ... the participants in the ... in the ... in the project, I ... I'm not sure about external participants. But, yes, there is a big concern for ... for students and for transfer of knowledge in ... in this project. It is a characteristic of it.

PEDDICORD: Thank you. I ... I’m looking at your home page for ... for the project, and it’s very impressive so well done.

VILLAR: Thank you.

BAHR: Maria Victoria, thank you so much for joining us at a time that’s late for you. And we ... we really appreciate your insights. I think we need to move on to our next speaker. So again, thank you so much.

VILLAR: Thank you. It’s been a pleasure.

BAHR: So our next speaker is Chris Neuzil. His ... has a long experience in the U.S. and elsewhere looking at field scale as well as laboratory scale processes in clay-rich rocks.

NEUZIL: Yeah. Thanks to the Board for inviting me. I’ll be looking at ... at the barrier properties or talking about the barrier properties of formations, what I’m calling the knowns and unknowns. And I want to emphasize ... and Jean mentioned this earlier in the meeting. I’m going to be looking at this ... at the formation scale, or you could consider it a repository scale.

And basically that is over the thickness of the formation and a footprint that would be on the order of kilometers squared. So some of the knowns or that we think we know, anyway, or that I think we know ... we know that these materials have a low matrix permeability. When I say “matrix permeability,” I’m referring to the permeability of an attacked sample that you would measure in a laboratory setting.

Another thing that has become apparent in the last few decades and is kind of surprising is that ... what I call pressure anomalies are quite common in these formations. And when I say “these formations,” I’m talking about clay-rich lithologies that are pretty consistent throughout the formation and that are within about a kilometer of the surface. And in ... on-shore locations. These pressure anomalies ... and I’ll ... I’ll tell you a little bit more of what I mean by “pressure anomalies” in a moment ... appear to be hydrodynamic responses to some kind of forcing. Forcing is a disturbing ... a disturbing ... a disturbance that’s created by geological activity, crustal dynamism, that kind of thing. We can usually identify a plausible forcing in each of these cases. Not always. And this implies that the matrix permeability also applies at the scale of the formation or the scale that you would be interested in for a repository.

Just for a little bit of context ... and I'm going to apologize ahead of time to folks who are remote. I may be using a laser pointer, and you won't be able to see it. I'll try to describe what I'm talking about. But this is a compilation of matrix permeabilities for clay-rich materials. It's plotted as porosity on the vertical scale, the log of permeability or hydraulic conductivity on the horizontal scale.

And hydraulic conductivity and permeability, I'm going to treat as equivalent. The hydraulic conductivity includes the fluid properties, whereas permeability does not. But if ... if that's not familiar to you, don't even worry about it. The colors are a percentage of clay. This ... these are data taken from onshore settings, erosional settings, offshore depositional settings and accretionary complexes where the oceanic crust is diving under the continental crust and scraping off huge amounts of clay-rich sediments.

And what you can see is that, as these things compact, as the porosity gets lower, the permeability decreases pretty dramatically. It was about eight orders of magnitude difference in the permeabilities. Okay. This goes to some of the discussion yesterday because as ... as the porosity decreases, of course, these rocks become stiffer.

And also, there’s a trend toward lower clay contents with lower porosities. And I think that has to do with what happens when ... what happens to cause the lower porosities besides compaction. There is also diagenetic processes occurring. Just to orient you, the total range in permeability and natural earth materials is something like 16, maybe 17 orders of magnitude. And we’re here in the lower eight or so order ... orders of magnitude. I wouldn’t even know where to put salt on this plot. You guys probably can speak to that better than I can. Okay. Pressure anomalies.

A pressure anomaly is where you have an apparently isolated low or high in the fluid potential in a subsurface, which is indicating either a net inward or a net outward flow. I'm indicating that with the arrows in red. And as opposed to a system where the ... the head changes monotonically between the boundaries of these formations, which would indicate a flow in one direction of these systems.

Upon implication, the fact that you have a pressure anomaly is an indication that something has happened to the system to disturb it and that, left to its own ... left in a stable situation, these would gradually dissipate. This would be a transient flow kind of phenomenon. The fact that there is an arrow across these other formations does not mean that there is flow going through them from one side to the other. It means that flow is in one direction apparently in these ... in these other non-pressure anomaly clay rocks. These are all plotted to scale. This is depth, and this is hydraulic head or fluid potential. Fluid potential or fluid head takes account of both the elevation energy and the pressure energy.

And so generally, you can think of it as flow from high to low potential. Potential ... the use of fluid potential is an approximation. But it works in the cases I'll be talking about. So what are we ... how do we think about these ... these systems? We can think about two end members, one where there is ongoing, if subtle, perturbation that is maintaining these pressure anomalies.

Or there is something happened in the past. And what we're seeing is the remnants of that perturbation in the past. And if we strip these ideas down ... or I ... I should say there are several of the ... these pressure anomaly sites where the anomalies have been measured in more than one borehole. And these will be the focus of the talk because these are where the ... we have the most confidence of what's going on. The Bruce site in Ontario, Canada ... this is near Bure in France. This is the Wellenberg in the Swiss Alps, which is an interesting site. And I understand this is being held in reserve now, that the ... the site in Switzerland has been decided upon. And this is work that I did in South Dakota many years ago.

But if we strip down the idea of pressure anomalies to these two end members ... and the simplest way to think about it ... all right? ... based on analytical solutions. And although this is the citation I give, this goes back ... the solution is an analytical solution for heat flow that goes back to the 1960s, I think.

And it says that if we have a forcing rate and we know the dimensions, this would be the thickness of the formation or the half thickness and hydraulic conductivity. If the forcing rate is great enough and the thickness is ... is great enough and the hydraulic conductivity is low enough, this ratio is greater than one. We should see a pressure anomaly. Okay?

Forcing rate has the dimensions of inverse time because we might be thinking of, for example, a strain or a strain rate. So a strain is dimensionless. And its ... its rate would be for time. The other end member would be ... we're looking at a remnant of a past perturbation. And this ... this solution is due to Karl Terzaghi. This is almost a hundred years old.

And he was worried about the compaction of soils under foundations. But we can ... we can ... this is a criterion that I adopted. This is the time it would take to ... where you would lose about half of the original perturbation, just as a for-instance. We got the length again. We got hydraulic conductivity. Here is the time. We got other quantities, specific storage. This is a measure of how well or how easily water can be stored in or released from the material as the head changes.

Okay? The higher the specific storage, the more flow ... the more water would be released for a given change in hydraulic head, units of one per length of inverse length. So if we plot these relationships, the criteria for when we'd expect to have pressure anomalies.

ILLANGASEKARE: Chris, sorry. So that ... that specific storage is a very, very small number in this case. Is that correct?

NEUZIL: The numbers are small.

ILLANGASEKARE: Yeah, okay.

NEUZIL: The numbers ... well, so we're

talking about ... these sites that we're talking about were sited in geologically stable areas ...

ILLANGASEKARE: Yeah.

NEUZIL: ... where you would say nothing is happening. Many of us would say nothing is happening. So if anything is happening, it's very, very slow. A good example would be erosional down-wasting, changing the overburden, decreasing the overburden on one of these sites. So if we plot those criteria that I just showed you for active ongoing forcing for past forcing and plot them in terms of hydraulic conductivity and length, vertical and horizontal scale or this ratio, hydraulic conductivity to specific storage to length and you put in the criteria that I ... I showed you in those earlier ... two earlier ... or the earlier slide, we get these plots here. And if we plot on those, the measured properties of the ... the sites that I was ... that I showed you the ... the profiles from before, these are laboratory-determined values. Of course, then, the thickness is ... we know pretty well the hydraulic conductivity and this ratio, which is a hydraulic diffusivity or ... I'd like to think of it as a pressure diffusivity.

You see is the anomalously pressured and non-anomalously pressure sites segregated, and they segregate in a way that you would expect if, indeed, we're thinking about this correctly as a hydrodynamic ... trinity of hydrodynamic phenomenon. Mainly, the sites that are ... are anomalously pressured and the ones that require the smallest rates of forcing. So they are the most easily perturbed or in which the perturbation, once created, would last the longest.

This is a little messier, a little more ... little less separation between the two populations. There is reason to think that these may be overestimates of the hydraulic diffusivity. I'll mention why in a little bit. This is a ... a nearly imperceptible background strain rate, for example.

The largest strain rates ... natural strain rates aside from seismic displacements and so on around 10 to the minus 13 per second in accretionary complexes. So on ... we'll talk about how reasonable these are.

In terms of past perturbations, what would they be?  The most obvious one in high latitudes would be glaciation.  And that would be on the order of 10 to the fourth years ago.

So let me talk about Ontario.  Those are kind of very general, broad-brush really stripped down, simplified ways of looking at it.  Let's look at ... dive into a little more detail in ... in the Bruce site in Ontario.  And this is one of the sites I know better than most.

When I was first shown the pressure profile in this system, I ... I, quite frankly, did not believe it.  I thought it couldn't be correct.  And it took me a couple of years of talking to people and looking at the data before I finally did believe it was ... that this is actually what the pressure regime looks like in these rocks.

It's a ... these are Paleozoic rocks.  So here we have the depth on the vertical scale.  This is the head or fluid potential, and it is measured relative to sea level here at zero.  This would be the head that you would expect in a static column of water.  And as you can see, they have a little bump down where ... up here where there is a huge excursion at about 600 meters' depth.

Now, one of the things that's hard to believe here is that the fluid heads at a minimum are something like 200 meters below sea level. Okay? So what that tells you ... first of all, this is no ... to the extent that these are actual measurements of what's going on there, there is no question that this is anomalous because there is no drain for this to go to. It has to be something perturbing this whole system.

So what might that be? Of course, we're in Canada. And I should have pointed out ... let me go back. These are ... these are four different boreholes that all give you about the same pattern. And it even ... it's even better than that, which I'll ... I'll describe later. But the obvious ... the gorilla in the room in terms of perturbing this system is glaciation. And this is work I did with Alden Provost some years ago to look at what the effects of glaciation might be. And we're using a lot of information that was generated by Dick Peltier of Toronto in his ... I forget the name of the ... his glacial model.

But they keep refining it. But he's shown something like two-and-a-half to 3 kilometers of ice over the site, last glacial maximum. So ... and what we found out was looking at the last 40,000 years in this system was sufficient. The prior history didn't really matter too much.

So these are some simulations. And these ... these dots here show ... the red dots show the stresses on the system and ... I'll be honest with you ... I've forgotten what the two plots are. But the ... the brown line is the ... is the overall compressive stress on the system with time.

And we're starting it at 40,000 years ago. And we ... we follow the red dot as the ice advances, minus 30,000. And what we see is the pressures in this system. This is a very tight system. The pressures in the system are increasing dramatically. The heads go up by about the height of the glacier. Okay? And this is some 30 ... 30 megapascal, say. Fifteen thousand kilometer ... you know, by 15,000 kilometers, we've started to retreat, the pressure is going back down. Now, these ... the stresses on this system are due to the weight of the ice. But they are also due to the bending of the crust. Okay? This crust ... crustal flexure. But little bump-out here. Actually, I remember now. The blue is the ice height. Stresses are the brown. So the crust takes a little while to unbend. And finally, we get to the present, and we can reproduce basically what we see in the measurements.

Now, this looks ... this looks convincing. Don’t be entirely convinced because we found there are many, many ways to get profiles, it looked like, what you see the many, many ways to not get them. Okay? It was very specific but unpredictable conditions, combinations of conditions that gave you this. So I’ll say that just as a caveat when we think about this.

But that’s kind of the complexity of diving into these things and trying to explain them. And even just ... this is a very simplified model as it is. So let’s say that, in fact, we’re interpret ... the conceptualization of these things is reasonable. What does that tell us about the system. Well, a lot of these sites, if we take their laboratory values and plot them over the matrix permeabilities, what it’s telling us is they're pretty close. That is, the matrix permeabilities appear to apply at the scale of the anomaly at the scale you'd like to know about for a repository.

This is ... and I want to point this out. This is the Boom clay in Belgium. You can see the porosity is fairly high and compared to ... here is South Dakota. This is the Pierre Shale. This is Bure. Here is the Bruce site down here. This is Wellenberg here.

So this is ... this is part of the geologic history and the history of diagenesis that is making these things behave differently when you look at them. Okay? Some are soft. Some are brittle. Some are ductal. So this goes to some of the discussion yesterday.

I should add that these grayed-out areas are ... are huge volumes of sediment at accretionary complexes. The Nankai, Barbados, the Hellenic accretionary complexes ... and there is also some ... some permeabilities that were backed out of the Gulf of Mexico clay-rich sections many years ago. And they also suggest that, even in those huge systems, the matrix permeability pretty much prevails at those scales. Okay. Those are some of the things that I'm pretty confident about.

But there is a lot of things I'm not confident about. Here are some of the unknowns. And one of them is the constitutive law that we use, which is Darcy's law, the proportionality between the driving forces characterized by the gradient in the hydraulic potential and the flux. Are these thing ... is the flow Darcian when you get to nanoscale and you really compact these things and the pore throats are extremely constricted. I'll say more about that in a moment.

The reliability of the pressure and other data, it's nontrivial measuring pressures in these system because it's not ... most of ... most of the data we've had up until 40 years ago ... it's a new oil patch. And they would drill through the less permeable stuff. And if they had found a reservoir, it could be an isolated reservoir. It measured the pressures there.

So our understanding of pressure anomalies on that scale at those depths is largely from those kind of things also. And compactional, depositional environments, we get anomalously high porosities at depth indicating overpressures, those kinds of things.

But in these systems, it's really ... you have to measure pressures directly. And that's ... that's a difficult thing. I'll say more about that in a moment. Gas phase methane, there is gas ... there is methane in the Pierre Shale. There is methane at the Bruce site. I think there is methane at other sites. Is it completely dissolved in the pore fluid?

I think, in many cases, it is. But when you put a borehole in these systems, you are making a huge pore with essentially zero capillary pressure. And what's going to happen? How does that affect, among other things, your pressure measurement?

And are there ... are there instances where you generate a gas phase or a gas phase gets generated as stresses change and that sort of thing? And I ... I'm very uncomfortable with multiphase flow, particularly in really fine-grade rocks. We can't always identify the plausible forcings and there ... there is issue of dynamic permeabilities.

Permeability, the changes ... permeability change is unrelated to any human influence. But that might be on relatively short time scales. So I'll talk a little bit about each of these. Darcy's law. This is an old plot. And this ... the ... what we have is the hydraulic gradient on the vertical scale, hydraulic conductivity on the horizontal scale.

