United States
Nuclear Waste Technical Review Board

Transcript

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PUBLIC MEETING
In-Person and Virtual

Knoxville, Tennessee

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Ronald Ballinger

Tissa Illangasekare
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[Music]

SIU: Okay, let's get rolling. It's 8:00. Hello, welcome back to the U.S. Nuclear Waste Technical Review Board Summer Meeting. I'm Nathan Siu, Chair of the Board. Just as a reminder we have information on the Board at our website www.NWTRB.gov. And as a response to one of the comments we received yesterday, our question, just a reminder the Archive webcast recording will be available on our website by May 30th and the transcript will be available by June 25th, again on our website.

Yesterday we had a busy schedule. Tim Gunter of the DOE Office of Nuclear Energy gave our opening remarks and then we heard from National Laboratory Researchers on various aspects related to geological disposal of spent nuclear fuel and high level radioactive waste in crystal and host rocks. We also heard from Laura Pyrak-Nolte from Purdue regarding fracture characterization and representation of fractures in fluent transport models. So again it was a busy day. It was great information for us.

Today we'll start with a presentation by Erika Holt from VTT Finland and Barbara Pastina from Posiva Oy. And they'll provide an overview on current status of the Finnish Disposal Program. Their presentation will include a description of flow and transport models used to support the safety case for a deep geological repository being constructed in Finland now. They'll also discuss some of the technical challenges and lessons learned from the implementation of the Finnish Disposal Program. And I know we're all excited to hear about that.

Following that Andy Parmenter from the Nuclear Waste Management Organization, Canada, will present the overview and status of the Canadian Disposal Program. And Andy I do apologize for misspeaking on your name yesterday. He'll describe the site characterization efforts at the Wabigoon Lake Ojibway Nation Ignace site, which is being considered as one of the sites for deep geologic repository in Canada.

We'll have a ten minute break after that and then we'll have two presentations related to the corrosion of commercial spent nuclear fuel left after disposal. The first presentation will provide an overview of the R&D efforts and international collaborative programs by Dave Sassani and Brady Hanson. The second presentation will describe the implementation of the fuel matrix degradation model and the geologic disposal safety assessment framework, the GDSA and electrochemical testing by Paul Mariner and Sara Thomas.

We’ll have a public comment period after this presentation at 12:10 pm Eastern Daylight Time. As a reminder those attending the meeting in person wanting 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 commenters will be taken in the order in which they are signed in. Public comments can also be submitted during the meeting during the online meeting viewing platform using the Comment for the Record form. Time for each comment may be limited depending on the number of comments we receive. But the entirety of the submitted comments will be included as part of the meeting record. This meeting will end at approximately 12:15 pm Eastern Daylight Time. In the do as I say not do as I do department, please remember to identify yourself when you use the microphone, so our online viewers know whose speaking.

So without further ado, we can start with the first presentation from Erika Holt and VTT. And that’s online. Thank you, Erika.

HOLT: Thank you. Welcome to the Board members and distinguished guests. Ladies and gentlemen, my name is Erika Holt from VTT, the Technical Research Center of Finland. I'm joined by my colleague Dr. Pirjo Hella as well as Barbara Pastina from Posiva. And we look forward to sharing with you today some of the experiences from here in Finland to advance the understanding for the DGR and the crystalline rock.

The route that we will take through our presentation is first just to give you a status update, where we are in the Onkalo and the repository program as the first repository to have construction and soon hopefully an operating license. We will actually have a spoiler alert. We would like while you're still fresh in morning attention to start by telling you some of the key lessons and then we'll go into a little bit deeper dive about what we see as the features, events, processes that are really affecting the safety and Barbara will cover those areas and then we'll go a little bit more detail into some of these key takeaway messages and conclusions.

We ask that you please maybe hold the questions to the end because they might come up a bit during our presentation. We also really gained a lot of insight to yesterday in hearing the various presentation from the labs and it really set a good basis for what we're going to share with you about today on issues for instance in bentonite erosion and high temperature issues and what type of models to use, why are the fractures important, the salinity. A lot of those topics that we have been reviewing and developing for years and a lot of those that we have done in cooperation there in the United States and we anticipate to keep cooperating together to solve those challenges for crystalline DGR solutions.

So first just to tell you where we're at right now in the Finland disposal program for the DGR and to remind you where we're at. Finland, Scandinavia, Nordic country have to handle the spent fuel from five existing reactors owned by to different utilities. One of those being TVO, Teollisuuden Voima in Finnish, which is on the west coast on the peninsula of Olkiluoto and then Fortum Nuclear Power, which is located a couple, having two plants located approximately 100 kilometers to the east of Helsinki. Posiva, the high level repository owner is operated at the same Olkiluoto site. They are taking only spent fuel. So, the low and intermediate level wastes, those are the responsibilities of our two utilities and they have their own repositories that have been in operation since the 1990s. And please be aware in Finland also we do have a research reactor. That's here at VTT, the technical research center of Finland that has recently been decommissioned. And we also have a uranium mine. So, our regulatory authority STUK also oversees these issues.

Talking a little bit about the who's who and these names that you'll see we report and we receive a license from our Finnish government, which is the Ministry of Employment in Economics. We have the oversight by our Radiation and Nuclear Safety Authority, STUK. And for each kilowatt hour of electricity that is produced, we put in money to finance the Nuclear Waste Management of Finland. And that also includes the National R&D Program and is responsible for competence development in the country and also national infrastructures. Posiva as the operator and owner of this high level waste repository called Onkalo is owned by the two utilities. So, it is not owned by the government though the government is a shareholder in our two utilities.

Pirjo and myself are from VTT, the National Research Center. We’ve been operating for over 80 years and we also report to the government so we are similar to a national lab like Sandia, but covering all disciplines of science and engineering. And we are one of the key players that is supporting Posiva with resources and technical competences in a variety of fields among other consultants, for instance, universities and the geological survey.

Here is a bird’s eye view of what Olkiluoto and the Onkalo peninsula look like. In the back you will see three reactors of Olkiluoto 1 and 2 which have been in operation for decades and the Olkiluoto 3 reactor, which is the largest new-build reactor in Europe, which went on the grid last year. The disposal facility for Onkalo of spent fuel is on the same peninsula. It’s in the foreground of the picture. And we’ll look at a few more pictures of that in some later slides. The repository for the low and intermediate level waste is the responsibility of TVO Utility. And that is also adjacent to the plant. So, when we talk about transport of spent fuel, we’re looking at just a distance here that as you can see is only about a mile away, done by road, where spent fuel is moved from wet storage into an encapsulation plant. The first spent fuel will come from that near location and that near power plant and in a future cycle will come to the farther transport distance from Fortnum.

Then just a bit of a timeline about where we’ve been. It has been four decades that we get to this point where we are now in getting ready to start operating for Finland and Posiva the readiness of final disposal. It started in the 1980s in the site investigations at a generic level and a governmental decision in principle to prepare for high level waste disposal. The construction of Onkalo started in the early 2000s where we went through a very iterative process at the detailed designs and the concepts in the facilities and that culminated in the year 2015 with the submission of the construction license.

We started first with excavation of the tunnels, encapsulation, preparing the aboveground details of the encapsulation plant for the spent fuel and getting ready for operations. But we really also want to emphasis that this does not mean we stop doing R&D

or development. We need to operate the facilities for 100 years going forward to account for the five plants and the time it takes for our newest plant for the fuel to cool and we also need to do a safety assessment every 15 years. So, we continue always to look at the impacts of new technologies, of new materials, of course keeping the processes safe, but looking at if we can do it in a more efficient time cost manner and we need to keep our competencies strong. So, we'll go into a little bit more about this on the iterative nature also in some of the next slides.

Right now, we're in the phase of the getting ready to operate that is called our EKA project here in Finland and the budget of that is 850 million euros, which a lot of is related also to the equipment and the purchasing and the excavations.

So where we're at now, the detailed design and construction of Onkalo, the underground has been pretty much completed. We submitted a construction license to our regulator at the end of December in 2021 and we expect the final review comments will come now during this year. For the past two years, Posiva has been in the role of answering the questions that come from STUK and VTT and others as technical supporting experts are assisting in answering those questions. Next phase starting for actual physical showing of a final full scale demonstration is called the Trial Run. And I'll explain that a moment in the next slide. And the anticipation for deposition of the spent fuel is starting in the next year or two.

A few pictures here. On the top you see the picture of the encapsulation plant where the spent fuel is opened and put into the disposal canisters, non-destructive evaluation of the quality ceiling with welds and transferring by the underground hoists to the lower location you see the control room and automated systems. And the lower pictures you see underground how it looks for deposition holes and tunnels and the facilities underground such as for the HVAC systems and vehicles. On the right are, excuse me, the bottom left you see pictures for areas where we're fabricating of the actual EBS kind of components like canisters and bentonite.

As far as the underground, the site has been fully characterized with dozens of boreholes. And we'll tell a little bit more about these methodologies. But a lot of work in construction methodologies and demonstrations in readiness underground. The underground itself we’ve had the first five whole deposition tunnels excavated and we’ve located where the first vertical deposition holes will be in the KBS-3V configuration. The elevators and HVAC system and those type of things are also nearly ready underground. Above ground, the encapsulation plant and control rooms is at 95 percent readiness. The materials for the engineered barriers, the clay, the concretes, the canister, those designs, all the emplacement vehicles, robotics and also the method statement and the training of those people is also ready.

So where we’re at now, is to do the Trial Run for final disposal. This is the last requirement to use all of the same people and procedures and methods and equipment as it will be operational. We will demonstrate the transport, the encapsulation, the process of doing the final disposal and we will actually retrieve one canister as if it were damaged to show we know how to reverse the process back to the encapsulation plant. So, the Trial Run will contain four canisters and this one that is retrieved. Of course, this is also considered a great learning experience for worldwide and any other WMOs or, for instance, the Department of Energy or others are welcome to join in and participate in this. There are already multiple WMOs who have committed to co-funding and participating in this project where they get firsthand oversight and learning what happens for final disposal.

And the next two slides is a sneak preview of what’s going to come now as Barbara starts to tell in more detail. But some of our most important lessons learned in these next two slides are just to remember that the whole process to get where we are has been very fundamentally based on setting the requirements and the specifications and then verifying that the safety of the disposal is met. We’re always improving the experience and the knowledge that we have as new information becomes available as we actually practice it as we monitor it and we get through the production processes. We’ve also had to optimize as we are doing this quality control and the procedures to make them streamlined and compatible. And we’ve had to have very detailed change management processes. And that is allowing the traceability and the iteration for the safety assessment.

So, we have these four components that are shown in the graphic. A safety case with the performance assessment and scenarios that leads into the fundamental safety cases. And then that is iterated with the design basis to look at what are the safety principles, understanding how the systems perform, what kind of long-term loads and conditions they have, the performance targets and then the design requirements. So, from that we can specify the materials for the engineered barriers and the processes and make sure that we have construction and emplacement and design solutions that fulfill these requirements. But then when we do implement it, when we do small scale lab and upscale it to the full scale and handling of transport and logistics we try to optimize the cost and schedules and it gives feedback all the time between these. But it’s been important to have certain design basis freezes as well.

And we really have a key message that we’re going to elaborate in the next slides too about these changes are normal. We know that we’re getting more information and this is an optimization process. And that also comes from the wider and international scientific community and also changes that might change from social and economic environments and the demands of, for instance, the local population about what they might want to be monitored to ensure their safety.

So, this kind of iterative process and assessments is always being done and making sure that the initial state continues to fulfill the long term performance so that when we construct it it's still going to function and as we bring in new materials that it's not jeopardizing what is there. And this is really handled through our configuration management.

With that, I will let Barbara continue and she'll tell about the disposal system and the FEPs and touch on some of the key topics we also heard yesterday in these different materials. So, Barbara, please go ahead.