And this is ... this was data that, at the time, I could find where you could plausibly say yes. Darcy's law applies in these experiments. And this is the range of conditions in the black where Darcy's law, I would say, has been literally observed to be the case. And it ... at the lowest permeabilities, the gradients are very, very high because you're trying to generate a measurable flow.

And being able to measure the flow is the limiting factor here. And at higher hydraulic conductivities, you can get very small gradients. Now, there is work being done in Switzerland, University of Bern, Urs Mader. It has run ... by now, it's, like, a

20-year experiment. And he’s looking ... he says that, down to about this region here, flow is Darcian.

And it’s just kind of nipping at the edges of the ... this area of interest, which is the conditions in these pressure anomalies. So bottom line still is that when we apply Darcy’s law to these analyses, it’s an assumption. Okay. I’m going to talk now about pressure measurement.

This site here, the Benken site ... and by the way, the yellow is indicating estimates of the reliability of the pressure measurements. Those are the spans of reliability. We got these kind of ... this kind of crazy pattern here at Benken. This is data that was available when I wrote this in 2015. And it does stand out as being different from that regard.

And in fact, a follow-up study here showed that, in fact, these data are erroneous. The pressures at ... or at this site are actually anomalously low. And in fact, it should be an under-pressure here. So that’s my way of saying this is a very touchy and delicate thing to measure these pressures. This is a diagram of a scheme used by ANDRA. This is early on, where they used an autonomous pressure gauge, what they called an autonomous pressure gauge. This system here was put in place with a packer. And then they grouted the hole above it with no connection ... no physical connection.

It was interrogated by radio. The casing was the antenna. Why would they go to this effort just to have no physical connection? There was little possible ... little connection as possible up the borehole. The worry was you didn't want any communication, any permeable roots, through the borehole. This ... in a way, this is kind of like an early bit of thinking, maybe, about what has to be considered in sealing the access to a repository.

So this is maybe some of the early primitive thinking about it. I did the same thing except I had cables going up. But I cemented the transducers in because I didn't want any problems with leaks that you can have with just the packer, although a lot of those problems have since been solved.

Here is what I considered the gold standard for pressure measurement. Again, we're at the Bruce site. And this is not something that could be duplicated everywhere. But here, the long-term pressure measurements in one borehole, these look familiar, I'm sure, from the earlier slide that's on the right. On the left are estimates of the pre-drilling pressure based on the behavior of the ... of the borehole during pipe drilling and hydraulic testing.

That is, as the pressures ... fluid pressures in the borehole have changed, you track that. And then you run an analysis. This is Rick Boeheim and colleagues who did these analyses. They are measuring hydraulic conductivity, the storage properties, but they can also back out the predrilling pressure. Bad news is what they are doing is not very sensitive to the predrilling pressure.

Good news is it's sensitive enough that you get some idea of the pattern. And it looks a lot like this pattern. These are two entirely different ways of getting at the predrilling conditions. So I consider it's the gold standard of determining the original fluid pressures in a system like this.

BAHR: Chris, how long did they have to wait to get the ... which I think is the in situ?

NEUZIL: The long-term monitoring?

BAHR: Yeah.

NEUZIL: Years. And I think what ... what limited them, they were using a Westbay system. And the ... the ... the seals started to go, although I think it’s our ... quite reasonable to think that they are pretty close to what they would have gotten with longer monitoring.

So there’s ... that’s the issue of pressure measurement. Another issue is I’m saying ... I’m presenting to you, that, say, 10 to the minus 15 per second is a reasonable background even in a stable area for the kind ... you know, for the forcing that you would need. Is that true? I don’t know. I mean, you can ... you can make that work. Where is the Hayes ... or this is South Dakota here. This is based on just the long-term erosion history of the ... of the site being able to explain the ... under pressures of that site. You saw what happened at the Bruce site. That was more ... had to do with glaciation. And some of these sites, it’s not entirely clear. And in particular, at Bure ... which one is Bure? ... here and here, it’s not clear what exactly is going on. And some ... we don’t ... we can’t ... we can’t call on glaciation if the site wasn’t glaciated with one exception maybe.

So we need a closer look at how dynamic the crust really is, maybe, to explain this. And with regard to that, let’s look at the Bure site. What they have ... and this ... this site ... with the Benken site now ... we now know is under pressure. The Bure site is the only site that has credible measurements of overpressure. All the rest are under-pressures.

Here’s the ... the different data. This is ... this is a boundary here. This is a boundary up here. A linear gradient between the two aquifers on either side is the straight line. So you have a few tens of meters of head over something like 150 meters of thickness. The EPGs is the autonomous pressure gauges. That’s ... that is those data. I think the judgment at ANDRA now, the last that I heard, was we’re really not sure what’s ... what’s causing this. And I think what we need to do ... one of the things I want to do is look at the possibility that, although this is not glaciated, it was close enough to the glacial boundary that, in fact, the bending of the crust under the glacier bulged it up. And then as the glacier retreated, it came back down, which would have been basically a dilational strain followed by a compactional strain. So that's one possibility.

Dynamic permeability ... so this is a paper by two Chinese authors and Michael Manga. The location is Taiwan. And this is a case ... this is following the Jiji Earthquake of 1999. A thick sequence of shale or shaley material. It's mountainous because it's a tectonically active area. And this is probably quite faulted. But what ... what was discovered was that, following the earthquake, there was a large release of water from this section of shale. Now, I bring up that there are other examples of ... of ... of these kinds of phenomena, some in China. This is the most compelling analysis that I have seen. It is quite believable. I recommend if you ... if you're at all interested, go take a look at the paper. This was published in Geology, 2004. But they ... they document what looks like about 100-fold increase in permeability following seismic shaking.

Now, going to the idea ... how ... how rapidly do shale self-seal? That was another question yesterday. Because this is a tectonically or a seismically active area, with ... I'm not sure it's [inaudible] but it's, say, on the order of 10 to the two years, let's say. Clearly, this is closing back up in that time or less when you can release this amount of water with shaking. So that's some way of looking at maybe the healing time. And other ... other seismic-related changes are kind of like this, similar interval time ... intervals of time.

Okay. And finally ... and I should have added this to the unknowns, is ... is there is a dichotomy, a scale dichotomy among clay-rich lithologies depending on whether you look at a ... a repository scale, let's say, on the order of kilometers squared ... oh, excuse me. This one up here. Or you look at a larger area, something greater than about a thousand kilometers and up to maybe a million square kilometers.

So let me point out the Pierre Shale in these plots. The Pierre Shale ... and for those who don’t see my pointer, it’s the uppermost ... the leftmost of the uppermost yellow in terms of the ... this is depth and permeability on the horizontal scale.

This is the Pierre Shale and a site scale on the order of a few kilometers, square kilometers. This is the Pierre Shale across whatever the size the state of South Dakota is. Over on the right, we’re looking at ... there is two orange trend lines that are curved, the rightmost one and the shallow ... the shallowest part of that. There is a huge difference. Now, the Pierre Shale, as we’ve pointed out, is high clay. It’s ductal. It’s not brittle, yet we have this difference. And it prevails between a lot of formations at ... at the smaller site scale and at the larger regional scale. And it’s unclear, in most cases, what causes that.

So with that said, what do we need? What would we like to know? Well, more data, to put it simply, fluid pressure, carefully measured pressures in these ... in the interiors of these formations. Lab and borehole permeabilities. There ... these are not trivial. Mechanical properties. I mentioned that we may be overestimating hydraulic diffusivity.

That’s because we’re using, for the mechanical properties, the deformation behavior on a laboratory timescale. If you have visco or viscoelastic or viscoplastic deformation, you would have a higher specific storage that prevails at millennial or larger timescales. And so we might have a better time ... easier time explaining some of these things.

Fluid geochemistry is ... this goes in tandem with the fluid geochemistry as an indicator of the behavior of these formations. It’s tremendously difficult to study, for example, the Bruce site. Porosities are a few percent or less. Getting the pore fluid to analyze is ... is an exercise in difficulty and a broadly based look at what the forcings might be. Okay? I’m not ... I’m not ... I don’t think that I have the best handle on what we could be looking at in that regard.

Constitutive flow law, it’s really ... you know, the limiting thing for laboratory measurements is stability, mechanical stability of the ... the apparatus, thermal stability of the apparatus, making sure you don't have leaks because the fluxes are so tiny that I don't know that it's doable. We'll see what the experiment in Switzerland tells us. Can you approach that through molecular dynamic simulations? I don't know.

Multiphase physics, you folks know a lot more about this than I do. Many of you do. I'm uncomfortable with it. Much of our understanding of it comes from pore ... larger-pored materials, larger grain materials where the pores are larger and ... and so on. And we get down to these tiny, tiny scales ... as an example, the ... the thought fled.

But anyway, I'm uncomfortable with multiphase ... multiphase physics in clays. Dynamic permeability, fluid geochemistry should help us see what's going on with that and then this dichotomy in local and regional scale permeability. And I remember what I wanted to say about multiphase physics. The capillary pressures of some of the materials of the Bure site are tens of megapascal. And so even ... it's a ... terrible to even try to simulate this. All right? It was so extreme. Okay.

So I've gone a little bit over time. Apologize for that. The ... I just want to say here are the references I gave you. There are so many sources of the data that are presenting. But they are all included in these references. Okay? If you don't see what you need in any of these, it's within the references that are cited here. So with that, I'll just say thank you.

BAHR: Thanks, Chris. I'm going to take the chair's prerogative and ask the first question. You ... you mentioned at the beginning that the matrix permeabilities do seem applicable at larger scales. But that seems in contrast to the data that you presented at the end that suggest that there is a scale effect going from what you call local to regional scale. I think, for a repository, long-term repository performance at the regional scale, we're ... we're interested in those regional scale permeabilities. So should we be using matrix permeabilities, or do we need to worry about those ...

NEUZIL: Well ...

BAHR: ... larger scale?

NEUZIL: I’m confused by you’re saying you need to know at the regional scale because that’s, like, over a thousand square kilometers.

BAHR: Okay. Just to clarify what you mean by ... by regional scale versus local scale. Okay.

NEUZIL: Right.

BAHR: Thanks. Another question that comes to mind is that when we build a repository, we’re excavating a system. We’re changing the fluid pressures locally. And the fact that some of these systems take a very long time to re-equilibrate, do you want to speculate on what the repository construction itself might do to the pressure field, to the flow field?

NEUZIL: Sure. Well, so it was said yesterday that you have this beautiful system. And then you put a hole in it. And then you stick something hot in that hole. And so, yeah, I don’t ... I don’t know the answer to that. So one thing is that if ... if you create a ... a permeable access way ... right? ... if you fail to seal that as well as you would like, you are going to allow some flow down that permeable access way. And in an under-pressured system, you would expect that there isn’t going to be very ... except for what the thermal effects do in the repository itself. You would expect very little tendency for flow back ... out of the system. It would be done in ... into the system.

But I think it would be so ... such a trivial amount of flow because the amount of uptake of water in these systems or the rate of uptake of water in these system is so slow. It would hardly matter. So, yeah, then there is the issue ... I’ll state the glaciation issue where you have now introduced a line or along a linear section and a ... and a ... and a footprint within the formation.

Totally different mechanical properties. You have these open or nearly open areas that you’ve tried to backfill with bentonite. How are they going to react when you run a glacier over it, and you change the stress regime. Stress regime would be of the ... of the system. And is it going to be a locus of fracturing and that sort of thing? I don't know.

But the idea of one of the ... one of the ... I think if you can choose the formation that's fairly thick, the worry about the nearfield effects decreases as the amount of rock ... in-tact rock that you have around you increases. So I guess that's what I'd say.

BAHR: Okay. Thank you. Are there questions, remote questions, questions from the Board, Tissa and then Paul?

TURINSKY: I can go first because mine will be short. If you can't use Darcy's flow law, are there alternatives, or is that the point of doing some MD simulations?

NEUZIL: So probably for a good 80 years, maybe longer, people have found non-Darcian behavior. And maybe they have a ... back in the '80s when I first looked at this, a colleague named Hal Olsen looked carefully at some of the claims of non-Darcian flow and found that in most, if not all, cases that there ... there were credible systematic experimental issues that could explain the non-Darcian behavior. What is invariably invoked is that the flow becomes less than

Darcy’s law would predict as you approach smaller and smaller gradients.

That much, there is consistency about. Otherwise, there are ... it’s ... some say there ... you know, some have found a threshold gradient bore which flows zero. Some have found just a ... a deviation but no zero flow. And I ... I ... I don’t know what to think about it. I ... that’s what I would say here.

TURINSKY: You’re going to use the Darcian model. Are you overpredicting the flow or underpredicting it?

NEUZIL: Using the Darcy?

TURINSKY: Yeah.

NEUZIL: If you ... if ... if the Darcy ... if the Darcian relation is not correct, you are probably overpredicting the flow.

ILLANGASEKARE: Yeah. Tissa Illangasekare, Board. Thank you very much. So the question about multiphysics in clays. So I think in the textbook, when you look at Darcy’s law, we always sort of… we go into a very, very low gradients we sort of say... But my question I was asked in the previous talk was that ... following a traditional retention functions and then relative permeabilities, my guess is they won’t work actually because I work with sandy material in the lab.  And then you could look at this theory just going to field soils with little silt, we found the multiphase flow equations, the traditional relative permeability, Brooks and Coreys and, you know, those things doesn’t work.  So I was always thinking about this issue.  Yesterday, I was asking the same question, the multiphase flow phenomena in this type of material. So I think it is an interesting observation because when you are trying to apply traditional multiphase flow, if you’re getting stuck, I’m going to get a retention function, and I’m going to get a relative permeability.  These are all based on formulations which assumes that Darcy’s flow is valid or Poisson’s flow and those things doesn’t happen in this material. So these are really entering observation in the context of how do you get the constitutive models to look at these problems.  I think the second question is, I think, the question Jean already asked.  You made the statement that the regional large-scale permeability can be ... the lab scale can be applied. How do you measure the lab scale permeability in the field?

NEUZIL: Right. So that’s a good question. So most of those data come from more traditional hydrogeology where people were concerned with water supply, for example.

ILLANGASEKARE: Yeah.

NEUZIL: Where you had confining layer and an aquifer.

ILLANGASEKARE: Yeah.

NEUZIL: And if you know the boundary conditions of the aquifer and you know its permeabilities more or less well ...

ILLANGASEKARE: Yeah.

NEUZIL: ... you can ... based on its behavior, you can back out how much leakage had to come through the confining layer. And sometimes these are regional aquifer systems.

ILLANGASEKARE: Yes.

NEUZIL: And you can back out these numbers. So that’s the source of it. And the numbers that you get are as good as your understanding of the aquifer and its ... its state and its boundary conditions.

ILLANGASEKARE: And so that’s what I’m ... good news in some ways because they are not upscaling. If you measure the permeability in a core, then you can generally apply.

NEUZIL: Right. Now, so the one difference with that is it’s a one-dimensional thing...

ILLANGASEKARE: Yeah.

NEUZIL: ... thing. So the lowest permeability horizon is what’s governing that ... that number.

ILLANGASEKARE: I think that’s sort of many question you raise. So that’s ... those are good observations when you look at these type of materials. So in a away ... some of the simulation do at the barrier scale. Some of those physics, you can investigate. When you go to the field scale, the question remains. If there is a leakage event, then the material goes into a larger regional systems, how things behave, maybe more control by the faults and microfractures and cracks rather than the material itself, I think.

NEUZIL: Right. So I think the implications of the regional ... it's a local dichotomy, I think, would be mostly ... is if you happen to, by bad luck, pick the place where there is a fracture zone or a fault zone that is contributing to these regional scale. It is apparent that there is ... that these are local ... it is local features ...

ILLANGASEKARE: Yeah.

NEUZIL: ... that are ... are controlling the regional value. And if you happen to land on one, you'd want ... you don't want to do that. The other thing is ... the other question is ... which I think is a little far-fetched but are these ... are these dynamic permeability effects? I don't think so, but I don't know how you rule that out.

ILLANGASEKARE: That's another can of worms because when you go to dynamic permeability under multiphase flow conditions because, you know, they are ... people are looking at the dynamic retention behavior because the surface ...

NEUZIL: Right.

ILLANGASEKARE: ... area, we need to post changes. And when this is under dynamic effect, you are going to have completely different flow equations and ...

NEUZIL: I think, mostly as a mechanical thing with the porous medium itself ...

ILLANGASEKARE: Yeah.

NEUZIL: But, yes, for sure in the case you’re talking about as well.

ILLANGASEKARE: People and earthquakes probably they are looking at. Yeah. Thank you very much.

PEDDICORD: Excuse me. Lee Peddicord from the Board. Looking back at your slide 16 where you captured a lot of information from a lot of sites, all ... yeah, this one. All very intriguing. You know, you spent a fair amount of time talking about Bruce and the challenges to understand that originally and so on. These profiles for Wellenberg look a bit similar. The one really interest ... well, really interesting one here ... the others look fairly well-behaved, I guess, is Benken that you ... you circled that seems to go all over the map. If memory serves me right, that is the site in Switzerland they didn't pick for their repository. And I wondered if you had the data for the site they did pick for their repository. That would be kind of interesting to overlay on that.

NEUZIL: It would and I ... I have ... I have not seen those data yet, nor have I seen ... there's another site in Ontario that data have been gathered for that I have not seen as well. So ... now, so those will be very good to have the data from those additional sites, but they are in ... in similar or the same formations, I should say, that have been studied ... already been studied. So it would be nice to have data from completely different formations just to get more ... more different data into the mix to help understand these things. But I'm certainly ... I look forward to seeing the data from the ... the work that's been done recently in Switzerland and Canada.

BAHR: Questions from the staff?

ZHENG: I have a comment.

BAHR: We ... we're going to go ... or this is ... we'd like to ... to answer?

ZHENG: Yeah, this ...

BAHR: Okay. Go ahead and ...

ZHENG: Sorry. This is LianGe from Berkeley Lab. Just to answer Paul's question about the non-Darcy flow, actually, in the last two decades, people have implemented non-Darcy flow in a typical, you know, groundwater flow simulator. And the idea is to develop a threshold gradient. And this gradient can be related to different, you know, type of empirical relationship. At Berkeley Lab, we developed this non-Darcy flow model in our simulator. And actually, it did a pretty good job to explain the anomalies of pressure in the shale formation. Of course, when you use it in a bentonite barrier, it opens another level of complexity so just, yeah, with the combination. Yeah.

NEUZIL: Yeah. And I should add that the non-Darcian ... non-Darcian relationship would make it easier to explain these anomalies. You could get by with slower forcing or a longer go forcing to explain.

BAHR: Thank you. Chandrika?

MANEPALLY: Chandrika Manepally, Board staff. I just want to pick on the comment that you made that if you use Darcy’s law in predicting your flow, you are overestimating it. So I’m thinking, as an implementer, the implementing of organizations in Switzerland and NWMO, I think the numerical models do use some kind of Darcy’s law. So they can say, yeah, we are overpredicting the model flow. So, you know, our repository is safe so ...

NEUZIL: Right.

MANEPALLY: ... can you make the argument that way?

NEUZIL: Yeah, so as I ... as I say, I think the main implication is for understanding these pressure anomalies. We can turn the pressure on anomaly argument around and say let’s ... let’s ... are these systems recording crustal activity that we’re not aware of or that we’re ... we wouldn’t otherwise be able to characterize? In other words, are they ... are they recording ... excuse me ... recording crustal dynamism? And it would be helpful to know in that regard as well. But, yeah, it would ... it would ... it’s not damaging to a safety case for sure.

PARIZEK: Yeah. Richard Parizek, emeritus faculty at Penn State. Chris, you mind if I refer to you as Mr. Argillite as out ... from here on in? And we’re looking for people who would understand argillite materials and their behavior. But several ... several points. You know, yesterday, I raised the question about surprises in repository media. And you’ve made a lot of progress.

And we’d ... only weighing some of the ones that many people wouldn’t even be aware of dealing with argillite behavior. So this is a challenge for the program to say, well, you know, where do we go from here? The question, Chris, you asked about repository disturbance, I asked yesterday. You opened that up. And what’s the time frame for the effects of that to change the flow field? It’s going to, you know, be a challenge in designing repositories and planning their future. The use of isotopes ... there has been some literature recently implying that you could get a lot of value out of it. And I think you referred to this too in terms of isotopes moving in, moving up to show that there is this negative pressure effect; right? But are there errors with this? And I’m sure you have some information on ... on how ... how that might help constrain flow in the time frames that you’re talking about.

NEUZIL: Yes. So there is an entire aspect of this that I didn’t dive into, which is the semi-permeability of these materials. That is, they act like semipermeable membranes to some degree. So they are subject to osmosis. They are subject to ultrafiltration. They can segregate ions. In other words, they can change the ... the mix ionically. And they ... so they make it a little more difficult to interpret, say, any particular geochemical marker that you might choose to use. And I think it’s particularly ... I don’t want to say “dicey,” but it’s ... it’s really open in terms of using isotopes as tracers.

BAHR: So I think ... I think we need to ... we are scheduled for a break right now, so maybe you can continue some of your discussions during the break. Okay. Thank you, Chris. So we ... we are scheduled for a break from now until 2:25 Eastern time, and we’ll reconvene then. Thank you.

(A brief recess was taken.)

BAHR: Yes, okay. So, welcome back to the second half of our afternoon, and our next speaker is going to be LianGe Zheng, who is going to talk about coupled thermal-hydrological-mechanical-chemical processes under high temperature in bentonite buffer. So, LianGe, thank you.

ZHENG: Okay, thank you. You know, I'm originally from Lawrence Berkeley Lab. Of course, I'm first going to acknowledge our co-authors of this presentation, and it, you know, is a teamwork. Absolutely, you know, I got a help from all my, you know, colleagues.

Yeah, I think the key words of my talk is first, the THMC, and the second, high temperature, and then we focus on the bentonite buffer. You know, of course we talk about lab tests, the field tests, and the model work.

We have been talking about the bentonite in a couple of talks, and I think we are pretty familiar with the process, you know, involving bentonite evolution, but here, that's going to quickly recap and just refresh our mind.

So, you know, yesterday, Ed Matteo had actually talked about, you know, the features of bentonite and the reason we use them as a bentonite buffer. You know, low permeability, high swelling pressure, and other high retention factors.

So, we need to ensure that those favorite features are sustained for a long time. So, understanding the model in this early time, the THMC process, actually is critical.

So, regarding thermal, we have, you know, heat emission from waste package, thermal hydration from hot rock, and then in the middle of bentonite, you can see there's condensation and evaporation and you know, mechanically, you know, yesterday Jonny Rutqvist showed this increase… the stress evolution or increase and eventually stabilized.

Then geochemically, you know, we saw that solute transport, with nuclide migration also, and other changes.

So, also this process is coupled, and has also evolved, you know, spatially and temporally. I think Dr. Villar's presentation gave us a fantastic illustration to cover the process. Let's take the thermal conductivity as an example.

Yesterday, you know, in Jonny's presentation, you know, he mentioned that simulating temperature is one of the easiest tasks, but even though for this thermal behavior, that thermal conductivity, we learn from Villar’s presentation, is a function of dry density, water content, and also temperature. This is typical in a couple of processes, not to even mention the swelling pressure which is, you know, the function with density and water content, you know, or other factors. So, this processes are coupled, and also involved temporally especially, you know, studying from the heat emission, you know, you initially have really high temperature, and then you're going down, right?

And then for bentonite… in a bentonite buffer, you really installed it unsaturated, then it will go through a desaturation, then resaturation, and they eventually become fully saturated after a given times. You know, stress increase, then fall, then eventually stabilized. Geo-chemically, you know, we can conceptualize that initially some minerals with high solubility, for example in calcite and gypsum, you know, they dissolve, and they… you know, early time, precipitation at early time, but the reaction for clay minerals… the reaction rate is really, really low. So, typically, those… the alteration to those minerals happens at a much later time. So, this is coupled and also evolves temporally and spatially.

So, to build, you know, a reliable process model, there's a lot of things we need to know. The only model actually has a couple parts. First, you know, first we call conceptualization. So, we see a physical phenomenon. How do we conceptualize it in the… in the model? Which is, you know, the question is now, what are the key processes we have to include in the model? The other way is, you know, how do we represent, how to conceptualize those phenomena in the process, and then how do we represent the process numerically, so which is, you know, do we have a reliable, stable relationship of parameters that describe those processes?

For example, you know, for the bentonite buffer in terms… in terms of THM processes, you know, how do we simulate the porosity and the permeability changes? You know, how about the stress evolution, the mechanical behavior? And regarding chemical models, you know, do we have, you know, reliable chemical models and parameters to describe, you know, those processes.

For example, the evolution of porewater chemistry. Actually… and this is another trivial… even though that's major, the porewater chemistry in bentonite is really difficult, because it's really tight, you know, and it's not easy to get the water out of the pores of the bentonite. And the way you'll try to imagine it, actually, introduce a lot of artifacts. Actually, I'm working this for years; it's not that easy. Then there'd be no change, you know, it's really slow, right? So, you use… you know, I'll just use an example, you know, we always talk about retardation, then you know, we imagine, you know, typical XRD has no resolution, but the one percent… but to have one percent retardation, you know, you need hundreds of years in normal conditions. How do you know… imagine those changes? It's really difficult.

And another is retardation capability and then the interaction between canister bentonite and host rock, so, yeah, so, we need to know a lot of things to be able to simulate those.

But in the last two decades, you know, scientists, you know, in this… in this nuclear waste disposal community, we spend a lot of effort, you know, try to simulate those processes, like, you know, Dr. Villar mentioned, you know, there's a lot of data, you know, and study being conducted for low temperature. Well, one of the reasons is, you know, the most disposal concepts, you know, they assume the thermal limit is a hundred degrees. So, what's the point of going higher than a hundred degrees, right? So, that's a lot of study, folks, in, you know, in the low temperature.

However you know, the question is, what if the temperature is higher than… is higher, some 200 degrees, you know? About seven years ago, actually in the SFWD program, we started to look at this high temperature effect. There are a couple of motivations. One of them is the dual purpose canister. We know that this large canister can generate, you know, much higher temperature, you know, in the engineered barrier system in the near field.

Another issue, another motivation is to open the possibility of raising the thermal limit. You know, the only thermal limit that is… imagine the be a compliance point, and that interface between the canister and the bentonite. So, they… you know, it's managed by the spacing between tunnel and also the spacing of which package within the single tunnel.

So, if you're long term, thermal limit is higher than basically you… the footprint of your repository is much smaller because there's a lot of saving, you know, in cost. And also, Dr. Villar actually mentioned this, you know, I agree with her. So, even though you eventually choose a hundred degrees as your thermal limit in your design, but then knowing what happened at much higher temperature will greatly boost your confidence.

So… but I know, like I also know Villar, great to know… so happy to, you know, we invite her to talk about this issue. There are a lot of unknowns when you go to a higher temperature. For example, the… you know, the hydrological behavior when bentonite evolves from partially saturated to fully saturated at a hundred… no, under 200 degree heating, what happened, you know, to high pore pressure, high stress, gas transporting cyclically, like I said, there's a lot of issues we need to understand.

And another issue is the mineral retardation. You know, we believe that the temperature is higher, retardation will be enhanced, and there's no, you know, issue of losing your swelling capability, and that's why our colleague, Florie, did a lot of study, you know, those hydrothermal lab tests to look at the geological chemical minerology change of bentonite, and high temperature.

Another challenge is the model. You know, is our model ready to simulate high temperature behavior? For example, consider the relationship, like, you guys probably remember that… because they… there's a model retention curve, when you really… we believe it is… well, we're assuming it is independent of temperature for low temp… you know, thermal condition, but is that true?  You know, do we need to revisit this assumption? So basically, you know, in the… in DOE's SFWD program, you know, we use generic models, lab tests, and the field tests to address these questions, and also the approach we took is very interactive and iterative. You know, our goal is, A, has a better understanding, B, to build a reliable process, even eventually we grow towards a performance assessment, which has to include what we learn from this exercise into the larger scale model to… able to assess the performance of the repository.

So, the approach we take is, you know, close in action between modeling and test, and notice that we always start with, you know, simple, then gradually increase the level of complexity so that you don't get lost, because this is so complicated… it's so… there's so much coupling process, and it's so complex.  You know, a lot of process entangle each other, you know, it's really hard to delineate, you know, a single process if you throw everything, you know, together in this one… in the one test.

And then we first learn from low temperature, then we go high temperature, and there is a lot of synergy, you know, among multiple modeling and test effort, and as we expected, they're always a discrepancy between the model and the… and the test, right, than we… when we see the, you know, difference, and we revisit and revise our model, either improve our conceptual model, you know, and revise our parameter calibration, and you know, do a much… overhaul our modern concept than try to, you know, explain the data. Knowing that, and actually we provide a suggestion to test, you know, maybe there was an issue with the test. So, so in the next couple of slides, I will give you some examples that we have been doing in the last couple of years.