PASTINA: Hello, everybody. My name is Barbara Pastina. I work for Posiva. I was the Project Manager for the safety cases in the operating license application. And in my previous life I actually used to work for the National Academy of Sciences and I would like to say hello to my former, two committee members, Alan Croft and Tissa Illangasekare and so it's great to see you here. In my previous life I was a radiation chemist, so my area of expertise is actually fuel processes and corrosion, copper corrosion and insert metal corrosion processes. Enough said, let’s go down to the actual messages we would like to give you.

We have been analyzing the performance of two repositories within the same disposal system, so within the same chunk of rock, crystalline rock at Olkiluoto. So, we have at the depth of 430 meters as spent to be a fuel repository for 6,500 pounds of spendable fuel. Some of it is boiling water reactor type fuel and some of it is pressurized water reactor fuel. It’s actually in Olkiluoto we have the Olkiluoto 3 reactor running, PWR, like western type PWR and then in Loviisa on the eastern side of Finland it’s the Russian type, VVER type of fuel. So, we are disposing both of these fuel types in our repository. And then we have another tiny repository at the depth about 180 meters. If you look at the right hand side figure you have two boxes. So the box on the bottom is Spent Nuclear Fuel Repository and then there’s one, it’s not to scale, but it shows the repository that is not yet built. It will serve the purpose of disposing low and intermediate level waste coming from the encapsulation plant. So it’s different than the operating low and intermediate level waste that is coming from the reactors. So we have our own repository. It’s a preliminary design and then we had to include it in the license, because we know that one day we might need it.

So if we go to the next slide, Erika, thank you. Yes, so I think you are familiar with the KBS-3 disposal method. This was a matter that was originally developed by our sister company, SKB, in Sweden. We actually collaborated heavily on the development and especially on the implementation of the method here in Finland. So, it consists of, well, it’s direct disposal of spent nuclear fuel. First of all, the spent fuel assemblies are in place in cast iron insert and then the cast iron insert is enveloped by a copper shell. It’s sealed tightly. We use frictional steel welding for a sealing method. And then the copper canisters are in place vertically, each in its own deposition or disposal hole.

And this is the figure with the yellow color that is bentonite swelling clay, bentonite buffer. And above it we have disposal tunnels. They are backfilled with more swelling clay. High grade bentonite, so it actually maintains a very low hydraulic connectivity. And then, we ensure that the depth at which we dispose our spent nuclear fuel is sufficient to separate the processes that happen at the surface from what is happening on the ground. We cannot completely isolate the two systems, but a depth of 430 meters is, in our safety case we show that, in our opinion, is enough to ensure isolation. Next slide, please, Erika.

I think yesterday you have made a great background for this slide, crystalline rock has great properties. Most important is the stability. In Finland we have very low seismicity in this area. And it is very easy, relatively easy to construct a repository in crystalline rock. So, we have some very good features. We know where the big fractures are. Those are relatively easy to locate. But crystalline rock, as you said it very well yesterday, has its own constraints. So we know that there is water, there is advective flow in the system, so we have to adjust. We use design tools to adjust the location of the canisters to ensure that the performance of the EBS and then radionuclide releases if there are any that they are very slow and they do not cause any harm to the environment. So crystalline rock, yes, it’s very good medium. But it has its own constraints and I will talk about it in the next slide. Thank you, please, Erika.

So just one slide to let you know that we have produced a digital safety case. So, this is actually our second one. We produced one for the construction license application in 2012. And at the end of 2021 we produced, we submitted the one for the operating license application. You can access our reports. The figure on the right shows the methodology. I do not have the time today to go through the methodology we used. All I wanted to let you know is that these reports are readable on this portal, mentioned on this slide, and you have to register to gain access to the portal. And it takes a few days between the time you submit your request and then you’re granted access. It’s just for security reasons, data security reasons. Yes, it’s a portfolio.

Our safety case is a portfolio of eight main reports. They have different titles. The key reports for us are the design basis. As Erika mentioned, we have to be able to explain how our understanding of the site translates into safety functions and performance targets and down to the design of the EBS. Then the second, I would say, most important report is the initial state report. We have to show that we understand how the barriers look like or the system looks like once the barriers are installed and then the repository is constructing at the time when we actually do not have any more control over the system. So, at the time where everything is said and done. So that is called the initial state report and that’s the report where we also look at potential deviations. We acknowledge the fact that human error is a possibility and that we can have some quality non-conformances that are undetected and then what does it mean for us. So that’s the initial state report.

Then we have another masterpiece, I would say. No, I'm just exaggerating. I just wanted to give a shout out to my colleague Pirjo Hella here today, because she was the … one of the main editors of the report or the main editor of the PAFOS report, it’s performance assessment and formulation of scenarios report. That is the report where we actually describe the evolution or lines of evolution of our disposal system taking into account different types of uncertainties. Of course, in our work, line of work, as is in yours, we have to look at very long timeframes. So all we can say is that we have scenarios. We cannot say really this is going to go down like that. So, we have different sources of uncertainties and we formulate scenarios based on them and then we assess whether we have possible risk of canister failures, how many and when. And that is called the PAFOS report.

And then we have a different report that looks at the radiological consequences that is the analysis of releases report. That is the report that calculates the milliSievert per year that could come out of a given scenario or the background per year, depending on the timeframe. So, these are really the cornerstone reports. And then, of course, there’s the synthesis report of bring it all together. But as I said, please register to gain access to our reports and then if you have questions or specific modeling details then we have actually a report called the Models and Data. You might be interested in that one as well.

The timeframe of our safety case is one million years and it’s not explicitly given in our regulations. The regulations only mention several hundreds of thousands of years, but in practice we follow what most countries do when we go to one million years as our timeframe. Next slide, please.

So the overall conclusions is that we have explored, we have accessed the performance of our components, engineer components and natural barrier over one million years. We have assessed the impact of uncertainties. There are always uncertainties remaining so this is something that we acknowledge very explicitly in our safety case. So, there are always residual uncertainties and the point of a safety case is to show that we can acknowledge live with them. We believe we have a robust enough system that we can live with these uncertainties. Yes, there might be potential releases, but the consequences remain within the compliance limits and even in the bigger picture we have also a look at what do these limits mean 0.1 milliSievert per year is actually, in regulatory terms means negligible consequences from our repository.

And, in fact, when we look at the bigger picture, even in the worst case scenarios, we still remain within natural backgrounds. Those ranges and even much less than what is caused by non-nuclear industries. So, we try to frame also the releases from, eventual releases from a repository so that we have more elements to compare with. Next slide, please, Erika.

I think key features, events and processes for crystalline rock. Yesterday you went through very well through all of them. We have a report by McEwen and Aikas from 2000 that I very much encourage you to read, because it describes very well the site selection process and what kind of processes were considered at the early site selection so that the slow and steady natural phenomena, the slow periodical phenomena, sea level changes of course. In Finland we have to think about future glaciations and then the sea level changes that come after that. The fact that we will go under water at some point after the melting of the next ice sheets. So, we have to really consider these type of processes. We have rapid periodical processes like discharge, recharge off the natural groundwater. Sudden catastrophic phenomena we called them today rare events, earthquakes, volcanoes that we don’t have today. But actually, I’ve learned myself that Finland in the very, very, very early phase there were actually volcanoes here. Very interesting.

But anyway, we consider this type of typical real events that are common to all repository programs-flooding and, of course, earthquakes are the main ones for us. And then human activities always have been present from the beginning of the geologic disposal programs that we have to consider the construction from human activities search for natural resources and non-deliberative results of other human activities like wars and such. So, these are the … I think common processes that everybody looks at. But then when we are really approaching the operating phase, we have to consider very much the interaction between the site and our engineer barriers and how they actually play together and the interfaces. Particularly these are very important. And then, yes, of course, as we go further in the safety case some of the FEPs have been excluded because we have learned that they do not apply to our site or design, so we have been screening FEPs as well. Next slide, please.

Yes, the safety concept. This is very important and you have also identified this point yesterday that for crystalline rock the main barrier is the canister, so we have to rely on the EBS very much, although the geosphere provides given safety functions, isolation for example and slow transport of solutes and radionuclides out our main barrier is the canister.

So, if you look at the safety concept it has two colors. The figure on the right has two colors and two types of pillars. We have the blue pillars. The blue vertical ones they really talk about the performance of the EBS. The right hand side is proven technical quality of the EBS. That means that we have to use materials that are well characterized and their behavior can be predicted well enough in the future so that, we go to the left vertical column, so that we can prove that we provide, the other EBS provide favorable conditions to the canister. So we want to make sure that the canisters stay alive, stay intact for as long as possible as the canister provides containment. So that is our main safety. That is the safety function for the canister.

So, the three yellowish pillars in the middle they are there because in case we lose containment, we lose the canister breaches in fact, the radionuclides are released slowly from our spent nuclear fuel. I think you will talk about it more today. The ceramic UO_2 is very, very slowly, releases very slowly radionuclides. But then we have also the buffer, the clay buffer which retains and retards transportation of our radionuclides and the rock of course. There is absorption along the fractures. There’s absorption in the matrix of the rock. But this is very important because it’s a different safety concept. You’re looking at other host rock formations.

And then the safety concept again is important because it takes into account the constraints in the system. As I mentioned earlier, we have constraints due to the fact that we’re working with crystalline rock and we have constraints due to the type of spent nuclear fuel that we have to dispose. That spent nuclear fuel cannot be designed, so we have to design around the constraints from the host rock and the spent nuclear fuel. And then there are constraints that are also introduced by the engineer, other engineer barrier system, for example, buffer. You heard yesterday that it’s sensitive to very high temperatures. It’s sensitive to very high pHs or very low pHs. So there are come constraints we need to accommodate. And we do this through the design tool. Next slide, please.

So from the safety concept then we develop, we use a top down approach to develop the design basis. So we go from the very high level laws and regulations that say that the repository should be safe. In the long term what does it mean? Then we spell out the safety functions that we are given to our barriers. We define what our barriers are, EBS and natural barrier. We give them safety functions. And from each of these safety functions then we define performance targets. We call them long term performance targets. Other waste management organizations call them in different ways. But basically, this is what the barrier should do in the long term. And this is where the FEPs become very important. This is where the loads and conditions become very important. This is where the site understanding or the geologic, the area, understanding if you do not have a site, at least you have some ideas of what loads and conditions each area or geographical location might experience in the evolution. And that is used to formulate the design requirements for your barriers or for the construction of your repository. For example, how far apart the disposal holes should be or the disposal tunnel should be and so on and so forth.

So, this is very important. It’s your first step before you even start thinking about radionuclide releases you have to think about the performance of your system, what does the design into account and then what are the residual uncertainties that need to be assessed in the safety case. And this is one of the main lessons learned I would say, a key message is, for me at least, because we have been struggling with many of the requirements that were not spelled out explicitly or some assumptions were not spelled out explicitly in the 80s or in the 90s and we had to sort of backtrack the loads and condition or the design basis scenario that was in the mind of our designers.

So the message is that at the early stage you will have some assumptions, even many assumptions about the loads and the conditions that you will encounter, might encounter in different locations. But it’s important to write them down, especially if they are just assumptions. Write it down and label it as assumptions so you can iterate them and can go back to them and check them, is this assumption important? Yes. Then let’s do some characterization of that area to confirm or update the assumption.

And the same thing is with data. If you have some hard data about a region or an area, write down what that is, actual measurement, but what the measurement tool or what was the measurement method and the reliability of the data is, so you know 10 years, 15 years in the future you will know what this data is actually saying and can it be relied upon or not. So, the idea is that the design basis is iterative and you will have to go back to this assumptions, early assumptions and early data. And it has to be traceable and transparent, so you can explain the changes that have happened throughout the time.