I'll start with the experience, again, from low temperature THMC test. This is one of the tests in Switzerland, the Grimsel test site. It's called a FEBEX in situ test. You have two heaters, and the heater was surrounded by bentonite bricks, you know, that is prefab, think, you know, compacted bentonite that they mounted one by one. But in the later… you know, the practice is different in HotBENT or in modeling, you know, because this is really labor intensive. The heater… now, the heating study in 1997 at a hundred degrees. So, in 2002, they dismantled the first heater and take a lot of samples, because there were sensors buried in the… in the bentonite. You can imagine the humidity, temperature, and the pore pressure. But the full geochemical management, you have to take the sample, shut down the test, and take the sample.

So after a 15 day, they dismantled the second heater and a lot of lab tests to do the THMC calibration. And then we develop a THMC model. All model we can see… you know, for the thermal model, we can see the heat convection and conduction is model… a two-phase flow model, and for mechanical behavior, we use a poro-elastic model, and we use a surface approach, and for a chemical model, we're considering a whole much of chemical reactions, including, you know, aqueous complexation, surface complexation, cation exchange, and mineral dissolution precipitation.

So eventually, the model actually was tested with the data, and they… I think they did a pretty good job.  Here, what I'm seeing… showing here is the water content.  So, the red… the red symbol and the line is the data collected after first dismantling after five years, and the black symbol and the line are… you know, are the data and model of the second… of the second model, which is 18.3 years.  So, you can see the model actually did a pretty good job and notice that we have… we have… here, showing the chloride concentration profile.  Actually, the model also did a… you know, a decent job.  So, we learned that, you know, to reproduce THM data, we need to consider vapor diffusion and the porosity and permeability change to deal with the swelling, and also thermal osmosis.

There are a lot of lessons we learn.  Here, there's a single out a couple lessons that we learned by this THMC modeling exercise.  First, the model is THMC model … you know, there's a lot of constitutive relationships, a lot of parameters.  The model is really complex, and the data is limited.  So always, we are looking for more data, even though actually for this FEBEX test, this is only… this is just… this… the only test in situ test… has all kinds of THMC data, but still, we're looking for more data so… to better construct our model. We have too much degree of freedom to tune our model. We like more constraints.

Another thing we learned is, you know, the deficiency of some model were not revealed by the short term data. So, when FEBEX started, there’s tons of models that have been developed, and some model actually look pretty good in the early time. Imagine here, you know, if we… the test that has taken, like, three years. I mean, here, I'm showing you three models, the TH model, Darcy flow model, you know, the THMC model, another Run C, which is, you know, a sensitivity run for the THMC model. If the test took about three years, all of them are doing pretty well, right?

So… but if we go to five years, you'll see the model… the TH model is… you know, didn't do well. Here, a single out Darcy flow actually… and we have model using non-Darcy flow, and they did a horrible job. You know, I can… you know, I don't think I have time to explain why, you know, it didn't work, because there's a lot of factors affecting this multi-physics, you know, model.  So, but here, you know, also, you know, after they dismantled the first heater, the sensor was damaged, you know, and we don't have data after that.  So, for example, the base model and the Run C, you know, they are pretty similar, but later on they're different, and if you have data until, you know, 18 years, we will be able to say, okay, which one is better, right?

So, another lesson I learned is actually the multiple types of data is really helpful.  So, Run C, it's the same as the THMC model, except, you know, the two differences.  In this Run C, the vapor diffusion coefficient is a little bit higher, but it still was within the uncertainties.  However, that doesn't consider the thermal osmosis.  So, in terms of matching the relative humidity data is quite similar, but if you look at the chemical data, you know, it's getting… especially that… at the radial distance is about a 0.6, you know, it's underperformed the basic model.

So, we have multiple types of data, long term data, you know, the model will be much better constraints, we have a much better understanding of what really happened in the site.

So, yeah, this is what we learn by low temperature, you know, what are the processes we need to consider, you know, what type of chemical, you know, evolutions, and we need a long term and multi… you know, multiple types of data.  So, I won't repeat here… just whether I just say… what I had just said, you know, before.

So, after learning, you know, to build the THMC model for low temperature, you know, we want to explore what happened in high temperature.  This is one where the, you know, generic model we, you know, built for a clay repository, you know, assuming the tunnel is 500 meters deep, you know, assuming the clay… the host rock is Opalinus Clay, and we test two types of, you know, bentonite buffer, what is the Kunigel bentonite, which is the Japanese bentonite, and also the FEBEX bentonite, the Spanish bentonite.  So, we created two cases, one we… one we call high T by adjusting the power output, and another we call a low T.

So, in a high T case, the temperature to point A, which, you know, is the interface between canister and bentonite reached 200 degrees, and in the low T case, you know, the temperature only reached 100 degree.

So, the model is kind of similar to the previous model, and here, I want to call your attention to how do we simulate illitization, to simulate it as a dissolution of smectite and also precipitation of illite, and the reaction actually was calibrated by an independent model. So, for mechanical chemical coupling we use, you know, extended linear swelling, or we use Barcelona, and dual continuum … dual structure expansive clay model.

And you know, it's very complex model, but here just show you an example, the results, and here, showing the results for the Kunigel bentonite, and the four points, A, B is in the bentonite, and the C, D is in the host rock, the argillite, and you know, it's those three lines, and why is… okay, one, okay, so, assume there's no heat released. Another low T case, and another high T case. You can see clearly there is illitization and also temperature play a key role in the interaction between the host rock and bentonite, and it's very important.

But the one thing I should stress here actually is a lot of time we focus on the temperature in fact, but to… for temperature to play a role, you need to have the right geochemical conditions. For example, you need to have enough of a supply of potassium. But in this case, you know, the opalinus clay actually has the pore water… or, the Opalinus Clay has a fairly high concentration of potassium, which is why illitization happens, but even changed to another type of, you know, host rock, there's not a guarantee that there will be illitization.

You know, this kind of modeling, you know, really opened our eyes and our… and our… you know, for us to really study what happened at high temperature, but the model has to be tested by… you know, by… by… you know, the model has to be tested by experiments and also field tests. So we also, you know, move forward with lab tests. This is one of the lab tests that is running at the Lawrence Berkley National Lab.

So, this structure actually is quite different from what Dr. Villar was showing, but it is more like miniature of the field test. So, you have heater in the middle, you know, you have bentonite layers, and you also have sandy layers to distribute the water. So, it's very much like, you know, a field test that is not real. Then water was injected as a constant pressure and the heater was maintained at 200 degrees, and even though at the very outside, you know, in the… in the space between that sandy layer, the temperature was still at 80 degrees. It's actually very much aligned with the field condition.

So, we… while the column is heated and hydrated, you know, we put it in the CT scan machine and try to scan it, you know, actually, the… one of the first ones, I could use a CT scan to track, you know, the evolution of water and bentonite that was in the… in the bentonite buffer. And there's a lot of data collected.

You know, we use CT scan, we use a ERT, there's also a lot of analyses with this model… this column, and here, I'll just show you one example, you know, the evolution of density we use to track the hydration upfront. Here you can see, you know, this is the four days, eight days, you know, 22 days, you know, it's… the change of density combined the effect of hydration, also compaction and the expansion, so it's very complex.

A couple take away messages. One is, you know, is… initially when we would pack this column, it's sometimes really hard to pack it homogeneously. So, there's some factors, you know, after the first scan… CT scan, but after the water flows in, the fractures quickly seal, and the hydration is very much axi-symmetrical. So, that's really confirmed you know, our model and our assumption. And also, you know, this… you know, this is dried out because of heating, which opens up a lot of field tests and other column tests.

And of course, you know, we will have such a nice test that you want to model it to improve your modeling capabilities. So, we have the THM model developed to… for this test, and you can see the model did, you know, a decent job, if you're here, just to use one example, and we'll use stated density as an example.

You can see, you know, the model matched the data pretty well, but if you look at it here, eight days, the discrepancy here. So, this is really dynamic, you know, process, the swelling, hydration, you know, compaction, and the expansion work together. So, we need to refine our mechanical model to really catch this dynamic behavior. So, it's not that easy.

Another thing we're trying to focus here is the water retention curve. Like I mentioned, you already assume water retention curve is independent of temperature, but the question is, is that true for high temperature? Do we need to include temperature as a factor in your water retention curve? Because water retention cannot be measured, by something like this. You need to calibrate the flow column test like this. And then of course eventually we will expand, you know, the THM model and the THMC model.

You know, in this test, I forgot to mention, we're also collecting the water… the influent, and also we… when we took it down, we measure, you know, the mineralogy change. So we would have, you know, a THMC model to, you know, to learn that the chemical… what happened there geochemically.

And then, you know, after we learn and gained experience from low temperature, we have, you know, an exploratory model, and then we have the lab and the lab temperature test for HotBENT. Lab - -the high temperature column test, and those are our models, and then eventually widen, you know, bentonite can survive, you know, at such a high temperature of heating.

We need to confirm, you know, study the field test, which is why, you know, the HotBENT field test, the new study, that this was about seven years ago after we published our modeling work, and then, you know, we… we were contacted, you know, by NAGRA, and they say, okay, actually, we called NAGRA and wrote a paper together to see, you know, this model is good, but it… you know, I think a large scale field test is warranted. So, at that time, we started thinking about, you know, to do a field test at, you know, a much higher temperature. And then after a couple years of planning, so finally, you know, in 2018, you know, we started designing the test, and then started construction.

Yeah, so this is… had a lot of participation from other organizations, including us, you know, because NAGRA is the leading organization, you know, Japan, UK, Czech Republic, Canada, and also Germany and Spain.

So, it was running in the same tunnel that FEBEX's test was running. So, when the FEBEX… the FEBEX tunnel was cleared… so, they used the same tunnel, because the longer it is we know… because, you know the host rock really well, so we can focus on… really focus on what happened to the bentonite.

So, this is the design of this test. You know, it has four modules, and, you know, you have heater one, which is 200 degrees, and heater two is 175, you know, heater three and four are 175. So, the model is different not only on temperature, but they also have other properties.

For example, the bentonite is different. So, heater one, two, three, was surrounded by… was surrounded by Wyoming bentonite. Heater four is Czech Republic bentonite.

Also, you know, there's a concrete liner around heater one. We want to understand, you know, the interaction between the concrete liner and the bentonite and host rock.

So, the… and also we'll plan for two different time lengths. You know, this heater three and four, we call the sector two. We plan to dismantle this much earlier, you know, five years, and then we keep heater one and two running for another, you know, 15 or 20 years. This is the lessons that we'll learn from the FEBEX and phase two test. We found out, you know, have two dismantle events is extremely useful to understand the… some transition effect.

And also, the… what do you call it… this is a, you know, cross section, and the vertical profile is also different. First, they used… which, you know, is compacted bentonite, with dry density about 1.7, or 1.8, and then you put the heat on top of it, and then the space will be filled with, you know, a big auger machine. They use granulated bentonite. Later on, I'll show a model… I'll show a video, how do they, you know, install the entire test.

And this is the timeline. So, after a lot of, you know, discussion, planning, then in 2019… October in 2019, they started construction, and then… but… and they… you know, in 2020, they're almost finishing the construction, then last year in September, they started heating, and this year in June 2nd, they actually… the heater reached the targeted temperature.

So, phase one is supposed to last five years. Then we have a discussion, you know, whether we should, you know, run it longer and revise the time, but still, there are two phases. One phase is shorter, about five years, and not as long.

So, this is the video to show, you know, the construction, you know, of this field test, just… so, I need to wait, like, three seconds? Okay, cool. This is how they construct the pedestal. The heater is three meters long, with a diameter of about 90 centimeters.

This is the big auger machine to fill the space with bentonite. These are the wires, you know, to connect all the sensors. So, this is a big bag of granulated bentonite. This is the retaining wall between sector one and sector two.

So, the construction was finished, you know, I think in later 2020, and then middle of '21, and then last year… yeah, like, you know, you see the video, the entire site was heavily instrumented with a lot of sensors.

Here is one example at the… at the… you know, this sector 53 with, you know, sensors of temperature, pore pressure, and relative humidity. And this is the milestone of, you know, the construction. So, yeah, in August of 2021, they finished the construction.

So, in September, they started heating the… of course, we started with low temperature, 50 degree, and go 200 degree one time, right? So, the heat gradually ramps up in these steps. So, in June this year, you know, the temperature reached the target temperature, which is 200 degree for heater one, 175 for the rest of the heaters.

You know, when you have such a nice test, you will… you'll come up with modeling work. So, they also established a modeling platform. The goal is, you know, initially, we started an initial model, and it was more like a planned prediction. So, we used the parameter gained from other lab tests, you know, sort of predicted behavior in the test, and eventually, you know, when the data came in… the data came in, we would recalibrate our model, then we make predictions. So, in this model platform… this… also participation from different organizations in the UK, you know, Canada, including us, from the US side, we have Sandia National Lab, which we are going to do some THMC modeling folks in the official area at the Berkley Lab, you know, we are trying to develop a THMC model, 3-D THMC model for the test, so this is ongoing, you know, I've got we have the 3-D… 3-D TH model, so we, you know, expanded, you know, to a THMC model, and then make a blind prediction, and eventually test our model with the data, and then we recalibrate our model based on the data and make long term predictions. So, the code has been Jonny showing this code, you know, is a couple of THMC code, which allows us to, you know, to simulate such behavior.

So, all this exercise, you know, I would like to stress, you know, will eventually be integrated into the performance assessment. So, by doing this exercise, we're developing… you know, and once the modeling tools and the way we construct, you know, multi-physics, coupled process model and the testing model with large scale experiments, then eventually the information and the lessons learned from the conceptual model we built will supply, you know, the performance assessment with a reliable conceptual model and parameters, and also providing, you know, a PA model with well-tested constitutive relationships, and eventually we find the ways to integrate the process model into the PA model, which is one of the larger efforts. You'll probably hear some in the next talk from our next talk about, you know, how do we integrate? Basically, we use a process called a reduce model or surrogate modeling to do that.

Just to summarize. So, I think, you know, by… in the last decade, there was a lot of effort working on the THMC modeling and test, and we, you know, we gained a lot of experience for low temperature and also the recent study has been dedicated to high temperature conditions.

We use a generic model, lab, and field

experiments, and also the corresponding modern work to, you know, tackle this issue. I think the lab tests and the field… the modeling, you know, work… to deepen our understanding and importance.

We think, you know, our understanding of the modeling capability has been improved a lot in this… in this program, and eventually what we learned that will be integrated into the generic nuclear disposal system and the latest full performance assessment. Yeah, that's my last slide, and then here is some reference if you want to learn more about, you know, the things I presented, and looking forward to some questions.