So, then the next slides, because I think you have said many, many things yesterday in your modeling slides, I think what I want to show is the interaction between the design basis and all this modeling work that we do in Posiva. The first thing we need to do is we use this models to explain what the sites or what are the key FEPs, put the understanding of the areas into numbers. And then we need to make sure that we have a conceptual model that is actually correct before we go into the numerical model that has its own issues as well as you discussed yesterday we have to first and foremost make sure we have a conceptual model that is robust and we can explain how it relates to the understanding of the different sides and then we use that to formulate the performance targets and justify the requirements on our barriers. And then we talk about the models that are predictive in nature and that we use for radionuclides transfer, for example.

So, the modeling approach changes, of course, as the level of understanding changes and then computational efficiency changes. So, the bigger the model, the fancier the model. Yes, all that is great. But make sure it does not become a black box in the end, because you have to be able to explain what is happening in your model.

This slide I don’t need to say much about it. It’s just that you have characterization activities that translated into interpretation. There’s a lot of interpretation between the hard data and then what you use in your safety case. So, there’s interpretation, then you translate that into a conceptual model and a numerical model. Next slide, please.

Yes, this is another example of conceptual model. So, showing our DFN model and then how in the fractures we have different features in our fractures. We have rock matrix, we have absorption. We don’t need to discuss it because yesterday you have, I think you have covered a lot of these issues very well.

This is just to show that the conceptual model for groundwater chemistry. We have a layered type of chemistry in our repository. And we have shown here two pictures. One is from the early 2000s and actually we had this type of conceptualization even earlier than this. It is to show you that the conceptual model has kept quite stable throughout the years. We just added a few details and we have, of course now, monitoring results that can help to corroborate the conceptual model. I just wanted to show you this yellow feature in our groundwater chemistry. We have a sulfite rich water, which is from early water, seawater intrusion from the last glaciation. And that is one of the key scenario drivers in our safety case is sulfite, the corrosion for the copper canisters. So, we have this pocket or layer of water with sulfate and then with microbial activities transferring into sulfite and this is why we are very much interested in everything concerning sulfite and for a sulfite cycle and copper corrosion. Next slide, please.

Yes, another application of site understanding and the tool, the design tool is the definition of Rock Suitability Classification. So we have rules to select the location of disposal cavities and disposal holes, so that we can design around the constraints from our site so that we do not locate canisters where they should not be, so near a fracture that could move or near a fracture that could bring in sulfate and so on so forth. So we define criteria. And then if we go into scenarios. So, of course, we cannot design the other message is that... we cannot design for any kind of load and condition. So, we have a given design basis. That means that, okay, so the design takes into account these type of conditions and then there are residual uncertainties that are taking into account in our safety case. And that means that those uncertainties are included in the form of scenarios. So, we have three ways to break the canister- 1)corrosion, 2)rock shear and 3)isostatic failure. So I don't think I need to talk about the rock shear for the earthquakes. I think this is quite self-explanatory. The isostatic loading is, the maximum load comes from the icesheet, when it will be on top of the repository.

HOLT: I need to jump to the last couple of slides, because our time is up.

PASTINA: Yes. But these are very site specific I would say and safety case specific. So, for this kind of questions, you might have I don't think … I think you can see the slides and then go in our Safety Case reports. And if you have further questions then we are happy to help you try to figure out. What else did I have in terms of … yeah, we have.

HOLT: I'm going to jump to the conclusion slides, because we need to have sufficient time for Q&A.

PASTINA: Go ahead.

HOLT: I’ll just note that we have done a lot of studies on the stability of buffer, similar to what we heard about yesterday and some of the citations that were also yesterday on issues of erosion and clogging and looking at alternative bentonite materials. We have also spent a lot of time on looking at issues on the canister and the corrosion. Some examples there and different scenarios that can be used and what type of releases there are.

So if I take one extra minute to send kind of these key messages and then you will have these slides and be able to review these in more detail. But overall one of the main things we wanted to emphasize is that the safety is really driven by the rock. And until you select a site there’s … of course we can model and model, but it needs to start at a very generic level. And for us in Finland we had no difference between our final four sites. There was … the greatest impact was the deviation within one site. So getting ready and preparing the safety of the repository, first we need the site and after that we can design the EBS and the layout.

And that means that it needs to be quite systematic. We start with a very generic design and then we understand and phase you’re in there in the United States to understand the techniques and what to model and where to measure your site, so to set the requirements for the design and the site and the suitability of the rock. So, of course, there’s processes to understand in the rock and as you gain more information from the site characterization, it’s allowed then to iterate that layout design and the EBS and better assess what are the impacts of the FEPs and the interaction on issues like geochemistry and that modeling will change as it gets more detailed as the site is selected. But it shouldn’t be a black box as Barb noted.

And, of course, just emphasizing this iteration. It needs to be really design basis from the top down with the requirements and after that it gets more and more detailed. But really important to have transparent documentation of the assumptions. And taking care to have the requirements management. So I think some of the presentations we heard yesterday also about setting up these tools where it is transparent and open and well documented are exactly the right way to be going. And then understand that there is a lot of feedback that’s going to come from safety assessments from authorities, from the characterization and the adaption of the wastes and keep that database and keep iterating it and communicating accurately for the people who need to use it.

And so our last two slides were a couple of recommendations for what the focus of the programs could be there from an R&D perspective, and I think there are many things that we talked about already, but just really keeping it conceptual and being prepared for when the site is further developed then the modeling could get more accurate. So making sure you have good inputs for the EBS and the design and making sure that you have clear documentation of these assumptions and processes.

And, of course, ourselves and others around the world are doing this too. We’ve been through it, we have these lessons. We could spend days explaining safety cases and going into details on any of these topics. And we’re definitely here to help and we really, really want to cooperate with anyone there. So please feel free to reach out to us. So in summary you cannot design the rock that you have and you cannot change your inventory, but it is very possible and realistic to change your repository designs and select the barriers to be able to fit these constraints and successfully input the high level and spent fuels safely underground.

So thank you for your attention. Here are references where you can register to get the safety case documents as well as a few of the citations that we gave with some of the details. So thank you for your time. Apologies for going a few minutes over and let’s please take questions now.

SIU: Thank you very much, Erika and Barbara. That was excellent. Lots of very great information and we’ll be looking at the slides too of course. And I do appreciate your sensitivity towards the schedule. With that, open questions.

TYLER: Erika and Barbara, thank you very much. This is Scott Tyler, member of the Board. Outstanding presentation. Thank you very much for joining us. At least not too late on your time. So much appreciated. I had maybe a question that came up just at the end as Barbara was describing the operational side of the repository of defining proximity to fractures and proximity to where to place waste once you’ve chosen the site and as you iterate. And I'm just curious how that process has progressed both time wise and decision making wise. How is … I'm curious, a little more on how that process has evolved.

PASTINA: Should I say the first …

HOLT: Go ahead Barbara.

PASTINA: If Pirjo has something to add, since Pirjo also has been involved very much in the rock suitability criteria. This is also an iterative process. So we started with … well, we knew where the big deterministic fractures are in our system. The issue is not so much to avoid the big fractures is to avoid the middle sized fractures that might move in the case of an earthquake event. And then all this was like a blind exercise in the beginning before we started to go underground and before we started to build our first disposal tunnels.

So we had to use rules that were quite conservative in the beginning knowing where the big fractures are and where the middle sized fractures might be. And then as we progressed with our construction of the repository, we could constrain the size of some of these middle size fractures that might actually pose an issue. And then the other assumption is that a fracture that might move is big enough to move is also the fracture where water flows. So we are also looking at corrosion issues based on the not only the size, but the transmissivity of these fractures.

We use the offset distances at first. Well, we still have offset distances. But we had to adjust them given what we know about the site. So, we were a bit more conservative in the beginning and then the more we know about the rock then, of course, we were able to optimize the system. And the process is still ongoing. We still have many years of construction and observations ahead of us.

HOLT: I could also add that during, you know, construction, which is where I’ve been involved a lot, also that we are changing the locations, you know, as we go. So, we do a very small drill hole, we check that that tunnel is accurate and okay, then we change and adapt and we’ve learned how to do better excavation methods to minimize the … for instance, how to create a plug notch. And then even when we choose where we drill a specific vertical hole, we may slightly adjust that to avoid a certain fracture. So, every day it’s an iterative and learning process based on the tests that we’re doing. And we’re also monitoring and we’re modeling with flow rates the rock that we’re in to iterate the design as we’re going where we place something.

PASTINA: Does Pirjo have additional comments?

HELLA: The rock suitability classification or host rock classification as it was first called started around year 2000. So, it’s now been ongoing for the last 25 years, around, or at least 20 years. And I think one of the observations in the development was that we really need the … site is such that we really need information from the local rock. So a very important step in that development was building the Onkalo and creating the disposal depth where the construction of the tunnel, from early on already helped, but then especially then the conditions when we got information of the rock condition. So even everything was not ready with the RSE. That was really a big thing and a big leap in how to develop and where the in the criteria development. And I think what I’ve been discussing with the people now working in the tunnel and so they have like a good understanding of the rock conditions that although it is known that the rock there is heterogeneous but the people kind of understanding so that we have this type of rock … they vary and then you really have to look at the exact sites and the tunnels.

HOLT: Maybe we need to go into some next questions though, because I know we’re only, we’re less than 10 minutes to go. So maybe when we answer we'll just take one person answering I guess so that we can get through all the Board members.

ILLANGASEKARE: Yeah. Thank you very much. Again Barbara thanks. Twenty years ago, we worked together. So again I'm going to make my comments short and I really appreciate the time and efforts spent on the slides and I'm sure there's a lot of information, we may get back to you. But one of the questions which came out yesterday was the issue of the dynamics stress field around … you did mention this … but can you give a little bit of any information you didn't say in your talk and the second one did you attempt constraints, anything you learned as you go through the process, you keep updating I think the conceptual model. You mentioned the use update. As you learned the system you update it. So can you give a little bit of the issue stress field and the dynamic loading as well as how the conceptual …

PASTINA: Yes. So, of course, this requires a lot of time and I only have very little, very little time to answer. Yes, we do consider the dynamic stress field as a result of both temperature in the beginning and then glaciations and earthquakes. And that I would say is one of the sources of uncertainty is how that flow field vary with the stress field. We know it varies, but how much and how to implement it in our safety case, I think here, I would encourage you to look at the safety case reports and if you have a specific question then I can also point you to the expert that looks at that particular expertise. But, yes, we do have a dynamic stress field and we do try to take it into account. The other one was the temperature sensitivity. Do you mean with respect to bentonite?

ILLANGASEKARE: Bentonite and the temperatures.

PASTINA: Yes, yes, we have done a lot of work with the temperature, because, of course, we want to make the footprint of our repository as small as possible. It’s a matter of optimization and sustainability of the costs. So I think yesterday mentioned the HotBENT exercise, European project. We have been involved with that because we have currently one hundred degrees temperature constraint, but we think we could go higher. But, of course, we need to characterize what happens to the clay.

ILLANGASEKARE: Thank you.

TYLER: Can I just ask one quick follow up with respect to the stress field? Because I think that is important. Can you tell us where in the process of the repository design did you begin to build the models that you’re using to understand the stress field as you’re building the repository, so the impact of the repository construction? Where was that in the process?

PASTINA: Again, a long story but very short answer. You have to … well, we have to understand the regional stress field, so where the brittle … how the site was … how the rock in the site was formed. So we understand the regional stresses and then we understand how the local stresses might be, so that we can design the repository in the correct way. So we align the disposal tunnels according to the main stress. I will not go into details because a, I'm not an expert in this and b, we do not have time. But the short answer is as you understand the site understanding and the brittle, the formations understanding. That’s where it all starts.

TYLER: Thank you very much. Thank you.

SIU: This is Nathan Siu. I think this might have been answered a bit in one of the first questions, but I was curious about your views on let’s say realistic modeling versus good enough conservative analysis to demonstrate the safety case and how far would you go beyond this good enough, for example, do your optimization?