BAHR: Thank you very much. Have the different modeling teams all done their one-year blind predictions at this point, and have you had a chance to compare your models to others?

ZHENG: The modern platform, we just started it, so we're going to have another meeting in November. So, I think a lot of teams would just look at our study, and so far has still… don't have any results yet, so, you know, including other teams. So, I think the prediction… blind prediction probably will be a little bit later, but we have… just wait until, you know, a bit longer, so…

BAHR:  Okay, well…

ZHENG:  Also, they did…

BAHR: … we look forward to seeing that.

ZHENG:  Yeah.  Yeah, they need more time to process the data as well, so, yeah.

BAHR:  Are there any questions from online Board members?  Tissa?

ILLANGASEKARE:  So, thank you very much.  So I understand, what you're trying to do is sort of get a high resolution model for the source, and then basically the barrier system can become part of the GDSA large model, basically, so, I… so, I just wanted to follow up on the question I had from the Spanish talk earlier.  So, yeah, they were trying to… especially looking at the clay, the retention function, they are quite different from the traditional granular retention function, then I asked the question that, you know, assuming the multi-phase TOUGH code, so, you use a basic retention function to get the relative permeability functions using van Genutchen, Brooks and

Corey… so, my question to you is that it seems like the answer to the question when I ask that they are not measuring those things. They are basically running infiltration experiment, and then use that to back calculate the constitutive models. So, in a way, in your… in the intermediate scale lab testing, are you looking at… because in your models, you are actually adjusting anything. You are using the constitutive models as you got it, and then put in the model and make predictions, is that correct? Are you doing any calibration or…

ZHENG: Yeah, actually, the column scale… the column scale test will give us a chance to calibrate the water retention curve.

ILLANGASEKARE: Okay, okay.

ZHENG: Like you said, we started with van Genutchen type, and…

ILLANGASEKARE: Yeah.

ZHENG: … then the recent publications, more like, improved the water retention, but including temperature factor.

ILLANGASEKARE: Yeah, yeah.

ZHENG: So, this is in calibration with UC San Diego. The problem is that I updated the water retention curve.

ILLANGASEKARE: Yeah.

ZHENG: How has the temperature affected there? But I can only be tested by data up to sixty degree.

ILLANGASEKARE: Yes.

ZHENG: So, the data… like, you know, Dr. Villar mentioned, you know, the data higher than 80 degrees is very sparse, you know? So, we're trying to, in collaboration with, you know, other universities to collecting data on higher than a hundred degrees, and you know, calibrate the water retention curve…

ILLANGASEKARE: Yeah.

ZHENG: … in the smaller column test and apply it to the larger scale. This is one of… probably one of the major uncertainties in the model. Another is, you know, relative permeability, yeah.

ILLANGASEKARE: So, my question is this. So, using the same approach, using the field, or basically the field, and recalibrate the model in the field, then we do a verification for independent data sets.

So, in these large scale experiments, are you looking at the possibility of generating one set of data, and then instead of getting the constitutive models from the… from… adjust the constitutive models to fit that particular experiment, and then run an independent experiment in a way for verification, so that way you don't do any adjustments, and then you see whether the model gets verified, I know, with… either you can run a different temperature perturbation, or some flow incubation. Have you thought about that instead of trying to get a model and adjust the parameters, like, run a completely different experiment, and then you see whether the calibrated model can be verified?

ZHENG: This is not what we planned, but actually we are doing that. You know, we… after this… the column test that I presented here, we start another set of column tests. You know, the temperature is different… the temperature is the same, but the bentonite structure is different, and the hydration is different. So, that second set of columns can serve as an independent water retention model, but however this small change, you know, like Dr. Villar said, you know, the… a coupled of the processes in bentonite is so complex, you know, it's sometimes really hard to reproduce, even though, you know, you use the same construction, same bentonite, the same density, but if you write again the reproducibility is really, really low, so, because, you know, it's a geomaterial, so, it's bentonite.  But I know we still have another set of columns which can serve as more, like, you know, independent, you know, test.  So, you know, if the model… the same set of concepts and same set of processes and parameters can reproduce data from both… different column tests and from our field tests then our confidence will be really, really high.

ILLANGASEKARE:  Yeah, my question is can you do that… do that in the… in the field test?

ZHENG:  We can try to… I mean, it would be kind of difficult to do the field test.  You know, this field test is, you know, $10 million, you know, test, so it's not that… it's really expensive to do it, but we can apply the same concept, you know, to some… like, potentially multi-radius… it's somewhat verified but not entirely, because you know, the host rock is different, the bentonite is different, and you know, a whole host of other conditions are different. So, but you know, the basic process are the same, so you can see, you know, you'll verify it, you know, somewhat, but not entirely I would say.

ILLANGASEKARE: So, in the field, the test is a continuous heating, is that the case? Not a pulse heating, it's a continuous heating?

ZHENG: Yeah, once the temperature reached the target, it's a continuous, you know, heating, and you know…

ILLANGASEKARE: Yeah.

ZHENG: … the target temperature, which is 200 degrees, or 175. Yeah.

BAHR: This is Jean Bahr. You are sort of doing that, and you're not changing the heating regime, but you're going to be calibrating models to the first year of data, and then you'll have years two, years three, years four, so you'll be able to see if your initial calibration takes you forward in time, because even though you're bringing the temperature up to a fixed place, the saturations are going to be changing, the clay is going to be changing over time.  So, you'll have some way using the long term tests to see if your predictions based on early data hold out for later time, isn't that right?

ZHENG:  Yeah, so, basically in all those predictions, we… what we're trying to do is first we try to gather as much information as possible for some temperature is something we know and is our boundary condition.  We won't change it, right?  So, some parameters, for example, permeability, we can gain from other tests, right?  But however, some parameters, like a water… you know, a water retention curve, relative humidity, had to be calibrated by other column tests, which is going to be the things we calibrate later. So, I wouldn't, you know, be surprised if you see the discrepancy between model and the data, but you know, hopefully the calibration will only force those, you know, unknowns, you know, like a water retention curve and stuff, yeah.

And also, this is a coupled process, and a big unknown is how swelling affects your permeability. That's another big unknown here, you know? There's a lot of empirical rate changes, but those empirical rate changes is really, you know, test specific. So, can we transfer the same relationship from another model for the FEBEX test to the HotBENT? This is a question mark, and there's… whether we can test it out, which we'll… you know, if those data can be transferred, then which… you know, when we simulate a much higher temperature, then our confidence will be much higher. Yeah, there's a lot that can be learned, you know, through this process.

LESLIE: Bret Leslie, Board staff. How long did it take to emplace the granular bentonite? I… and again, I understand this is an experiment, but I mean, I'm having a hard time trying to conceptualize, if this was a repository, how fast could a waste package be emplaced? How long would it take to backfill?

ZHENG: I would write down this question and ask other people. Actually, I never really pay attention to how long, you know, because we are sitting here, and then the same answer could be, hey, you know, construction is done, and I didn't really ask him how long, but I… if you see the video, actually you'll see the machine is fairly powerful. I would imagine, you know, it wouldn't take really long to fill, you know, a five meters long tunnel, right?

LESLIE: Yeah, okay. Thank you.

ZHENG: Yeah.

LESLIE: Appreciate it.

MANEPALLY: Chandrika Manepally, Board staff. I have a couple of questions. The first one is you're talking about how you start off with a simple model, and then you add components that is, I'm thinking you start off with the TH, and then you add the geo-mechanical, and then you add the chemistry. Have you thought about, depending on your understanding of the processes, if you change the order of coupling, what if you do TM first, then add H, then add C? Will it… will it give you a different set of results? Will you be able to match the data differently?

ZHENG: That's an interesting thought, and we are… we never really practiced it that way, because TH is one of the most basic processes, you know, encoded in the model. Mechanical depends on, you know, the hydrological behavior.

So, started with a TM instead of TH is quite difficult to do. Then chemistry, you know, especially chemistry, you know, to simulate the chemistry, you need to know the flow rate first, then you… otherwise, there's no way to simulate it.

So, yeah, you really will start with TH, then THM, then THMC, but then with the TH model, you can go the route of THM, or go to THC. That's okay, but you know, starting from TM may be quite difficult to do, yeah, but it is a very interesting thought, and maybe you can… you know, maybe Jonny can practice that and see if you can do… it's doable, yeah.

BAHR: Okay, just for clarification, that's sort of in the process of model development, but there also may be issues in how the model is actually constructed if you're… if the coupling between the processes is actually a sequential model, have you tried… once you've identified the processes, and identified what the couplings are, are there differences that you see if you run the model couplings in different orders?

ZHENG: Yeah, yes. That's a good question, actually. Our code is a sequential coupling, and we come up with a TH first, then we go to the mechanical. Actually, we kind of go to THC first. So, there's a sequential coupling in the TH first, and then the mechanical and the chemical. So, because the code instructs them the other way, so you really would start with TH.

So, this study shows, you know, different ways of coupling. There's some fully coupled that the THMC are so, you know, simultaneous, that's more adequate but also a more time-consuming way. Actually, I didn't mention, you know, the reason for example we… we brought the FEBEX induced test into the ISKB task force, which is more like… and national modern platform, and try to encourage people to do THMC model, and eventually it ends up the only team to THMC, because a lot of code does not have this capability, and to try to implement that in the time is really time consuming to run such a model, especially if you go to, you know, three dimensional, you know, the simulation time is huge. So, the fully-coupled implicit way actually is theoretically the… is more accurate, but it would take a really, really long time to finish running the simulation, but with the sequential coupling, which gives us, you know, the simulation is faster, but you sacrifice a little bit of the accuracy. But actually for the geology application, you know, studies shows actually it's accurate enough, yeah.

ILLANGASEKARE: Yeah, but… can I comment? Yeah, so, I think the… I understand the issue, because the chemical process, the time… anyway, I agree with you that implicitly coupled model is impractical. They have to be decoupled and then recoupled, but then they have to… they have this issue of time… of time, because the chemical processes are more long, I assume. So, I think you don't have a choice in the sequence. So, I don't think you can… yeah. So, you can run the thermal model, you can run the mechanical, but even the mechanical thermal, you can switch, but the chemical, I think is going to be much more longer.

MANEPALLY: Yeah, but I was just… since we have been in the previous Board meetings, we have been asking you to look at, you know, unexpected results or think outside the box or not just stick to your… the usual way of doing things. So, this was along those lines. The other… may I… can I ask one more question?

I was just wondering, the discussion about the moisture retention curve, are you considering hysteresis, that is, the wetting versus drying paths, given that it… for clay, the hysteresis can be quite significant?

ZHENG: Yeah, you are making things even more complex, yeah. So, hysteresis actually is implemented in our code, you know, the TOUGH simulator. It is there. They applied it in, you know, in some other similar scenario, like a CO2 sequence, but we are not planning to use it, because you know, THMC is already complex enough, and also the data we are going to have is fairly limited in a way, we're going to have temperature, you know, relative humidity, and the pore pressure, so, on another level… but what you're saying is definitely an important process, and you know, it should be there, but we're just trying to constrain ourself a little bit so that we don't, you know, go wild with those models and otherwise, you know, because hysteresis basically is another level of complexity for the water retention curve. So, now you're thinking about adding temperature effect, now you add hysteresis. You know, just the water retention curve may kill a lot of people, you know, yeah, this is really… but yeah, it's a great… and I mean, once this model is mature enough, you know, adding more processes, you know, like as this is tested out, you know, that would be, you know, that would be the… I think that would be a great idea.

But I… you know, there's also a possibility where you run into a non-unique solution. So, you know, for example, I believe that there's one model without hysteresis is… but I use another, you know, for example, with a diffusion coefficient, you match the data.

Then you have another model, you know, and use a different water diffusion coefficient, but use hysteresis, and you also match the data, then that's like, you know, I have been an advocate for a long time that we need a lot more data, long term data, multi-type of data to really constrain the model.

ILLANGASEKARE: In my experience with hysteresis is that we had difficulty when we were incorporating hysteresis into the… we used TOUGH for hysteresis looking at the carbon sequestration problems, so I think it will be a major, major problem doing the same thing to clay, because I don't think there are… I think we had some percolation models, types of ideas, but I think you need to re-look at the issue of hysteresis… incorporating hysteresis into this type of retention behavior.

ZHENG: Yeah. Well, another point is in the… hysteresis is probably not that relevant in this case, because you know, you started with unsaturated, but then you saturated it. Now, with hysteresis, what is relevant is the multi-type of multi-round of, you know, saturation, desaturation, the wetting, and the drainage, and then you get to hysteresis, but if it's just a one-time thing, you know, probably not that important, yeah, because we started with saturated versus unsaturated, and then maybe, you know, a small zone near the heater you have back-and-forth flows in this saturation and this saturation, but eventually it's more, like, a one way, you know, hydration. Yeah.

MANEPALLY: Can I ask just one more question, and then a last one?

JUNG: Yeah, this is Hundal Jung from the Board … staff. Last year, I remember that you had presented for the potential application of machine learning techniques to get us some ideas and answers from this very complex processes, because this kind of the nature of this process. So… and also, I really… I recall that you are… you are planning to prepare some kind of white paper with any publication. So, the question is that, what is the… any progress that still is ongoing, or the second question is the… is there any other countries or groups to use for this machine learning for the… for the disposal research?

ZHENG: First of all, the machine learning white paper was out, and we published that, as I know, as a… as I put in the white paper, you know, my full report, if you like, I can share a copy with you. Second of all, you know, we didn't use machine learning in a lot of, you know, applications, you know, as they relate to our geologic disposal related to nuclear waste disposal. So, using the machine learning to… actually, we… in collaboration with UC San Diego, we planned to use machine learning to develop a water retention curve, so that it, you know, could include multiple factors. Because you know, when you have multiple factors affecting the water retention curve, you know, just by, you know, just by trial and error or just by, you know, a simple matter, it's hard to really get a good, you know, handle on this. So, we're planning to use that, and then but of course using machine learning in all kinds of, you know, applications.

So, while attending the Clay Conference in May, actually, there's a lot of machine learning topics with applications to all kinds of aspects, you know, in the… in the nuclear waste disposal, you know, ranging from derived parameters for chemical reactions to, you know, large scale phenomena.

JUNG: That's a good approach.

ZHENG: Yeah.

JUNG: And you can save us some time learning things.

TURINSKY: Yeah, but machine learning, if you're going to… you know, if you're going to do multi-layered networks, deep learning, it requires an incredible amount of data to be effective.

ZHENG: So, that's why actually we have a…

TURINSKY: To at least live with the problem of, what's the uncertainty?

ZHENG: That is a really good point. You know, machine learning relies on data, right? So, we have a collaboration with Stanford and UC Berkley, you know, try to develop a method that requires much less data, but still, data is the variable… an inevitable barrier to be able to make a machine learning useful, yeah.

TURINSKY: And then you live with the uncertainty.

ZHENG: Yeah, yeah, yeah, yeah.

LESLIE: Bret Leslie, Board staff. Could you go back to slide number 11, which is the HotBENT modeling, and just… I guess I'm trying to understand what kind of direction was provided for all of the teams. You know, like, in DECOVALEX, they kind of lay out what the task is. Can you… oh, sorry, 22. 22.

ZHENG: Yeah.

LESLIE: Sorry.

ZHENG: I'm not controlling it, but…

LESLIE: Yeah.

ZHENG: Yeah. So, HotBENT, I know with… when we started this modeling platform, the thought was, you know, we don't want to duplicate another DECOVALEX. So, the idea is really different. For example, we allow… each team has their own conceptual model. You can… you know, and you don't have to do a 3-D model for the entire test. You can just focus on one particular aspect, or one particular area. So, there's a lot of freedom, you know, in doing things. The idea is to bring, you know, different conceptual model, you know, a different aspect that we learn from each other, but I… you have to follow certain criteria so that we can eventually be able to compare to each other and improve. So, this is something similar to the DECOVALEX, and also something different from DECOVALEX.

LESLIE: So, what are the criteria? And… when

I'm…

ZHENG:  One thing…

LESLIE: … trying to get back…

ZHENG:  Yeah.

LESLIE: … to what Chandrika and Jean said, is you know, is one of the teams going to start with the TM model, and then do the H, or are they all… did you say do THM modeling?

ZHENG:  Well, the criteria is, you know, you first need to use… we have the same set of data, you know, the basic properties.  You can just go wild with them, right?  And then you start with the basic process, but the… you know, we always start with the TH process, but however, how are you going to simulate the thermal or hydrological?  We leave it to the… each participant, how they want to do it.

LESLIE:  Thank you.

ZHENG:  Yeah.

MANEPALLY:  Chandrika Manepally, Board staff. If you could go to slide nine, please?  So, this point where you're trying to illustrate how well the… your TH model does, I was just trying to understand, is this a typical representation of your model results, the… where you kind of do well within the first couple of years, and then it starts to deviate? My… I'm trying to understand in a spatial term, are you able to predict better of things that are little… far away from the heater, or otherwise close to the heater, and you just have to refine a few things in terms of understanding, just because you're so close to the heat source? So, that's where your uncertainty is, whereas as you move far away, you are… you have a better handle. So, I'm just trying to understand the spatial distribution of your understanding.

ZHENG: Yeah, a really good point. And so, here, what we see is… is the relative humidity and the real distance of 0.5, to which it's about seven centimeters away from the heater, and if you move further away from the heater, which, you know, unless they close to the bentonite, you know . You know, any model can match that type of data because it got to fully saturate in ... in a really short time. No matter what kind of model you have, you will match that data. Has no problem. This is the point that give us the biggest trouble. And this is ... we try really hard to match. So, yeah ... yes, this is a spatial issue. So that’s why I know we need a data multiple time and multiple spatial ... otherwise, without that, this point, you know, if we just ... for example, we just have the data near the ... you know, the interface within ... bentonite/granite, every model is perfect. So ... but here, you know, shows the deficiency of, you know, the models. And if we go longer, you know, we reveal, you know, some model is okay. Some model is garbage; right?

BAHR: Do you have any idea what causes that abrupt change at five years? Is it encountering ... is the wetting front encountering some fracture or some preferential flow path or ...

ZHENG: I’m sorry. What’s your ...

BAHR: So the green ... the data, they are following sort of a gradual increase, and then all of a sudden, the relative humidity makes a dramatic jump at year 5. Do you have any idea of what that might represent?

ZHENG: That’s the usual ... when they shut down the heater one and before the dismantling, imagine, you know, to make the field workable ... right? ... they shut down the heater first, then cool down for a period about three months. Then they start, you know, this model. The cooling period, actually, will increase the relative humidity. That's the cooling effect. For example, in model results here ... so here is a sharp increase; right? That's also where ... we also simulated that the cooling time ... so, you know, the cooling is critical. This is cooling. But, you know, unfortunately later, there is no data coming in, you know when we realized the center was ... was destroyed. Yeah. No data.

BAHR: Okay. I think we're actually at time for our final speaker. So thank you again, LianGe. And our final speaker this afternoon is Tara LaForce, and she's joining us remotely. So get her queued up and look forward to her talk.

LAFORCE: Hello. Hi. I'm Tara LaForce from Sandia National Laboratories. And today, I'm going to talk to you all about the integration into the geological disposal safety assessment or GDSA framework for our models that are related to clay-bearing host rocks and also engineered barriers. Okay. So I know you guys have seen the account manager slide, research accounts ... research control account slides a couple times. I just wanted to point out, on this slide, that GDSA is one of the disposal research accounts, but it's actually broken up into six subaccounts, and there is a lot of overlap between what these six subaccounts do. And today, I'm going to talk about one performance assessment case which involves mostly the framework and uncertainty and sensitivity analysis methods, control accounts and a small-scale detailed physics study which involves people and trend development, the integration task, and also the repository systems analysis test.

Okay. So where does the GDSA framework fit? Our overarching goal in GDSA is to develop and demonstrate numerical modeling and analysis capability to provide a sound technical basis for multiple disposal options. So we actually have three potential host rocks. I'm only talking about argillite today. And our goals are to fill gaps and enhance capability in process models and workflow and to also drive development of process models.

So the picture on the right is a ... I believe a slide that Chris Camphouse showed yesterday showing how the argillite engineered and ... engineered barrier and international collaboration were ... control accounts all feed into process model parameters that feed into GDSA. Our ultimate goal is to actually use our studies in the simulation models in GDSA to feed back into those other control accounts to help develop new models, come up with areas where maybe we need more physics research.

Our ... in GDSA, our recent focus has been on high-temperature waste package disposal. So our simulations are all of DPCs with various numbers of PWRs in them. In all of our performance assessment cases, we have only undisturbed scenarios. And the reason for that is that scenario disturbance at the large scale tends to be very driven by the particular site. And since all of our sites are generic, we only look at undisturbed scenarios right now.

We have generic features, events and process screening that goes with the generic sites. We use open-source software DAKOTA for sensitivity/uncertainty analysis. And our main performance metric is peak Iodine-129 concentration. And that is because Iodine-129 concentration tends to drive dose to the biosphere because it has such a long half-life.

So this is the ... a conceptual schematic of the GDSA framework. So everything within the GDSA framework is done in a software called the Next Gen Workflow, which they've developed over the course of the last few years. And the next generation workflow is essentially a ... it's a GUI which calls all the software ... so ... so it calls DAKOTA. It calls PFLOTRAN, and then it also provides a way of analyzing results right there in one integrated workflow.

So what the Next Gen Workflow does is we have some input parameters based on our uncertainties. We sample and do sensitivity analysis. We do sample them in DAKOTA. And then we run all of our simulations in PFLOTRAN. So PFLOTRAN is a ... our simulation flow software. It's been shown to scale up to thousands of processors efficiently, which is very important when you're going to run as many simulations as we are on models as long as the ones that we run.

So within PFLOTRAN, we have different conceptual parts. These aren't separate modules in PFLOTRAN. They're conceptual parts of the model. So we have our source term and EBS evolution model and all of the physics that are associated with that. We have the flow and transport model and all the physics associated with that, and then we also have a biosphere model.

So everything in here which is circled in green is something that implicitly or explicitly depends on the host rock or the engineered barrier because they depend on the temperature, the pressure, the geochemical environment. And those things are all determined by the particular host rock. As you can see, at the bottom left, I have "mechanical" circled. PFLOTRAN is not a mechanical simulator. You can't explicitly include mechanical effects, but you can include mechanical effects through a mechanistic model. And the second example I'm going to show today is ... is an example of us doing just that for disturbed rock zone evolution.

So all of our performance assessment models have coupled heat and fluid flow. They have radionuclide transport via advection and diffusion. They have sorption using linear distribution coefficients or $K_D$s. They include precipitation and dissolution. They have radioactive decay and ingrowth in all phases. We have waste package degradation and also waste form dissolution.

So this is our argillite reference case PA model as it currently stands. This was most recently updated in 2019. It has 3150 24-PWR waste packages and 2000 37-PWR waste packages. They are in 84 drifts. All of our waste packages are in drift placement. Our numerical model is ... actually only has half this many waste packages. It's half-symmetry domain. So there is a closed boundary at Y equals zero. Y equals zero is the plane of the ... of the schematic that's facing the page. And so there is a reflective boundary there which doubles the effect of size of the model. So our numerical model has 6.9 million grid cells as stands. And we are going to run it for a million years.

If you look at the right, that shows ... that picture shows the geology in our model. So at the top of the model on the top right, we have a sandstone aquifer. And that is one of our potential transport pass for radionuclides because someone someday might feasibly use it for drinking water.

We then have our host rock which goes from a depth of 60 meters to a depth of 510 meters. Our repository is that little red line that's at 405 meters of depth. Below our host rock, we have a limestone aquifer which doesn't have as much permeability as the sandstone aquifer but is also a potential transport path through radionuclides because, again, somebody could feasibly sink a well into it and produce water from there.

And then below that, we have a lower shale, which is low permeability. So in our model, we have a left-to-right head gradient of 0.013 just to get a flow from west to east. And as I said before, our monitoring points, our observation points, are the sandstone aquifer above the repository and the limestone aquifer below the repository. And our observation points in both of those will be immediately above and below the repository and then, at the far right corner of the model, 5 kilometers downstream. Oh, excuse me. But 5 kilometers downstream of the repository in those aquifers.

So more on our reference case PA model. Again, our repository is ... has 84 drifts. Forty-two are shown because this is half symmetry model. Our waste packages are laid along the drift. Our drift has bentonite backfill. The ... as I said, we are monitoring mostly iodine-129, so we have an instant-release fraction of iodine-129 of 10 percent at the time the waste package breaches.

So that's not the start of the simulation. That's whenever the waste package breaches, which is a stochastic parameter. And then after waste package breached, we have slow dissolution of the spent nuclear fuel. And that releases more iodine for the rest of the simulation.

So we have ... we use DAKOTA to do incremental Latin hypercube sampling of uncertain parameters. We have a final sample size of 200. So that means we have 200 of these 7 million grid cell models that we would like to run. As I said, our quantity of interest is iodine-129. The table on the right shows our 10 sampled parameters. All of the parameters indicated by green arrows are related to the engineered barrier properties. So we have the rate. SNF is the rate of spent nuclear fuel dissolution. We have rate WP, which is the waste package degradation rate.

We have the buffer properties, disturbed rock zone properties. Everything that doesn’t have an arrow is a geological parameter, like the permeability of the lime, the sandstone and the porosity of the shale. So this is the results of our base case or deterministic case just so you can get an idea of what this looks like in time.

So the top right figure shows what our repository looks like at 10,000 years. So the top right figure is plan view. You are looking down at the top of the repository. And all those little red dots are where waste packages that have breached are located. So you can, quite clearly, see the impact of sampling the waste package breach on the iodine ... on the iodine concentration in the repository.

You can also see that, at 10,000 years, we mostly have diffusive transport of iodine-129. The ... the ... we don't see these little dots of iodine-129 streaking off from left to right going in the downstream direction. And that's because they are surrounded by the bentonite backfill, and then they are surrounded by the host shale and the ... so transport is just diffusive at this time.

If you look at the bottom right picture, that's after a million years. And now I've changed the perspective on you. This is a slice through the middle of the repository. And so ... and Z is up. So you can see, at a million years, inside the shale, you still have a mostly diffusive transport. You still just have this sort of blob of iodine. But then once you get to the sandstone aquifer above or the limestone aquifer below, you can see that we are having advective transport of iodine downstream.

And again, these are our observation points. We have the sand observation point one, which is above the repository. We have the sand observation point three, which is 5 kilometers downstream. And then we have lime observation point one, which is below the repository. And then we have lime observation point three, which is downstream.

Okay. So these are our stochastic results. The main thing you should see ... notice from this is there is a significant spread in iodine breakthrough curves. So the bottom left is the ... is mole fraction of iodine-129 and ... versus time in years. And you can see that it has a log scale for iodine-129 concentration. And that is at the sand observation, .25 kilometers downstream.

The picture on the right is the same thing, but it's at the limestone observation point five kilometers downstream. So you can see there is a huge amount of spread in these curves across our 200 realizations. Another thing that's important to notice is that our mean is much higher than our median. So our mean, our average outcome, is that solid red line, which you can see it eventually reaches a maximum concentration between 10 to the minus 16 and 10 to the minus 15 in the sand observation point on the left, whereas our median, which is our middle outcome, is much, much, much lower. And it's that dashed line you can barely see on the bottom of the picture on the left.

And you see the same observation, the limestone observation point on the right, that you have a mean which is ... actually reaches a concentration of between 10 to the minus 11, 10 to the minus 10, whereas the median is so low, you actually can't see it on the scale of this plot.

Okay. So this is a picture of our sensitivity indices. So a sensitivity index basically says how much of the variance in the output is due to the variance in an uncertain input. And from this, you can see a couple of things. So on the far left, we have sand observation point one. So that's the sandstone above the ... above the repository. And you can see, at this point, the porosity of the shale is, by far, the largest sensitivity index. So at this observation point, that is the parameter that matters, by far, the most. If you look at limestone observation point one, which is the next ... the second from the left, it is the observation point below the repository. You can see that the porosity of the shale is still, by far, the most important parameter. And the reason for that is the porosity of the shale determines how much iodine is able to diffuse out of the host shale.

But at the limestone aquifer point, you can also see there is some importance from the rate of waste package degradation, the permeability of the limestone itself ... that’s kLime ... and the rate of spent nuclear fuel dissolution. So there is not a lot of importance on those, but they are having some impact on the results.

If you look at the two pictures on the right, the second from the right is sand observation point three. And you ... and that’s the sand observation point 5 kilometers downstream. And you can see the porosity of the shale, again, is a little bit important at this monitoring point. By far, at this monitoring point, your most uncertain ... most important uncertain parameter is the permeability of the sandstone itself.

And if you look at the downstream lime observation point on the right, you see that the permeability of the limestone is, by far, the most important sampled parameter in ... for that observation point. And what I ... one thing I want you guys to take from this is that the sensitivity depends not only on the properties you choose but also the choice of points where you measure sensitivity. And we call that the quantity of interest.