PASTINA: Well, the final answer I think it’s in the hands of our regulator. They will determine eventually if it’s good enough. But we make a case showing that we believe we understand the systems sufficiently to the extent that we can even incorporate the residual uncertainties. We know that there are residual uncertainties. We will never be able to say that we know everything. So the matter is how far can we go or how well can we make the case that we can live with residual uncertainties and that we still preserve safety, long term safety. So that’s why we have scenarios.

SIU: I guess the question is more, let’s say you think you have a good enough and even the regulator decides that’s good enough. Would you still pursue more complex realistic modeling for other reasons?

PASTINA: Of course. The drive to optimize the system is always there. And we will have definitely changes as we go along with construction and operation. We have new technologies and new instruments. So there is always a push and a drive to optimize our system. So, of course, every time we will have to …

HOLT: Same thing. Like we're still going to keep modeling our system and we're still going to get new data and we're going to reduce the safety factors as we get better knowledge. But I think as someone said also in one of the answers yesterday, we do it to the point where we're ready to submit it to the regulator and then it's up to the regulator to tell us have we not answered or justified it well enough with the robustness of the system.

SIU: Thank you. Chandrika?

MANEPALLY: Thank you all of you for a wonderful presentation. A couple of quick questions. The first question was did you actually … Erika said something about, or maybe Barbara said something about considering the temperature limit. Is that correct? Did I understand you all?

HOLT: That is correct.

MANEPALLY: Okay.

HOLT: Right now, our licensing is done for a maximum temperature of 100 degrees and Posiva, ourselves and Posiva and like a project coordinated by VTT in high temperature, the EURAD HiTech project that was cited yesterday has been looking at the impacts of temperature at 150 degrees as well as the cooperative project that's at Nagra on HotBENT. And that is directly for us, so that we can change potentially our canister spacing from six meters to a closer distance, which would impact the amount of excavation and the amount of clay that we need and still maintain the safety function. So, we kind of anticipate that it will change and hopefully that is something that we can account for in our revision of the next safety case or the next licensing.

MANEPALLY: Okay.

HOLT: But again, at very, very international collaboration and we know there’s a high interest there from the United States based on your inventory.

MANEPALLY: Are you also considering alternative buffer materials?

HOLT: All the time. So, we have reference case and then we look at alternative buffer materials and what the impacts are for either the buffer or the backfill, because they have different types of retention requirements and again very much dependent on economics and supply.

MANEPALLY: Okay. Thank you. The other question that I had was about your capacity of the facility in terms of how much waste you are going to be emplaced. Is that a fixed value that you’re designing for or does that change as you go with the construction?

HOLT: For the licensing that we have it is a fixed value. And our safety case is based on a fixed value. If there are additional reactors in the … for instance, we're looking at what are the implications when or if, probably when, small reactors come or other types of vendors. We had another reactor being built prior to the Ukrainian war. So, we have to have the readiness to expand the repository if we have more spent fuel in Finland in the future, which is anticipated.

HELLA: And it has changed over the 40 years. It has changed.

MANEPALLY: Okay. Thank you.

SIU: And we'll continue with questions a bit. I do appreciate you sticking to schedule, but this is really important to us. So Bret I think you…

LESLIE: Yeah, this is Bret Leslie from the Board staff. Thanks to you all for a really informative presentation, the slides especially. In particular one of the slides really resonated with me, slide 21, which is make sure you are evaluating what your inventory is. And so, you're only doing commercial spent nuclear fuel and for the U.S. program we have to worry about other waste forms. And I think that's a … what you said there really helps the Board to kind of review what DOE’s doing. So appreciate that. Thank you.

WOODS: Hello, Brian Woods. I'm a member of the Board as well. I'm real curious. I know you chatted a little bit about your relationship with Sweden, working with them and of course the U.S. I'm just kind of curious from your perspective what are kind of the major kind of international collaborations that you’ve had that have kind of helped you get to the place where you’re at right now?

HOLT: We have a national research program that’s been running for decades that is important. So that is here domestically. But as Barb mentioned the key alliance initially has been with SKB and the Swedish program. But they also had a different step that they had an underground research lab, which wasn’t site specific. And we made a different choice to have an underground research lab integrated with our disposal facility.

In general, we have a tightest cooperation typically with the other crystalline host rocks, which would be, you know, Canada looking at their sites now, at the Czech Republic, Japan. But we also talk about 75 percent of the issues are exactly the same. No matter what type of host rock it is. So, there’s times when we cooperated really closely, for instance, with Nagra in Switzerland. Our earlier backfilling protocol was by blocks. And Nagra and the international community developed a different technique to auger in place pellets, which was able to achieve the densities that were needed.

And therefore, even though we had a design freeze at the time of our construction license, we’ve changed our emplacement methodology just recently. And the same in the buffer blocks. We had solid rings or donuts as you might have seen in our earlier design, but we’ve changed that to segmented blocks. And that has come through partnership also with manufacturing methods and quality control in consistencies in bentonite. So, we have really strong cooperation on the European level within the Euratom or European Commission type of projects.

And we have, you know, Finland is contributing more than ten million euros every couple years in those projects and even going forward in the next five years we’ve had really strong discussions with the DOE and the National Labs of aligning the research programs between Europe and the U.S. to have added value, so that we’re not all duplicating each other but that we’re complementary each other. I know some of the topics that we talked on yesterday are exactly the topics we’ve discussed for looking at, you know, even future waste streams of SMRs, but issues about, you know, copper erosion and bentonite material robustness, preparing for climate change scenarios, how does that impact repositories. Those kind of topics.

WOODS: Thank you.

PASTINA: I have to say we also were inspired by the Yucca Mountain taught systems performance assessment. Some of the analyses were quite impressive.

HOLT: So we followed Yucca Mountain. I mean, we have pictures of our Finnish staff there in Yucca Mountain decades ago. So the cooperation with the United States has also been fundamental to our success and we hope what we’re doing now is bringing back helping your momentum there, move your program forward as well.

ILLANGASEKARE: I also have a short question. There was a point made a little later in the discussion we had yesterday. When and where to measure. So when you show when and where to measure that information came from modeling? Or that information came as you start working on the system, understand the system? Can you give your short answer to that? When and where to measure, how did you come to those type of visions?

PASTINA: It’s both modeling and understanding. I would say as Pirjo mentioned earlier our lottery winning ticket was to go underground and to have the opportunity to characterize the rock from below ground once we applied for the decision-in-principle in 2000. So we were allowed to construct and what was in the beginning an underground characterization facility that then became part of our repository. So, yes, it was, in the beginning, it was based from surface investigations and then we have had the chance really that … something that you do not have in the United States the opportunity to go underground and measure directly in situ. And it’s an iterative process again.

HOLT: But maybe we could also say regarding the EBS materials, you know, it is a process of developing for instance a very generic type of low pH concrete or cement matrices that were used for instance for rock grouting in the tunnel plugs and then as we learned more and more about what is the actual conditions at the site and the groundwater flows then we could and, for instance, the width of the apertures that are needed for the grout injection, then we could adapt our recipe once we got there on site.

So we did kind of robust type of materials with low pH injection grouts or bentonite materials that could handle a lot of different pressures or a lot of different microbes until we knew the really details of the site. And then we focused it again. So we always started very small in lab scales and even when we get ready for the full scale demonstrations we've done it at 1/20th scale and then 1/6th scale and then sometimes in Sweden, sometimes with us. So it has been a back and forth between models, but getting lab data and upscaling both in lab and in the models.

PASTINA: You can learn already from surface investigation with today's technology I would say. You don't have to drill boreholes everywhere. There is quite a bit of data that you can gain.

HELLA: And I would like to add that actually from the direct fracturing and even in the flow, groundwater flow, you kind of got a good understanding from the drillhole inspections. But that’s kind of general statistic and you saw that in the rock… and you really need then the rock information inside, for example, to locate, know exactly where the bad deposits over the good deposits are. Even though there was the basic understanding from the host that is.

SIU: So thank you again very much. It was very interesting and very helpful to us. And I think we’ll go onto our next presentation.

HOLT: Thank you.

SIU: Our next speaker is Andrew Parmenter from the NWMO, the Nuclear Waste Management Organization in Canada. Andrew obviously we ran a little late and thanks for your patience. We will still give you your time that you need. Thank you.

PARMENTER: Thank you very much. I'm just working on getting my screen sharing here. And how does that work? Looks good?

SIU: We don’t see anything.

PARMENTER: Are you sure?

SIU: Now you’re up.

PARMENTER: Okay. Perfect. Okay, thank you very much. I’ll get started. And just to make sure my slides advance. But I just would like to say good morning and thank you very much to the Board members and good afternoon to our colleagues on the other side of the ocean. I really appreciate the opportunity to speak to you today. So my name is Andy Parmenter. And I am here on behalf of really a pretty broad technical team to provide an overview of Canada’s Nuclear Waste Management Organization’s crystalline rock site characterization program. Now I really appreciate seeing the Finnish contribution earlier. It’s aspirational where we would like to eventually get to, being underground direct characterization. Canada’s program we’re maybe just a few steps behind in the process. So I’ll be talking more about our surface characterization at this stage and getting into some of the deep borehole drilling work.

Just a wee bit about myself. I am a professional geologist and I’ve been working with the NWMO for over 14 years. And I'm currently the Director of our Geoscience program. Now I would like to just begin my presentation with a land acknowledgement. I would like to acknowledge that with the hybrid format of our meeting we are all collectively gathered together from various indigenous traditional territories. I do encourage all of us to take the time today to acknowledge the traditional territory that we individually live and work on and recognize that we are all gathered here together with a collective mind, heart and spirit.

So, I'm in the city of Toronto in Canada. And I do recognize that I live, work and play on the traditional territory of many nations including the Mississaugas of the Credit, the Anishnabeg, the Chippewa, the Haudenosaunee and the Wendat peoples. In Toronto it’s a fascinating place. It is now home to many diverse first nations in Inuit and Métis peoples.

So today I'm going to first provide a brief overview of the NWMO then speak generally about our technical site evaluation process. And then this will lead into a bit more of a detailed look at the approaches and activities we’ve undertaken to complete the crystalline site characterization activities to date. Then finally I’ll touch on a few lessons learned and then open up for questions.

So, the Nuclear Waste Management Organization was established in 2002 as a requirement of Canada’s Nuclear Fuel Waste Act. We are funded by Canada’s Nuclear Energy Corporations and we do operate on a not-for-profit basis. Our approach was guided by a multi-year dialogue with Canadians, including representatives from indigenous communities and technical specialists across every province and territory in the country. And from these conversations, the NWMO began the development and implementation of our approach for the safe long term management of Canada’s used nuclear fuel in a manner that is going to protect people and the environment for generations to come, as we can all understand. It’s part of our business.

So a little of just a bit of our planning timelines. As we are all well aware, in this business timelines for this process are very long. We are in an important and exciting time at the NWMO with our plan to select a single site at the end of this year, at the end of 2024. After 2024, we move into the regulatory decision-making process with several milestones leading to the planned receipt of a license to construct a facility in the early 2030s and through to the beginning of operations planned for the early 2040s. Certainly there's a lot of documentation to do, a lot of interaction with communities and our regulators to get through this planning timeline. But over the next few slides I'm just going to go a bit further back into our history.

So, this map shows the location of all the communities that initially expressed interest to learn more about the NWMO's process. This process started in 2010. We had representatives going out to municipal forums and meeting with community leaders and, ultimately, we had 22 communities come forward and put their hands up and say that they wanted to learn more about our process. And now today again we've narrowed down to two communities remaining. One, and let me see if I can put my, maybe I won't get too fancy with the laser pointer here, but there we go. One is Saugeen Ojibway Territory, the community of South Bruce Ontario, an underlying by sedimentary rock. And I won’t be speaking about our sedimentary rock site today. And in Treaty#3 territory, on the traditional lands of Wabigoon Lake Ojibway Nation, the community of Ignace Ontario, underlain by crystalline bedrock.