So currently, our focus has been, as you can see, on points in the aquifers because this drives dose. But as complexity is added to the repository and we want to start looking at how sensitive different outcomes are to increasing levels of complexity in the repository and engineered barrier features, we need to start looking at different quantities of interest. And that is something which is a work in progress as of ... at this time in a GDSA framework.

Sorry. My slides have a little ... so that is our PA case as it currently stands. But the second half of my time, I’m going to talk about disturbed rock zone evolution modeling which we have been working with ... working on since 2019 in the shale case. So this was a project which we initiated in collaboration with LBNL back in 2019. It’s been worked on by the GDSA

PFLOTRAN Development and Repository Systems Analysis work package. So basically, the development people have developed this new capability in the software. The repository systems analysis people have been testing out how well it works and seeing if the results it gives appear plausible.

So the goal is to adapt an increasingly mechanistic modeling approach to PA scale simulations without sacrificing computational efficiency. So the questions are how can coupled thermal hydromechanical simulations affect PA-scale assessments? What can we learn from high-resolution near-field models that we can then use to upscale? And what are the process or scale relationships that dictate whether a simple functional form is appropriate for ... to certain process or if we actually need to go into a more detailed process modeling?

So the picture on the right is ... is a slide LianGe just showed you in the last presentation. And it shows the processes involved in bentonite evolution. So you have some kind of heat emission from your ... you have heat emission as your waste package decays.

That drives an increase in temperature. The next one up, you have initially partially saturated area near the waste package. It desaturates a little bit, and then it resaturates over geologic time. And the stress in the bentonite rises and falls and eventually stabilizes. At this time, we are not including alteration of minerals as a result of this process. So what this looks at is how does this buffer swelling affect the disturbed rock zone evolution because our host shale in our ... or in our reference case is ... it’s a soft shale. We expect that, as stress increases, it will self-heal. So this is our proposed workflow verbatim as was presented at the SFWST meeting in 2019. So first of all, was to use TOUGH-FLAC to derive a relatively simple functional relationship between water saturation and bentonite swelling stress and then relate permeability of the disturbed rock zone to the swelling stress in the bentonite through calculation of reduced order model for effective stress in the DRZ.

So we have finished those two bullet points. There is a publication in the peer-reviewed literature, Chang, et al. In the future, what we would like to do ... or sorry. I was going to say we have actually taken a little bit of a divergence from this because we have decided, instead of just adding DRZ evolution, we're going to start looking at other things in our small-scale model before we start scaling up. And that is what I'm going to talk about later in this presentation.

So in the future, we're going to compare these nearfield PFLOTRAN models with the reference case. For example, the DECOVALEX Mont Terri case, which you just heard about. And also, to use models in PA-scale simulation and compare the results back to the near-field simulation because, right now, this near-field model is very finely gridded, but in PA scale simulation, we really only have a couple of grid cells that represent each waste package and a couple that represent the engineered barrier system.

So this is our conceptual model. You've seen a lot of this in the last presentation. Our model is much simpler. So essentially, we have the waste package, which is in red, and it's radiating heat into the buffer, which is in the orange. The buffer swells as it re-saturates and puts pressure on the disturbed rock zone, which is the yellow circle on the picture on the left.

So we assume that stress on the disturbed rock zone is radial and isotropic. We assume that swelling stress is a linear function of the change in average liquid saturation in the buffer, so stress is a function of saturation because the bentonite swells as it saturates. And then we use Two Part Hooke’s model from Lawrence Berkeley National Lab to get total permeability in the disturbed rock zone as a function of the stress. So you see we are not explicitly including any kind of mechanics in here, but we have a mechanistic model which uses saturation to compute stress to compute change in permeability.

Okay. So this is a little more detail about our model. So the picture on the left is our model domain. It is one quarter of one waste package, and it has all closed boundaries. So what that means is ... is that we have reflective boundaries on all the lateral sides. So this would represent the centermost waste package and an infinite array of identical waste packages.

The center picture is our grid, our nice, fine simulation grid, which has been flexed in order to grid the waste package exactly. We have hydrostatic initial pressure and temperature. Inside the buffer and disturbed rock zone, the liquid saturation starts out at 65 percent. And it's liquid-saturated everywhere else.

And the picture on the right shows how the permeability of the disturbed rock zone varies as a function of the effect of stress. You can see in the 2021 paper, they looked at three different functions. But the Two Part Hooke's model is the one they decided to continue using. So that's the one I'm going to talk about most.

And that's the one indicated by the blue arrows. And you can see the Two Part Hooke's model does not predict nearly as big of a change in permeability as the other two models that were considered. But it does actually have a very large effect on the simulated saturation results.

So this is our simulation results. The picture on the left is the waste package heat as ... in the repository as a function of log time. And then all the pictures on the right are results for how all the different properties ... all the different properties depend on ... sorry ... change in response to that heat. It’s actually easiest if you start look ... by looking at the liquid saturation in the upper right-hand corner.

So you can see what happens is, in the DRZ, liquid saturation starts at 65 percent. As the temperature starts to increase, the liquid saturation decreases. And then at later time, as it starts to re-saturate, liquid saturation goes back up to a hundred percent.

And again, the Two Part Hooke’s model is ... Two Part Hooke’s model is the blue line there which actually experiences the largest desaturation and then the latest re-saturation. And then it has a corresponding effect in liquid pressure on the top center that it has the ... a decrease in liquid pressure, the largest decrease in liquid pressure and then a latest increase.

You see there is actually not a lot of impact on the temperature profile of all this stuff. It's mostly about the change in pressure and saturation. If you look at the permeability on the bottom right, you see, as everything resaturates, the ... or sorry. Until everything starts to resaturate, the permeability stays constant, and then it drops back down to the original permeability of the in-tact rock, which is what we expect from soft shale like the one in our reference case. So this is the work we've been working on this year in 2022. So the thermal conductivity of all ... all the different rocks was always saturation-weighted so that the thermal conductivity in the disturbed rock shown is lowest when liquid saturation is zero and highest when liquid saturation is one because it's a function of liquid saturation.

Also, in the last year, it's become available in PFLOTRAN that you can also have a temperature dependence of thermal conductivity. So we decided that we were going to add that to the small-scale model. And as you can see, at a given saturation, thermal conductivity decreases with increasing temperature.

So we expect this is going to magnify effects on saturation and pressure. Another thing we started doing in 2022 is we are looking at hotter waste packages or, at least, waste packages with different heat inputs. So we ... so we have, through another project, gotten access to several percentile waste packages for real waste packages as loaded in inventory.

We have the 10th percentile, the 50th percentile, and the 75th percentile, hottest waste packages in inventory. So we're sticking those in our model to see what happens. So the picture on the right is a bit confusing. Sorry. There is a lot on it. But to look at the impact of thermal conductivity, you want to compare the red line, which the Two Part Hooke's model, without temperature-dependent thermal conductivity for the 50th percentile to the green line, which is the same thing except with dependent thermal conductivity.

And you can see that you do see a measurable difference when you add this temperature-dependent thermal conductivity in the green line. You actually get a faster re-saturation of the disturbed rock zone and an earlier increase and ... an earlier increase in stress. And also on that picture is what happens if you use the 10th hottest waste package in inventory and the 75th hottest waste package in inventory.

So in our results to date, for our performance assessment modeling, we have done a statistical analysis over 200 simulations using DAKOTA and PFLOTRAN for our generic shale or argillite host rock. Our model behavior appears realistic, and our methods seem to be robust. Our aquifer and shale properties have a significant impact on peak iodine-129 results in the aquifers because that's what we've been looking at. And for the small-scale modeling, we have created a model for DRZ evolution in response to buffer swelling. A simulation indicates that buffer swelling does have an impact on the near waste package flow.

And we've also added to that, in the last year, temperature dependence of thermal conductivity, which, again, has been shown to have an impact. Okay. In the next one to two years, we would like to continue to drive development of process models, in particular, bentonite evolution. As you can see, we've been working on that and also waste package degradation, which is something GDSA framework has been working on, but I ... I didn't talk about at all today. We're also going to develop new shale PA cases since now we do have all of these different waste package heat sources based on as-loaded waste packages in inventory.

We're going to look at adding a certainly in waste package heat so we can sample on that as an additional uncertain parameters. We are looking at adding realism and uncertainty in geological structure. In 2022, we came up with sort of proof of concept workflow for that. It's not very realistic. It's just a proof of concept. So that is ... that is something we're working on. We are exploring sensitivity to new quantities of interest, in particular, things that are in or near the repository like the mean residence time of radionuclides in the repository.

In the small-scale modeling, we might look ... we would like to look at smectites to illite material transform as part of that one-quarter waste package study that is a new capability that's been developed in PFLOTRAN. We -- we are not yet using it in any of the reference cases.

And also adding anisotropic thermal conductivity. That is another new capability in PFLOTRAN, and it would be interesting to see what happens in that small-scale model if thermal conductivity is both temperature-dependent and anisotropic. So in the longer term, we'd like to look at gas generation, disruptive events such as induced seismicity or maybe glaciation, look at new material transform modules. The transform module that is currently set up for smectite to illite in PFLOTRAN can be used in a general way. We have not yet done that, but it's something we would like to try in the future and then also looking at exploring sensitivity as a function of time. All of the sensitivities we have looked at right now are iodine concentration at the end of the simulation in a million years. But if you can get PFLOTRAN to put that out, like maximum iodine-129 concentration at any time, then that is an additional sensitivity you can study. And that's something which they have been doing in the crystalline reference case but has not yet made it to the ... has not yet made it to the shale case. Those are my references. Thank you for listening. And I see ... I have a question.

BAHR: We'll go first to Allen Croff, who is listening virtually.

CROFF: Croff, Board. Referring to your slide 9, if you were to rerun that reference case without the buffer, how would the results change?

LAFORCE: Oh, if you ... well, it's hard to predict because we haven't done it, but my intuition is that if you ignored the buffer, you would see more transport because the buffer has even lower permeability than the shale itself and, therefore, is good at retarding the transport of the radionuclides out ... out of the repository and into the shale.

CROFF: Okay. Thanks.

BAHR: Paul?

TURINSKY: Where do your uncertainty distributions come from for ... for DAKOTA? Are they, you know, square wave or, you know Gaussian? Are they, you know, basically expert judgment?

LAFORCE: Oh, and on slide 7, what distribution they have ... are you guys in control of my slides, or should I move it? Okay. There. So it’s on slide 7, what kind of distribution they are and what the range are. And I believe these come from the generic FEPs analysis that was done by Vaughn in 2012, what the logical ranges are and what kind of distribution they are. The permeabilities are always log uniform.

TURNINSKY: Okay. And are they expert judgment, or are they based on experimental uncertainties or factoring that in, in addition to the model uncertainties?

LAFORCE: I think they are based on, yeah, experimental ranges, either experimental or observed in the field because a lot of our uncertainties are geological.

TURNINSKY: Yeah, well, obviously you got to add the model uncertainty in addition.

LAFORCE: Yeah, yeah.

TURINSKY: Okay. Sorry I missed that.

BAHR: Hi. I think Emily is going to answer some ...

LAFORCE: Oh.

STEIN: Yeah, this is ...

LA FORCE: Oh, good.

STEIN: This is Emily Stein from Sandia National Lab, currently on loan to DOE. But I was heavily involved in putting together that reference case. And those uncertainty distributions are kind of reasonable values for those materials pulled from the literature. So you could call that expert judgment of a single expert.

BAHR: I have a question ...

LAFORCE: Thank you.

BAHR: ... for maybe both of you. Did you assume a fixed value for the porosity of the sandstone and for the porosity of the limestone? And if so, was the porosity much lower for the limestone, which might explain the much greater transport in the lower limestone than in the upper sandstone?

LAFORCE: Yes. They do have fixed porosities. Off the top of my head, I don’t remember what they ... what the values were.

STEIN: That’s ... Tara, I can jump in there too.

LAFORCE: Okay.

STEIN: I ... I also ...

LAFORCE: Okay. Thank you.

STEIN: ... don’t -- I also don’t remember exactly what the porosities were of those layers. But I know one of the reasons that the transport is ... it occurs sooner in that lower aquifer because it’s so much closer to the repositories. So the diffusion just gets there faster.

BAHR: Thank you ... that clarified.

PEDDICORD: This is Lee Peddicord with the Board. Looking back at Slide 16, in terms of the time frames here ... let’s see ... we’ve had kind of two different ones from the left diagram and then the four on the right.

LAFORCE: Yes.

PEDDICORD: So to help me understand, when we’re talking about particularly the temperature one, which seems to be responding fairly quickly ... and if I can calculate my time frames right ... this is like in a couple of days. You start seeing the temperature rise. It's a couple of days from what? What is time equals zero? Is that when that emplaced ...

LAFORCE: Yes.

PEDDICORD: Okay. So ... so we see that happening. The other effects are, again, stretched out over a year, perhaps longer. But we really start seeing an immediate temperature rise at this point where you're modeling this. Do I have that correct?

LAFORCE: Yes. Yeah, that's correct. The temperature starts to rise immediately because ...

PEDDICORD: Yeah.

LAFORCE: ... they're ... I think it's a 12 PWR 50 years out of reactor. Don't quote me on that but ... so it's ... it's quite warm, and it starts to radiate heat into the surroundings ...

PEDDICORD: Okay. Thank ...

LAFORCE: ...

PEDDICORD: Thank you very much.

BAHR: I think we have a question from Tissa, but he's having trouble with his ... his microphone, so we're going to switch to another microphone.

ILLANGASEKARE: Yeah ... slide ... one of the hydraulic boundary conditions that you are using for the ... because you have advection there. So that means there is flow?

LAFORCE: Oh, for the single waste package case?

ILLANGASEKARE: Yeah.

LAFORCE: Yeah. So all of our boundaries are closed. So this is the ... so they are all reflective. So this is the centermost waste package in an infinite array of identical waste packages. So when you do have this increase or decrease in pressure, the flow has to go either up or down in this model because we have a … atmospheric pressure at the top and then a fixed pressure head at the bottom. So flow has to be vertical in this model. Well, sorry. Flow out of the model has to be vertical. You can have flow within the model left and right.

BAHR: This is Jean Bahr. One other question. You referenced reduced order KDs at the end. And I’m a little confused because you said that, right now, you are only incorporating linear isotherm KDs. Isn’t that the most reduced order KD?

LAFORCE: Well, the idea is that, instead of using a mechanistic model that would be even faster to compute ... it might ... it might not be. It's ... it's ... it's something to try but ...

BAHR: I mean, a KD just gives you a retardation factor, which is pretty much ...

LAFORCE: Yeah.

BAHR: ... a reduced order sort of ...

LAFORCE: Yeah.

BAHR: ... thing to begin with.

LAFORCE: Yeah, I agree. It's a simple model, but it doesn't mean it's not worth considering making it even simpler if ... if we can do so without losing important physics.

BAHR: Okay. Thank you. Do we have questions ... another one from Paul?

TURINSKY: Yeah. You're look ... you said you are using packages with 12 bundles, fuel ...

LAFORCE: I'm actually ...

TURINSKY: Or maybe it's 24 because your symmetry ...

STEIN: I can take that question while Tara is frozen. In the reference case that she showed you, there were 24 and 37 PWRs. In the smaller single waste package simulation, I think that is a 12 PWR. I ... and think that Tara showed a few results for that single waste package model that we're also using larger, hotter waste packages.

BAHR: So it looks like Tara is frozen. We'll wait a minute or so to see if we can get her back. LianGe has something to add to this.

ZHENG: Just to answer your question about the reduced order Kd. So that's a case we...we first ran a process model using really complex reaction for example, surface complexation, another way to simulate absorption desorption. We had that model, then we ran the model for a long time. And then we also ran the model for like a hundred simulations. Then we used a surrogate modeling approach to derive a Kd, you know, which is a linear, you know, retardation factor. But it's also a function of some chemical factors such as that in the GDSA model, then we have to use a really complex surface complexation. But at the same time, also consider the possibility of a changing Kd as a function of changing geochemical conditions. Yeah.

BAHR: Okay. Thank you.

[Pause for continuing audiovisual issues.]

BAHR: Okay. So Chandrika has a question that we think Emily might be able to answer. So we're going to put Emily on the spot again.

MANEPALLY: Chandrika Manepally, Board Staff. My question was what is the status of the high-temperature shale repository reference case? I know you published a report in 2020. Have you made any progress after that...with that? And when do you think it'll be implemented in GDSA? If you can give us some...elaborate on that, that'd be great.

STEIN: Okay. So that report about high-temperature shale reference case was really looking at laying out a range of options for a high-temperature shale case, including different options for the backfill or buffer around the waste packages, different options for perhaps the...the overpack on each waste package. So to some extent it is under implementation, like the reference case that Tara showed you is definitely a high-temperature reference case that includes some of the materials that were discussed in that report. I actually can't speak to...to future plans, in terms of looking at implementation of other options out of that report in the reference case, because I haven't been involved in the...in the planning conversations.

[Pause for continuing audiovisual issues.]

BAHR: For those of you watching remotely, we're dealing with some technical difficulties. So we'll ask your patience for...for another few minutes.

[Pause for continuing audiovisual issues.]

BAHR: I think what we're going to do, we do have two people who submitted public comments online. And so I think what we'll do at this point is we'll read through those and hope that maybe Tara can join us at the end of those. So I'll turn it over to Bret Leslie to read those comments.

LESLIE: Thank you, Jean. This is Bret Leslie from the Board staff. And I'll have to look at the inbox when I'm done with these, but we had two people submit comments.

The first commenter is John Buchser from the Sierra Club Rio Grande Chapter, which is New Mexico and West Texas. And he presented...or submitted his comment during LianGe's presentation.

He says, "Thank you for the opportunity to learn about the latest research on nuclear waste disposal. Several questions that could be addressed in future presentation:

"Number One. Turinsky's question yesterday about the very heavy weight of multi-purpose canister and extensive use in the U.S. compaction of packing bentonite seems worthy of more research.

"Number Two. Seems to be minimal research with actual fuel rods. Sister rod testing is one of the few experiments underway.

"Number Three. The researchers presenting appear to be very experienced, but we need new scientists, too. Only two"...oops. Bear with me. "Only two post docs being introduced in U.S. seems too low.

"Number Four. There would be significant opportunities for research if about a dozen U.S. sites we selected for preliminary evaluation. In U.S., seems unlikely anyone wants a site in their neighborhood, but we need to evaluate options scientifically, not just based on least political resistance.

"Number Five. What are the current staffing levels worldwide, within the many universities doing research?"

The second commenter came...came during Tara's presentation, and it's by Stuart Stothoff, Center for Nuclear Waste Regulatory Analysis, and he had a number of comments:

"Comment Number One. Maria Villar mentioned that there was high-salinity at the bottom of the column test used to provide parameters for the HE-E Test. That's consistent with an interpretation of thermal refluxing. When we modeled the column test, we were seeing vapor moving away from the heater due to the temperature gradient, condensation at distance and return movement of liquid towards the heater as a continual cycle. That cycling process would drive salinity towards the heater. Our coupled model for the HE-E Test in DECOVALEX saw this counterflow process in both the column test and in the HE-E Test. If a similar cycling process is indeed active in the HE-E Test (liquid water cycling from the buffer host rock interface into the buffer and returning as vapor), the HE-E Heater Test may have increased salinity on or near the heater.

"It would be interesting to have a core sample sequency radially from the heater, through the buffer, and into the wall rock to identify potential changes in chemistry that are indicative of liquid transport during that cycle.

"I wouldn't be surprised to see a salinity gradient in the host rock just near the wall. Such a result may have performance implication if there are dissolved components that influence corrosion.

"Comment Number Two. Dr. Illangasekare was asking about changes in permeability at high temperatures. One explanation may be due to the charge distributions in the thin layer of water and on the clay surfaces in the very fine scale of the gaps between the clay plates. These forces are temperature-dependent, which means that changing temperatures will tend to expand or contract the separation between the plates. Only a few layers of water atoms are typically found within the plates. So these inter-plate spaces do not contribute to permeability. This implies that the clay 'particles' will tend to swell and shrink, which will tend to alter the available pore space and the retention properties. However, I'm not aware of measurements to confirm or contradict this hypothesis.

"Comment Three. To clarify my comment from yesterday, the data from Mont Terri show rapid pressure changes distill from the source of perturbation. For example, one, boreholes of very rapidly registered large pressure changes greater than 10 meters from the initial tunnel excavation activities; and two, several heater power failure events showed pressure fluctuations well before the thermal pulse reached the sensor. Similarly, the Bure data show pressures responding to the initiation of heating within days at two sensor locations: two-and-half and four-meters from the heater. Then responded to the heating as the thermal pulse arrived.

"These observations suggest that pressure changes in the host rock are very tightly coupled to mechanical responses in both locations which have a response time that is many orders of magnitude faster than either the thermal or hydraulic diffusion. This is akin to the well-known Noordbergen Effect of Anomalous"...bear with me one second.

Again, "These observations suggest that the pressure changes in the host rock are tight"..."very tightly coupled to mechanical responses in both locations, which have a response time that is many orders of magnitude faster than either the thermal or hydraulic diffusion. This is akin to the well-known Noordbergen Effect of Anomalous Pressure responses to pumping for boreholes completed in clay and is entirely consistent with the"..."the discussion by Chris Neuzil.

"The important implication is that with"..."without accounting for the mechanical responses, which are essentially quasi-steady with respect to temperature and pressure, interpretations of thermal/hydrologic processes in clay-based host rocks may be quite misleading on the time scale of experiments.

"The concern regarding mechanical behavior is probably less for the buffer because a buffer is generally less densely compacted."

And that's the extent of the comments by Stu Stothoff. And that is the extent of comments that were submitted from the online audience.

BAHR: Thanks, Bret.

Have we ...

MANEPALLY: Yes, Jean...we have Tara back.

BAHR: We have Tara back? Okay. See if we can get Tara back. Thank...welcome back.

LAFORCE: Okay. Yeah, sorry about that.

BAHR: Do we have other questions from the technical staff? We...we fielded a couple of questions to Emily. But I'm not sure Emily was able to answer Chandrika's question about the hot...hot reference cases and how much of that is incorporated.

LESLIE: I think we asked her a question.

MANEPALLY: Chandrika Manepally, Board Staff. Hey, Tara. I was just asking about the high-temperature shale repository reference case.

LAFORCE: Okay.

MANEPALLY: At what...what is the status of that, and Emily partially answered us saying that some of the aspects that were identified in Stein 2020 Report has been implemented, you're working on it. I just wanted to have a better idea about the future plans, what exactly you...specific tasks that address what were the issues that were recognized or discussed in that report? Thank you.

LAFORCE: Okay. Well so the shale reference case...let's see, is my clicker working? The shale reference case is actually already pretty hot. It's...if we go to Slide 6, it's a mixture of 24-PWRs and 37-PWRs. So it's actually pretty hot already in 2019.

So what we're going to...but what...this year we did a study on comparing our sort of a generic 24-PWR and 37-PWR to as-loaded in inventory waste canisters, and also some hypothetical canisters that...for various heat...energy outputs. And what we discovered is that these are much hotter than a sort of average...than a average waste package would be. So our overall heat is probably higher than is realistic.

But they aren't as hot as the hottest waste packages. So our generic 37-PWR was...we figured it's between the 75th and 90th hottest percent waste package in inventory at...I think it's 50 or...50 or 100 years out of reactor. So what we want to do in the future is we want to populate our individual...our waste package stochastically with the full range from like our coolest waste package and the...the coolest one we have is the 10 percentile hottest. But we have the single-hot. We have the heat inventory...or sorry...the heat source information for the single hottest waste package in inventory. And we want to know that we can simulate that, because we do have to store it someday. Maybe not in its currently packaged form, but...so that's something we're going to look into next year.

LESLIE: Bret Leslie, Board Staff. Tara, thanks for the nice presentation. I have...I had a question which was...appreciate the high temperature calculations you've done. How far out does the 100 degree isotherm extend into the host rock?

LAFORCE: In PA case? I...I actually do not know that off the top of my head.

LESLIE: So this ...

LAFORCE: I know with that small scale reference case, which, while I fell off the...while I fell offline, I...I looked it up. It was a 24-PWR. That never completely dries out in the shale case, because the pressure is so high that far down, and so it never completely dries out.

LESLIE: Right. But I'm not...

LAFORCE: And it never goes above 100 degrees in the disturbed rock zones.

LESLIE: So...but for the high...high temperature, you don't know how hot it gets, how far out it gets, I guess is...

LAFORCE: No. Sorry.

LESLIE: Would that be in one of your reports?

LAFORCE: [No verbal response.]

LESLIE: So let me give you some more background. So you're conducting the HotBENT Experiment to focus on the...the greater than 100 degrees C. How thick of a host rock do you need if the 100-degree isotherm only extends 5 meters out from the repository? Or, if it extends 75 meters out. So again, you're trying to understand the...the range of how large potential effects could be from the hotter waste packages.

LAFORCE: To some extent, our full-scale PA models are not necessarily set up to do that because, as you saw in the previous presentations, if it gets very hot, then suddenly you have these, like, chemical reactions happening where you have smectites, illite transition, and that is not currently in the model. We're looking at putting that in the small-scale model, but it's currently not in the PA-scale model. So we're missing some pretty critical physics that we would need to study that in a rigorous way.

LESLIE: Thank you.

MANEPALLY: Chandrika Manepally, Board Staff. How do you determine the level of detail that as fully coupled was a simplified abstraction of processes necessary to adequately represent, you know, the evolution of...the host rock behavior or the EBS. I...I know that I...I recall that on Slide 12. I think you had kind of listed this question. But I'm trying to understand, do you use like your dose metric? What specific metrics do you use or does that guide use to the level of detail that you implement in GDSA?

LAFORCE: Well, I'd say it's an iterative process, both within the software and also with the process modelers from the other work from the argillite work package and EBS work package. I would also say in order to understand that you have to make sure you have the right quantities of interest in your statistics. So at the current state our...current status of our PA model, we focus on these downstream quantities of interest that account for dose. They don't tell us a lot about how specific parts of the repository are...how they're behaving, if they're retarding radionuclides in the way we hope. So...and...but it's a iterative process because we need to put more physics in the simulation and we also need to put the right observation points in to make sure that we actually capture the impact of that. And that is...is something we're...we're working on. Mostly we've been working on it in the crystalline case, but that will carry over into the shale cases in coming years when we do another iteration of the shale case in 2023 or maybe the year after.

MANEPALLY: Okay. Thank you.

BAHR: All right. Well, I think we're at the end of the questions for Tara. So again, thank you very much for an informative presentation.

LAFORCE: Thanks.

BAHR: And we already listened to the comments that had been submitted online unless there are any more that came in.

LESLIE: No.

BAHR: Which is not the case. Do we have any comments from people in the room that would like to speak? Dick Parizek.

PARIZEK: Yeah. Am I in comments or am I in questions at this point?

BAHR: Oh, I think we lost Tara, so I guess you're in...in comments.

PARIZEK: Well it was going to be for a previous speaker from Lawrence Berkeley.

BAHR: Yeah, I...

PARIZEK: I'll just make the points.

BAHR: Okay. Thanks.

PERIZEK: We're looking at the...the HotBENT Field Experiment and that we saw the bentonite blocks being used as a pedestal for the waste package. And then we saw backfilling them. The question is whether that difference in terms of density and material being placed in a drift would affect the results of the experiment or the measurements being taken, you know, is one question.

Earlier we heard discussions of bentonite behavior always in a idealized container and doing heater experiments in idealized container that was from the earliest presentation today.

And the question is in the HotBENT Experiment, I was watching the video, looking for imperfections in the rock. Were there fractures in...anywhere in that chamber, yeah, because it was a long enough chamber, there might have been some imperfections in the rock.

And then the question is bentonite would expand, it's going to ooze into some of these fractures as part of the...the beauty of that material. And if so, would that affect, essentially, the behavior of the...of the buffer in terms of its change and its density and its permeability and so on, because of imperfections in the host rock adjacent to the facility there. So that was a question.

And then the Board, it's a generic term, but the Board is different. Each of you have personalities. The staff is different. And that's about bentonite. I...I don't have the literature up to date, but surely Wyoming bentonite, we heard about that. We heard of Czech bentonite. How many other bentonites are being used by these international programs, and can we use the results from one experiment or another without understanding uniqueness of the properties of the bentonite being used. And so I hope...hopefully, that's all being identified as what's unique about this bentonite versus that bentonite and so on. Well thank you. Mm-hmm.

BAHR: Thank you for those comments. Any other people in the room that wanted to make a comment?

Well then, I think that brings our meeting to a close. Thanks again to all the presenters, and for everyone's attention, both here and online, and we look forward to a future meeting.

And again, the transcript will be posted eventually, as well as the video of this meeting on our website: www.nwtrb.gov.

Thank you.

[Whereupon, at 4:26 p.m., the meeting, Day 2 of 2, was adjourned.]

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