Now I’d like to share a bit of information about our technical site evaluation process. So, in 2010 again, the NWMO released our site selection process document that reinforced our commitment to the safe, security and protection of people in the environment and further provided a summary of the scientific and technical site evaluation factors against which the potential sites could be evaluated.

Now the evaluation process was driven by community willingness to participate and followed a stepwise approach. So first, you know, when we started out these communities, we looked at available geoscientific information through an initial screening and desktop preliminary assessment. So, at the desktop stage, we’re not collecting new information or gathering understanding from available geological maps, any available borehole testing in areas, which is quite limited in this type of rock. But we certainly gathered what information that we could. Ultimately this led us to completing field work activities in a subset of the communities. And an important aspect of this was along with the geoscientific assessments that we carried out they were done in parallel with socioeconomic and cultural assessments to determine whether the site has the potential to meet the detailed requirements of the project.

So, following the initial screening and each of the preliminary assessment phases communities were either screened out or could voluntarily leave the site selection process. So, we are now, as a noted earlier, nearing the end of phase two of our preliminary assessments. And according to the current schedule, we’ll carry on with detailed field investigations at one site as of 2025.

So, this slide just illustrates conceptually the approach of starting with assessments in relatively large areas within communities at the desktop stage considering general potential suitability and leading to more focused field activities in selected areas to better determine the potential to find repository scale sites. At the earliest stage, the potential was evaluated by assessing if the site has available land of sufficient size to accommodate surface and underground facilities. At the time, nominally, our surface facilities were on the order of about 500 meters by 500 meters and underground on the order of two to three kilometers by two to three kilometers. Pretty generic at that stage.

We assessed whether the available lands were … you know, we had to be away for protected areas, heritage sites, provincial parks and national parks. We also looked at the availability of groundwater resources. We wanted our available land to not contain known groundwater resources at depth or other economically explode able natural resources. And finally, we wanted to ensure that the available land must not be located in areas with known geological and hydrogeological characteristics that would prevent the site from being safe.

So work got more exciting when we transitioned from the desktop studies to starting to collect new geoscientific data in the communities. We collected airborne geophysics and did surface investigations. Importantly these activities really did provide us with an opportunity to engage with the local communities and our indigenous partners. We had support from our indigenous partners as guides for field work to help navigate the areas, take us out and walk the land. That was a very fascinating aspect of the work. And, you know, ultimately all of these activities led us to define potential locations for borehole drilling and testing.

So importantly as the process advanced and more geoscientific information was collected, we were able to more meaningfully assess the technical suitability of proposed sites. We needed to assess the depth and volume of the bedrock under investigation. We needed to understand key geosphere properties, including rock minerology, rock and water chemistry. You know, a lot of it, certainly I’ve seen yesterday and this morning the most important thing is the site specific geoscientific characteristics. So that really is part of the process, getting to the point of being able to collect more and more site specific information.

We certainly needed to understand the hydraulic character of the bedrock and have confidence that the proposed host rock will be able to withstand natural stresses and thermal stresses induced by the repository. Again, concepts that have come up over the last couple of days. And really all this information ultimately will be instrumental in developing a strong geoscientific safety case to demonstrate the safe long-term containment and isolation that is required of deep geological repositories.

So that’s really just a general look at our general post site evaluation. And with some of those things in mind I’m now going to move to our overview of the site characterization program that we did undertake at our crystalline bedrock location in northwest Toronto, Canada where again we are currently in the final stages of our phase two program leading towards site selection.

So, this is a bedrock geology map of Ontario and our crystalline site is located in the northwestern part of the province in the area noted here. So, we focused our investigation within several large granitic bodies in the Wabigoon Lake Ojibway Nation, Ignace Area. These granitic rocks are shown in pink and they occur throughout the northwestern part of Ontario. This is really part of the Canadian shield where the majority of the bedrock is more than two and half billion years old. So quite old bedrock to work with.

Now focusing in on that area, previous area, this map has a footprint of approximately 75 kilometers in the north/south direction by about 100 kilometers in the east/west direction. And it does show the bedrock geology of the Wabigoon Lake Ojibway Nation, Ignace Area. This is typical of Northwestern Ontario, large bodies of varying granitic composition. In the dark pink are surrounded in some areas by older mafic material in the lighter pinks and in others super crustal rocks we call greenstone belts in dark green. And they do wrap around like ribbons in some cases around these granitic bodies.

Four areas outlined in orange here, here and the other two, are located within the boundaries of the granitic bodies. These areas were predefined based on earlier phases of desktop work and were the areas within which we focused our field mapping efforts. Now to support the planning and implementation of the ground field work, we also collected airborne geophysical data within these red bounded regions, so two larger footprint areas where we collected airborne geophysics. Note that I have specifically labeled the Revell Batholith here in the bottom left corner in the southwestern most part of this area, which as I will come back to later, is the location where we ultimately ended up undertaking our borehole drilling campaign.

So, gravity and magnetic airborne surveys were collected in the two regions in 2015. And this is just an example of the magnetic data. So, the magnetic data in the two regions that I showed earlier here and here. And it’s sitting on top of Canada-wide geophysical data that’s publicly available across the area. So we had collected some of this in earlier desktop studies and recognize that we wanted to collect some new data to support our investigations.

So, for comparison the new data that we acquired was flown at a line spacing of 100 meters, while the Canada-wide data were flown at 800 meter spacing. So the resolution, you can see the difference. The new data really allows for clear and sharp distinction between, for example, the green stone belt fabric in these magnetic high ribbons that wrap around the more granitic bodies which often are varying degrees of magnetic character.

And in particular, I’ll focus on this relatively featureless low magnetic region of the Revell Batholith down here. There are very interesting things that come out of this data. For instance, the circular magnetic high region within the Revell Batholith does define a lake granitic intrusion, which supports the understanding that this body of rock is a composite of several intrusive events. There is a Proterozoic dyke that cuts through, also a magnetic high, very linear that cuts through the northern portion of the Revell Batholith. And other really neat things that come out of this data. In the broad area you can see to the north these subparallel sets of large fractures which are magnetic lows. So, this really is a fantastic data set to work with. And you know it starts to develop our understanding of fractures at a certain scale. And obviously crystalline rock fractures are a very important thing and that is a bit of an underlying theme to the story today.

Also to support the field-based geological mapping activities, we looked at locations of exposed bedrock. We predicted these locations using high resolution imagery. And I'm showing this because it’s especially important and useful in planning daily traverses to go out and look at the bedrock in the areas. We had to estimate the number of field days that it will be required to cover certain areas. And our intent was to investigate all these predicted outcrop locations. Now it turned out some of these locations, especially in the central area here were actually chipped wood piles from logging operations that are ongoing in the area. But many areas, especially in the north and in the west, turned out to be bedrock to be examined very nicely.

So, after completion of the initial field studies, a decision was made, both on technical and social grounds, to move forward with work at an area that we identified as the Revell site, this oval here, which was in the northern part of the area that we were investigating in the Revell Batholith. And this was the area that was agreed that NWMO would begin its deep drilling program. Now one of the first things that we did once we narrowed down to this specific area was to recognize that we needed to update our bedrock geology map, develop a new good two-dimensional representation of the bedrock geology. We did have existing maps of 1:250,000 scale bedrock map available. But you can see even in a comparison of the outline of the boundary of the Revell Batholith compared to what we see in the magnetic data there’s certainly a lot of detail that comes out of this new data.

So, we took this as an opportunity to refine the boundary between the batholith and the surrounding greenstone belts and better refined the nature of this Proterozoic dyke cutting through our area. Again, excellent data to work with. We also completed a structural lineament interpretation using the magnetic data and a digital elevation model built based on data from the LIDAR survey. So, the resulting bedrock shown on the right combines all of our available geological information, updated representation of the bedrock units and interpreted structures for the Revell site. And I'm just showing here where we drilled our six deep boreholes that I’ll get into in a bit more detail in a moment. And for again a sense of scale here all of these fit within about a five by five kilometer box.

And importantly the relatively low intensity magnetic region that we can see in the bottom left corner in the magnetic data did turn out to be with boots on the ground mapping. We’re able to ground truth it to understand that it is a relatively homogeneous granitic rock. This pink area here in the map.

Compositionally defined as a biotype granodiorite tantalite, there are few inliers of greenstone belts and a few other compositional phases of the batholith. We focused the rest of our work really in this area.

So, another important thing we wanted to really do was take the surface representation and build a three-dimensional geological model. So, this schematic just simply shows the three-dimensional body of the Revell batholith just pulled out and extracted from the surrounding greenstone belt rocks. You know, we were able to use available information from regional datasets on rock properties to help constrain the model.

Surface mapping and structural data helped us to define the boundaries and again that magnetic data was instrumental in building the geometry. So, you know, while the geometry of the margins at depth are only loosely constrained, we were able to determine with reasonable certainty that the central part of the northern part of the Revell batholith, again up here where we’re drilling our boreholes was at least two and half to three kilometers in thickness. So overall, you know, we went from this approach of updating the two-dimensional bedrock map to developing the three-dimensional model giving us a high degree of confidence that we're working in an area with sufficient volume of relatively homogenous bedrock.

So, with this prediction of our geology and the three dimensions in mind, we did begin to undertake our deep borehole drilling, coring and testing program. And, again, getting more exciting as we progress through the phases. So, this is just an example of a typical drilling pad, fenced off to prevent site creep and with plenty of space for the many trailers and infrastructure required to ensure safe and successful operations.

Now this aerial image shows the locations of all of our six deep boreholes drilled at the Revell site. All boreholes extend for a thousand meters along their length. The first borehole, IG_BH01 here, was drilled vertically, while the latter five boreholes were all drilled nominally at 70 degrees to intersect various topographic lineaments in order to understand the nature of these features at depth. Notably the northern part of the site has seen relatively recent logging operations, so there's quite a bit of bedrock exposure up here as well. And in some cases, it's only partially regrown. In contrast, further to the south, you know, we’re in thick boreal forest, so we did have to develop new roads in order to gain access to these sites. So, we developed these roads that lead to borehole 3, 6 and 2.

And this is just an example of the ground level view when these access roads were being developed. So the main objectives of the borehole drilling program was to obviously collect subsurface geoscientific information to advance our understanding of the site. Key to the program was completing a complete core recovery, so all 1,000 meters was collected to provide direct information on the bedrock and its structure. Along the way groundwater samples were collected at flowing fractures and core samples were collected for laboratory testing. After the drilling, geophysical logging and hydraulic testing were completed in all boreholes.

So this is just a schematic showing the construction of one angle borehole with a telescopic casing system. We had a conductor casing in the upper few meters and surface casing down to approximately 71 meters along the length of this particular hole. All of our surface casing were nominally between 70 and 100 meters. And these are designed to disconnect the potential water bearing fractures of the near surface from the borehole itself. The open hole is 96 millimeters in diameter and we extracted a 61.1 millimeter core during the drilling.

In these crystalline rock conditions, we did find that each borehole used about 10 diamond drill bits. Each lasting for about 100 meters. And you can see the contrast on the right between a new, brand new drill bit and a used one on the left.

So certainly, not new to anyone in this group here but just want to share that, you know, core extracted from the drilling was sampled at varying lengths and locations and subject to numerous tests. Really again constructed to build site specific suite properties: rock strength, thermal character, geochemical character, both rock and water and absorption properties among other things. In addition, you know one of the challenges is that there is not a lot of water at this site, so we certainly go to the length of extracting core waters and noble gas is trapped in the bedrock, again to aid an understanding the long term evolution of the geosphere.

And certainly along with collecting core samples during drilling and sending those off to labs, we opportunistically collected groundwater samples where possible at flowing fractures. We looked at fluid loss or gain as indicators of the presence of these sampling opportunities, paused the drilling, lowered the equipment down to collect the water sample. Now the drilling water was traced with a fluorescent dye to distinguish it from naturally occurring groundwater in the fracture. So, we purged that drill water, often for many hours or days, to remove the drill water and allow for collection of a clean sample.

And after completion of the borehole drilling, we began the geophysical logging program, again to collect additional continuous data along each borehole. And certainly, this data was instrumental along with the visual core logging to develop the integrated geological description for each borehole. So, this image on the right shows an example of one of our integrated geological logs. It includes our rock log, alteration log here, mapping the alteration of the bedrock and then several geophysical logs. Now just to say the pink color on the rock log here from one of our boreholes does represent this biotype granodiorite tantalite, which again as predicted from the surface characterization represents the majority of the rock by length along the borehole.

Overall, the same granodiorite tantalite rock was encountered in more than 60 percent or, sorry, 90 percent, excuse me, more than 90 percent of the six kilometers of recovered core by length. Minor addition rock types of varying mafic and felsic intrusive phases make up the rest of the length of each borehole. On composition variations that occur at rock type changes are often picked up by the geophysical log. For example, this summary log shows a sharp distinct density high right here and here and a few others and a neutron log low. So, this is a nice indicator of distinct rock type. And we were able to have again the direct comparison to the core to indicate that there is a spatial correlation with a suite of fine grain mafic bodies in the bedrock. And this same relationship was identified in all boreholes where similar mafic bodies were present. So again, the continuous geophysical data was very helpful in developing our understanding.

Certainly as well optical and acoustic televiewer logs were a fantastic dataset used to develop our integrated structural log.

They allowed us to define true orientations for brittle and ductile structures. We did not orient the core in five boreholes. We made an attempt in one borehole, but really found that the televiewer data gave us the most confidence in being able to reorient structures. And certainly, you can see things like variations in aperture, things that have been discussed in other presentations earlier. We can look at changes in rock type and really the key thing is some of these fundamental fracture relationships, orientation in particular, and intensity really come out of this data.

So, we have fractures at the regional scale, fractures at the core scale and now we're trying to … we fill in some of that additional intermediate-scale with 2D seismic investigation. So, we acquired approximately 17 kilometers of seismic data, primarily along the road network that we developed and the array design allowed for imaging down to about one and a half kilometers. So, this map just shows the seismic coverage of all these different lines across the site.

We also collected vertical seismic profiling data in selective boreholes to support our overall seismic interpretation and implement all these mafic bodies that we identified in boreholes also have very strong reflections in the 2D and vertical seismic data. So, we have this direct correlation between borehole and seismic data that allowed us to develop a geological model that incorporates these mafic bodies as sheet like structures within the volume of the site. Now these bodies are important, especially to characterize because they do often correlate with increases in fracture intensity and in some cases flowing fractures.

And then speaking of hydraulic characterization certainly along with characterize in the rock we want to characterize its hydraulic character. So, we undertook hydraulic testing program. So specific intervals along the borehole were isolated using inflatable packers on either end of a 20 meter long tool and tested for their pressure response to water being pumped from the interval. We generally tested 20 to 30 intervals within each borehole, covering a mix of sparsely fractured bedrock and increased fracture intensity.

I just want to highlight on the right some ongoing complementary research done by folks at the University of Waterloo. Now they compiled permeability measurements from various Atomic Energy of Canada research sites on the Canadian Shield. Atomic Energy of Canada did a lot of research back in the late 70s and 80s on crystalline bedrock in and around the area. So, the data was mined and compiled to show... to develop a permeability database, which includes a best fit of data for intact rock mass on the left and fracture permeability on the right. And the value of having this dataset is that it can be used for comparison against our site specific hydraulic test results. And, as a general observation, permeability does tend to decrease with depth relatively high in the near surface, but with depth decreasing as we would expect as the stresses increase in the bedrock.

Now some of the boreholes had long-term monitoring equipment installed to monitor for pressure variation over time and it continued to attempt to retrieve groundwater samples. Now these longer-term installations were very helpful in collecting additional site specific information on water chemistry from zones that were not flowing at a high enough rate to collect samples during drilling.

We also, along with the deep boreholes we also installed shallow groundwater wells to a maximum depth of 100 meters in order to characterize the near-surface bedrock groundwater zone. Certainly, this is important to help define surface boundary conditions for meaningful groundwater flow modeling. And at each of three locations, three shallow boreholes were drilled 50 meters apart in triangulated configurations. And another key aspect here is these boreholes required much less infrastructure than the deep boreholes.

So this map just shows both our deep, in the red dots, and our shallow groundwater wells, just showing the coverage at our site. Along with some of the watershed subcatchments of the area.

Additional site characterization work involved the ongoing collection of micro seismic data using a network of nine stations installed between 2020 and 2021. The pink triangles are the stations, including one at the center of our site at borehole 2. Now this network is able to identify events as low as magnitude one within a coverage zone that extends in a 50-kilometer radius around the site, which provides us the data coverage to support probabilistic seismic hazard assessments in the future. Right now, the key thing is collecting the data. Note that there are stations in the region. These blue triangles, which are part of, oops, right there, which are part of Canada’s seismographic network with publicly available data. So, the results here I'm just showing indicate seismic events in magnitudes over an approximately one-year period, from the end of 2020 to the end of 2021. So, you can see that there are numerous, a very small magnitude events that occur in the area.

So, the previous slides provide a high level overview of the key activities that we completed leading up to and including the deep borehole drilling in the characterization program at the Revell site. I just would like to finish my presentation today by noting a few lessons learned along the journey to where we are today.

And really firstly I would like to share how much of an honor it has been to work with our local community and our indigenous partners. We’re incorporating their traditional knowledge, participating in in ceremony and learning about their meaningful connection to the land. This work in particularly has truly opened my eyes to the reverence that our indigenous partners hold for the bedrock that we are studying. They call these rocks at the Revell site and elsewhere the grandfathers. And as a geologist, I can appreciate that that name signifies the wisdom of time and great strength that these rocks possess. We have also worked with our indigenous partners to interweave their world view into how we as Western scientists communicate about the journey that water takes within the bedrock, all these concepts looking at it from different lenses. And it’s been fantastic conversations.

And really overall we tried to be very respectful towards our indigenous and local community partners while we’re working on their traditional lands. Key logistical and safety protocols are translated into the local indigenous language and clearly posted at drill sites. We had monitors from the local first nations who were available to be onsite 24 hours a day to ensure that the site activities were done in a way so as to minimize overall impact.

And really this leads to another general lesson learned for us that this need to demonstrate a strong commitment to protecting people in the environment while doing our work. So especially these deep borehole drilling sites they become small industrial zones. But it is important to acknowledge that this is the land of many creatures and so, you know, part of the work we did was include multiple levels and styles of fencing, so really to keep these sites and our equipment contained. We also ran borehole tours so that members of the public could come and see the work during drilling operations and allowed people to come and see for themselves just how we were treading on the land.

This is just a nice drone image showing a defined borehole site. This one is approximately 50 meters, top bottom, by 70 meters in dimensions. And, again, with a very clearly defined boundary surrounded by several layers of protective fencing and plenty of space to move around safely and efficiently. Now I will say the first borehole, another lesson that we learned was our first boreholes very small, very tight. We really tried to contain it, but felt we needed to find a good balance between a reasonably sized site and ability to move around safely but still contain our work within the natural environment.

And, you know, again listening to the presentation before mine this morning and also, you know, the nature of being here with you all today is we are all learning from international experience. You know, I'm just holding up these two, the geoscientific site characterization programs and safety assessments of other crystalline sites are well ahead of the Canadian program. But, you know, again this is what we aspire to moving further in our licensing process and being able to eventually go underground. And although the design details vary from study to study, really, we are all able to understand that it is the geology that matters in these site specific locations. We need to demonstrate that the geology works, so that we can protect humans and environment from the long term hazards of the use of nuclear fuel.

And our Posiva colleagues would probably know exactly where this is underground. But again, just to say that other countries are doing this. These are real world examples that tell us that the bedrock can be excavated at depth in crystalline rock similar to the Revell site and be fit for purpose.

And, finally, really this aspect of documenting our findings and public-facing reports. All of us probably recognize, and the more years I'm on this job I understand and learn the key to success is communication, specifically communicating to an audience that is not familiar with the complexity of information that we collect while characterizing crystalline bedrock and how do we take this information and build a confident story of site understanding and safety that the public can accept. So, the NWMO has begun to tell our story for both of our remaining sites, discussing site suitability from a technical perspective, again relying on international best practices in terms of a multiple barrier system, which is again a whole other presentation in itself, and supporting key decision statements with results from site-specific technical studies.

Now in communicating this story we also do need to discuss results. And this is not my area of expertise, but my colleagues in safety assessment have completed preliminary safety analyses using site-specific data where available, and that’s an important aspect, for both operational and post closure phases. So, the post-closure safety assessment really considers how any potential contaminants from the repository, regardless of amount, could get into the shallow groundwater, surface water, air, sediment and soil and then looking at the potential impact. So, the assessment gauges impact in part by estimating the dose a future person could receive under a variety of post-closure scenarios and then we compare those against benchmarks, such as the annual background dose from nature, about 1.8 milliSievert here, which is the Canada average and the Canadian regulatory public dose limit of 1 milliSievert per year.

In the result of our preliminary assessment are illustrated and show calculated peak doses after thousands of years for different scenarios, including a what-if scenario if all containers fail for an imaginary person living, soon to be living at the location of maximum exposure and for a rural person living in the general vicinity of the site. So, in all scenarios considered in our preliminary assessment currently the estimated impacts from the repository are well below the natural background and regulatory dose limits. Now this is even true if every container fails in our current assessments. The used fuel in the rocks still provide a substantial barrier and will contain and isolate the radioactivity in the used fuel from people and the environment. And certainly, I'm excited to continue our journey for myself from the geoscientific characterization point of view, collecting more site-specific data that we can work with our colleagues downstream to continue to refine our understanding of what the potential impacts are. So I will leave you with a few key references cited above and say thank you very much for your attention.

SIU: Thank you, Andrew. We’ll start with some questions from the Board members.

ILLANGASEKARE: I'm a Board member and I'm going to leave my geology question to Scott. But I have a general observation and a question. So, you made in your site … you said technical and social factors. So, when you said technical and social factors, which one came first? When you go to the site do you look at the social factors and decide the technical factors so you eliminate technical decisions before the social factors? And what are those social factors?

PARMENTER: Well, I guess I’d say in a lot of ways the social aspect came first, in the sense that, communities came forward and put up their hands to say that they wanted to be interested or involved in the process, to learn more. And then ultimately as we moved forward, even at the desktop phase, I'd say things happened pretty much in parallel. So as we were doing the geological investigations at varying levels of detail, you know, we have a broad engagement, social engagement, indigenous engagement teams that were out speaking with the community, learning about what their values are, what their vision is for their community going forward. So I'd really say that they were happening in parallel.

ILLANGASEKARE: The second question came from the previous Finnish presentation, they talked about surface. When the technology of surface monitoring of … can become available, then they don't have to go underground. But in your case, you did a lot of surface investigation first and then you started drilling. So is an iterative process, you go back to validate the ground truth to the coring and then do you go back to the surface technologies again to see how good you are doing … how good you have done?

PARMENTER: Yeah. It really is in practice a validation exercise. So as we, and again it's a whole other presentation, to show the development of our geological model, but, you know … yeah, we develop the two-dimensional representation, our understanding of the surface of the type of bedrock that we were investigating and as we drilled the boreholes exactly that. We were verifying our assumptions, we were finding our understanding. But it really was this prediction outcome exercise every borehole. And then … so ultimately it is a very iterative process, but as you say it's … I mean, this is all really surface, characterization from the surface. And, you know, I guess to the point made in the previous presentation we, you know, with the 2D seismic data in the six boreholes that we have we feel like that is, even in a crystalline environment quite a lot of information to help us have confidence and develop a very good geological model that when we get to the next phase of work we continue to verify and prove out that conceptual understanding.

ILLANGASEKARE: And my last question, the slide 46 you had estimated impacts. So this estimated impacts based on models I assume. Is that correct?

PARMENTER: Yes, that's right.

ILLANGASEKARE: And then the models of course have uncertainties. So your numbers are very small. In your modeling it’s a detail, but my question is that … you are able to reduce the uncertainties I assume as you did site characterization and that information when you do a model and then now … so how much confidence do you have in those numbers at the bottom of your inverted pyramid?

PARMENTER: I would say that we have confidence that the site is going to perform its job. I do agree that … we are very careful in documenting our uncertainties and indicating that obviously the job is not done at this stage. Once we going to detailed characterization at one of our selected sites, we will continue drilling boreholes and learning more and hopefully shrinking that uncertainty. And that is part of the process. So this is what I call the preliminary illustration, but, you know, I do have confidence that this crystalline rock can do the job.

ILLANGASEKARE: It is possible that those numbers can go up also based on the uncertainties.

PARMENTER: Certainly. Yes. And that is all part of the process.

ILLANGASEKARE: Thank you.

PARMENTER: Yeah. You’re very welcome.

ILLANGASEKARE: Thank you very much for a very nice presentation.

TYLER: Thank you, Andrew. Scott Tyler from the Board. Appreciate the presentation. I, too, was going to ask a little bit about how that inverted cone pyramid would be communicated to how it would be changed as we go forward, because it will change as you refine your models. And so that is a preliminary first cut or second cut. How do you plan to go forward communicating, as you said communication is critical, communicating those changes in your expected performance of the site?

PARMENTER: Great question. And I would say that, you know, at this stage we are being extremely conservative in the inputs that go into the modeling work. And it’s not my area of expertise, but as the geoscience team our job really is to provide the data and the conceptual understanding to our downstream users in safety assessment to go through the modeling exercise. And, you know, ultimately really we just have to keep demonstrating to the public that as we collect additional information, keep going through this exercise and illustrating for them what the potential peak doses are. One of the things that I'm always thinking about is how can we have, develop simple illustrations to describe these very complex topics.

Now I would say is once we go down and select our single site we move into the regulatory process where we are going to need to be submitting a suite of documents for both technical and public and regulatory review. And that will be our first licensing phase to allow us to prepare the site. And so I'd say it's an iterative process and every time we're going to be submitting a new suite of documentation that advances our understanding, defines our uncertainties and presents our results with the information to date. So it's just an ongoing process where we will continue to provide the most up to date understanding of the geosphere.

TYLER: Okay. Thank you. Now I'll ask my geology question. Scott Tyler again from the Board. So I'm curious early on in your presentation you talked a little bit about, I'll call it site, generic site criteria where you had, you were looking for land areas that had, you know, two by two or three by three square kilometers on the surface, which I assume is based upon inventory, what you expect to be disposing of.

PARMENTER: That’s right.

TYLER: But then you move to the idea of when you got your three-dimensional model of the granite intrusion where it was a few kilometers, two to three kilometers in thickness. And that was, I’ll say that was positive in your view. And I'm just curious where in the process did the sort of, the siting criteria of how thick the crystalline, relatively unfractured crystalline rock where did that come into play just from a generic siting criteria? You know, could it have been 700 meters of granite? Would that have been a showstopper? Where did those design criteria, preliminary design criteria come from and how useful were they? And how did they evolve?

PARMENTER: So I guess nominally we’ve always spoken in terms of around 500 meters depth as an optimal repository location. We have done … you know, prior to collecting site data we did many case studies with generic crystalline rock data, using information from our Scandinavian partners and, you know, we looked at varying depths between 500 and 800 meters. So, you know, ultimately, I'd say early in the process we did talk nominally about 500 meters. We in general think about a depth around 500 to 800, you know, deep enough, not too deep, but sort of that Goldilocks' depth.

So I would say there would be a minimum thickness, you know, 700 meters might have been a bit borderline for a suitable target host rock. Now the challenge being that there's not a lot of boreholes in these crystalline rocks, so we might have developed a three-dimensional model that had some certainty or uncertainty, let's say 700 to 1,000 meters. It's possible we might have drilled in that location to ground truth that. But ultimately, you know, as I noted in the specific location we were very confident that we had a reasonable thickness of the same rock that would be both above, you know, a nominal 500 to 800 meter repository and enough rock below it.

I guess, you know, it would be a very, again, as has come up in the theme here, a very site-specific to get to some of those questions of what would screen in or screen out community based on technical requirements.

TYLER: Thank you, Andrew.

SIU: Chandrika. And in the interest of time, if you could keep it concise. Thank you.

MANEPALLY: Hi, Andy. Chandrika Manepally, Board staff. I was just curious you talked about iterative, you know, exchange of information between I'm thinking geologists, hydrologists, so I understand information going to them. But I was curious if any of the site characterization, like your location of a particular borehole, came from their modeling?

PARMENTER: I would say specifically a location of boreholes didn’t come from their modeling work. But what I would say is we developed an understanding of the surface fracture distribution, the larger fractures. And we worked with our safety assessment colleagues and our engineering colleagues to understand together, you know, which of the larger fracture zones we would want to investigate with our first round of drilling programs.

So, I wouldn't say that at the time that we were defining the drilling that there was the opportunity to get that feedback. But now we're at the point where we are getting the feedback from these models. And that would, you know, if we move to the next phase of detailed characterization at either site, certainly now would be the time where we're starting to have that conversation about where to align next boreholes to fill in some of the gaps and understanding.

MANEPALLY: Thank you.

SIU: Scott, any further questions? Okay. Thank you very much, Andrew.

PARMENTER: Thank you.

SIU: And we're almost back on schedule. Okay. We'll take a very, very quick break. Just stretch please, and try to be back in about five minutes. [Break]

Okay, switching gears for something completely different. You have David Sassani and Brady Hanson.

SASSANI: Thank you. I'm Dave Sassani. I’ll be talking for most of this. I know, I don't want to hear any groans, but then Brady will come on right towards the end and talk to our international work. I'm presenting work that Carlos Jove-Colon also put together. He’s from Sandia as well. Brady, of course, is from Pacific Northwest National Laboratories. Carlos’s son just graduated high school, so he couldn't be here. And he may be on the virtual if there’s questions on that area that I can’t address, always possible. We’ll have Carlos on and Sara’s also here from Argonne, may be able to address some aspects of this.

But I'm going to go over, do an overview of the commercial spent nuclear fuel degradation rate models within our program. I’ll put it in the context of what goes on in some other programs. And we’ll move through this and I just have to say, and I want to thank the Board for the presentations, for the whole meeting, but particularly today, because with Erika and Barbara talking to their program in Finland and what they’ve done there on the crystalline system and covering the large scale geologic aspects of the system and then Andy covering what Canada’s looking at for crystalline repository host rocks.

I am a geologist, geochemist, I'm a performance assessment analyst by working on the Yucca Mountain project, but I love that stuff. And it also, and I believe it was maybe Erika that said it, and it was highlighted, you have to think about the inventory you’re disposing of. In the U.S. we are leading the world in this area of inventory in a number of aspects, some diversity, magnitude, total mass, thermal load of some of the canisters we’re thinking about. So we’re leading the world in a number of ways still.

But what I love about it is it’s the two ends of the spectrum for this issue. It’s the large scale geology that you have to think about for the system and we’re going right to the heart, which is the source term, the waste form, the spent fuel that will be put into the ground and how does that affect our understanding? What do we know about it and how does that affect our understanding of the safety performance of these systems? So I really want to thank you because this is … and then there was a bonus because Andy talked about deep boreholes, which is another favorite aspect of mine, although I guess our concept in that context would be very deep boreholes for disposal. But all of this it’s really great. I love it. And it’s a lot of fun and I'm glad we’re here to talk about it.

So with that, I’ll go to my next slide. I have the controller. So just a real high level overview of what we’re going to talk to today. Concepts of the degradation rate for spent nuclear fuel. Whenever I start out any new aspect or a project to constrain, I start with concepts. I want to think about the concepts that matter for the processes that we’re looking at and get those together and see if there’s alternate concepts that may give you a completely different picture or way of thinking of it. Constrain that.

So I’ll go through some background on that. I’ll talk to some of the degradation rates for spent fuel, constrain for repository system performances. Then I’ll go into the models within our program that we’ve implemented, both for aspects of process understanding. As Erika and Barbara spoke to, they still look at the process understanding to figure out if there’s anything else needed to be done. But also the way we build some of these into performance assessment and the way it’s been done around the world. Professor Ballinger has said and asked there are multiple ways you can put these models into performance assessments. You can use a constant rate, you can do a stochastic selection, sampling methodology. Or you can build in something more mechanistic if you want to or really if you need to. The mechanistic aspects are more for understanding.

So I'll go into the fuel matrix degradation model and talk a little bit to the process models that make that up, look at the primary sensitivities, because this is also a question that's come up, how much do you need to keep doing and why would you need to go there and what is that? We look at sensitivities of these mechanistic models to see what actually matters the most and go after that if we need to refine it. We'll talk to the model couplings. A very high level overview of implementation for GDSA. Paul will speak to that in much more detail.

And then I'll talk to strategic approaches we've been taking thinking about doing addition spent nuclear fuel degradation testing for validation purposes, for a number of purposes. I'll go through the methodology for the prioritization, which relates to the prioritization on the large scale that we do for the road map reevaluation. I'll go through the activity status of this strategic spent fuel degradation testing and a little bit of why do you need to be strategic about it. And I'll talk to the path forward for that, because it's not complete, it's in process. And then I'll hand it off to Brady to talk about our international collaborations, some of which of course involve the EURAD-2 program coming up, starting this fall.

So a little bit of context. We've seen over the last, this morning and yesterday the context for a crystalline repository, the layouts, waste packages, different designs, different concepts for the waste packages in some of the reference cases on our program and these other programs. And this is just zoomed in on a breached waste package at some point, undefined point in the future. The package is breached, so you have fluid pathways in and out. The water comes in, it brings in some chemistry, which is dependent on the actual natural system plus the engineered barrier interactions. You have the fuel bundles. Some of these are corroding. There's fuel pins. So there's metal components in here reacting with the water. And then the spent nuclear fuel, of course, as it corrodes drives the radionuclide releases. And then you go away from the fuel surface and that fluid pathway interacts with corrosion products and then bentonite and at some point is evaluated either in the package and/or outside the package for solubility limited concentrations of a variety of radionuclides. Real high level overview of what we're going to talk to today in terms of source term aspects.

So in terms of the basic concepts when we put this together … and this goes back to when I was working in detailed technical areas, because I was in charge of having this work set up when we came out of the Yucca Mountain project where we had models for spent nuclear fuel degradation in a highly oxidizing environment open to the atmosphere, lots of oxygen around. That was a primary driver. So we went and started doing a literature search, looking through what's known for the saturated systems, which are either anoxic and/or reducing, particularly giving all the metals that are put into the system.

And so to a first approximation we said let's start thinking about spent nuclear fuel. And this is one of the things I love about spent fuel, it's a people made rock, ceramic, which actually changes in terms of its mineralogy inside the nuclear reactor. You had other phases coming in besides the UO_2 initially that's enriched. And to me I love that kind of stuff. The phase equilibrium, phase interaction is very important. So if you think about it as UO_2, we can think about it ore deposits as analogs.

These are stable for hundreds of millions to billions of years in saturated systems where your uraninite UO_2 is a primary ore mineral. So when we think about that we can then say, so these last for a really long time so they must have a very slow degradation rate. And, in fact, they may be sitting at thermodynamic equilibrium in these systems. But if you have any kind of fluid flux you can think about a lower bound on the degradation rate of this material as chemical dissolution. Well, what do I mean by that?

Well, that’s the uranium-4 in the UO_2 dissolving directly to uranium-4 in the acquis solution under very low redox conditions, very low EH in terms of electrochemical aspects. And that’s a very small concentration, which then is moved out by whatever the water flux is. So the flux of the solvent controls the rate of the degradation, the dissolution, chemical dissolution. The analogy I use for this for a higher level discussion, as some of you in the room will remember the commercial about how many licks does it to get to the center of a Tootsie Pop, right? So you have a licking process, which is the chemical dissolution part.

But then if you introduce something new, some new process, like biting it, well, then you only take three licks to get to the center of a Tootsie Pop, right? It goes really fast. So the flux of solvent and chemical dissolution I think of as a reasonable minimum bound for the degradation rate of spent fuel. And we'll see that in some of the data sets. But then what we want to ask is what else can really matter for reality? How do you increase the rate of degradation above the minimum? And from a safety standpoint we view our role always as trying to figure out are we missing something that could mean higher releases?

That's a much larger concern than are we missing something that would mean we're overestimating by a bit? We want to make sure we're not missing something that could make higher releases occur. So what else really matters to increase the rate above this defined minimum? Well, oxidation of the uranium-4 to the uranium-6 is a primary first order effect. What are the sources of materials that could oxidize this ceramic waste form? There's little to no oxidants in the materials that get introduced, so we always look at the systems that go into the engineered barrier, because they become a very large mass constraint for the local chemistry in the drifts.

There’s not really a lot of oxidizing materials in there, they’re mainly strongly reducing materials, metallic materials. You can think about groundwater influx. There’s possibilities for future events that are not continual or pervasive, but you could get oxidizing solutions coming in. So that’s something to think about. But the big part is the difference between spent fuel and uranium oxide naturally occurring, which is the alpha radiation field from a lot of the fission products and the transuranics. So these drive an alpha radiation field that can generate radiolytic oxidants, things like hydrogen peroxide and others, depending on the chemistry of the system.

But that’s what we view as the major source of oxidants potentially there. And the form directly at the surface of the spent fuel. So if the rate of production of those oxidants is used primarily to drive the spent fuel oxidation this would seem to be a reasonable maximum bound for the degradation rate of the spent fuel. So we know a lot about what the range might look like, unless something unthought about it could occur in terms of oxidation. In any case, that's what we would define conceptually as a maximum expectation. What else matters for reality again? Well, now we want to think about does it matter, this range is fairly large. Do we have a better feel for where we might be?

Well, the question becomes then are there any potential major sinks for the radiolytic oxidant production of hydrogen peroxide, which would decrease from the maximum this degradation rate? What are the other reductants in this system? There's other constituents in spent nuclear fuel, like americium and plutonium also have alpha decay. But these amount to a few percent of the spent fuel itself. So they're probably not going to offset that in a major way. There's steels in the package, but they're not directly at the oxidant source location, which is, and we'll get to it, within really microns of a water layer on the surface of the fuel, even if it's saturated, because the deposition of the alpha particles occurs in about 30 microns.

There’s cladding. It’s proximal to the fuel, but very unreactive at these relevant temperatures. But there’s something to think about there. But there’s hydrogen gas generation occurring in this canister from steel degradation, which occurs relatively rapidly relatively on a geologic time sense. There’s potentially abundant H_2 generation from steel surface corrosion. It’s labile and it could possibly reach the surface of the spent nuclear fuel and be reactive at that point. So these are the concepts that drive what goes into the modeling that we look at for the SNF degradation in a mechanistic sense.

And this didn’t just occur to us sitting around talking about it. But there’s a lot of work done in the literature, a lot of experimental data, a lot of discussion of the effects of hydrogen on the radiolytic oxidation effects. And Shoesmith and his group put together a mixed potential model, which considered all of these processes in a unidirectional fashion. And what do I mean by that? Well, if we look at a very high level for what we’re thinking about we’re thinking about reducing disposal environments. We do work on generic unsaturated systems still, but this is all for the reducing aspects, reducing environment concepts.

And there’s two primary release process concepts that are incorporated into our safety assessment models. There’s an instant release fraction model and we have a couple of different models for that. They are sampled distributions. One’s from the Yucca Mountain project for multiple fission products, things like iodine. I think we might have technetium in there, possibly a couple others. But the other one is from Johnson, et al, 2005, which is a function of burnup. It goes up to 75 megawatts, megatons per … sorry, gigawatt days per metric ton. So it gives us some ability to look at the variation as a function of burnup. So that comes from aspects that are in the cladding after the cladding fails in the gap and grain boundaries.

This is just a cross section schematic of what that fuel pellet in the fuel rod looks like with the cladding. And you have grain boundaries and the gaps between the cladding and the fuel pellet itself. So that’s where primarily the incident release fraction comes from. It’s about ten percent iodine 129 of the iodine 129 inventory. In all of our models to this point we do not have cladding as a barrier. Yucca Mountain did not take credit for it. We are not yet. We are working on some of that moving forward. But currently when the canister fails the cladding is all considered fail. So the entire inventory in the package can do an instant release.

I'm not going to talk any more about that instant release fraction. There’s been some updates in the international literature that we could look at and incorporate. But going forward we’re going to talk about the Fuel Matrix Degradation Model, which is the degradation of the matrix grains. Again we mention uranium oxide solubility limits. If that’s what the driver is it’s very slow, very load degradation rate, oxidated dissolution is faster from these radiolytic oxidants. But also need to consider potential reductants that react with these moving forward.

We want to evaluate a bit of the role of the Epsilon phase. I believe Sara will talk to some of this with the electrochemical testing that’s being done. Because it seems to protect the matrix grains from oxidation and seems this is a concept that’s out there, but hasn’t been demonstrated whether that is a cathodic coupling with the UO_2 or a catalytic phenomenon or a little bit of both. And that may matter for how you would understand how long that effect lasts and its duration in post closure.

So that model, this Fuel Matrix Degradation Model, FMDM, FMD Model, it includes all these above to assess the matrix degradation rate over time. So what do we know from some other programs? Why are we even thinking about this? We actually know a good bit. So this table here is some sources. The SKB source 2006 is part of the Swedish program work. Pastina and Hella, that’s part of the Finnish program work. Ollila is another compilation, which confirms this. These are measurements of rates that are constrained, built as a log triangular distribution based on the data in Werme et al, 2004. And this modeling work and King and Shoesmith and others this is built off of that for the Finnish program, this reference rate here. These are all in per year units. These are fractional degradation rates.

So a fractional degradation rate of 10^{-6} per year is a million year lifetime for the spent fuel. 10^{-8} per year that’s 100 million year lifetime. These are all primarily for anoxic conditions. These are from static batch dissolution tests. And you can see some of the exponents. I'm not going to speak to the leading numbers, but there all in here 10^{-6}, 10^{-8}. So there are datasets out there that demonstrate this. Well, these are all relatively short term experiments and that’s fine, that’s what we can do and they’re under relevant conditions.

Down here are a couple more references. Cite from 2001 and work from our program down here with the code. And these are in mass per area per day or per year. And so you need the area, you need the surface area estimate to convert to these fractional rates. But they are consistent. We’ve done that. And over here what I'm showing, this is … the source of this figure is the SKB 2006 work on the Swedish program. This is from a paper that Peter Swift and I wrote about what matters for repository performance. And this was assessing where there is a very strong dependence on the degradation rate for the peak dose estimates out at one time here.

So the regulatory limit is shown here. I think those are in microsieverts right there. And that, you can see there’s a couple of different sets of curves here. And the curves that are fractional dissolution rates from that is 10^{-6} to 10^{-8}. Those correspond to the fuel lifetimes of one million to hundred million years. And those are the basis that … those are the ones that they believe to be the reasonable basis for these reduced system conditions. But they also include much higher rates of degradation out here.

The work done here is a sensitivity off of the basecase, looking primarily at the dissolution rate and failing the canisters over a number of realizations for the analytical model, but failing them out at long timeframe hundreds of thousands of years to see how much does that impact. And it’s numbers of order of magnitude here for the rates that they expect to be the rates for this system. So this is why the degradation rate matters in a simple demonstration of that.

So why develop a mechanistic model? Well, we wanted to be efficient so we pulled the model, the original model out of the literature from Shoesmith, et al, 2003, because they had a nice approach to it. The model is really about what matters for the degradation rate of the spent fuel. There’s some chemistry aspects to it. But it does not model all chemistry going on inside the canister. It takes chemical boundary conditions and imposes these and says, these are the primary things that matter for the spent fuel degradation and so we’re going to use that.

Why do we care about that? Well, it’s to understand process. It allows consideration of the environment and its context for the results of the model, provides a basis for interpreting experimentally determined data, understanding what processes are major and dominant and it permits relating short term data from experiments to expected long term system evolution are the experimental conditions what you actually think you have in the system. And it creates a more transparent construct of application versus random sampling application.

There’s nothing wrong with the random sampling, it just doesn’t connect you to any of the driving variables in the system. So that’s the difference in the performance and the system model. You can do both. One’s faster. Much faster than doing the mechanistic aspects. So those are the reasons why though, so we can continue to assess is there something else we have to think about?

So this is a mechanistic representation of UO_2 dissolution. The words over here talk about what's in the fuel matrix degradation model. Radionuclides are just released congruently according to their stoichiometry in the spent fuel. But this plot over here, which is from Poinssot et al, 2005 and Cachoir et al, 2005 shows an interesting aspect, which is what I talked about conceptually but is in fact shown here in detail with some measurements and some modeling work that's been done in these studies. And what's important to understand here is they've got, delineated a solubility controlled zone, so that's how many licks does it take to get to the center and there is a radiolytically dissolution oxidative corrosion going on over in here with a threshold range of specific alpha activity over here where they doped some UO_2 with U233 to have a known set of alpha activities.

And the curves on here, which are measured is there are some measured rates shown in the green curve from ITU in Karlsruhe and there's some measured solubility here in the black curve from ITU in Karlsruhe and there's measured solubility here in the blue curve from the Belgium program SCK. And what you can see is the solubility values are much lower than the measured values, both for solubility, a little bit, and you can see this curve going up here, which is moving up into higher values and there’s also a deaerated hypothetical curve. And deaerated is somewhat anoxic and then there’s anoxic and then there’s reducing. This all was done because there was a lot of information in the literature about hydrogen effecting the degradation rate. Hydrogen coming from degradation of steels.

So this aspect indicates to us that, yes, we want to be able to consider both of these functions going on where it’s the alpha activity and for spent fuel were somewhere up in this region that’s driving the oxidative degradation of the spent fuel.

Okay. So I am going on to this. And I'm going to jump into the sensitivities that were evaluated in the Fuel Matrix Degradation Model. This is from a program report and it’s work done at Argonne National Laboratory by Jim Jerden. And this is looking at the fuel dissolution rate. Again, it’s mass per area per year. And it’s looking at the primary variables in the model. And these are the model sensitivities. And there’s a dose rate effect. The lower the dose rate goes … we were working with the 500 rad per second fuel characteristics, which is some higher burn up.

I think 60 megawatt gigawatt days per metric ton. If you go down from there it of course decreases the rate down. There's a temperature effect which was looked at 25 degrees to 200 degrees. There are some uncertainties in the thermochemical data here in the reaction rate constance for these at higher temperature. They are larger. But you can see that's a little more than an order of magnitude effect. Carbonate complexation, carbonate strongly complexes uranium in solution so that it can have a primary effect.

We saw that on the Yucca Mountain project. It was a primary variable along with pH for solubility aspects and potential degradation rates. And then there are a couple. This is no CO2. This is the oxygen content. And this is a pH variable which did not get varied quite very much. But it was on the basic side of neutral pH. This large line, this large purple arrow, this is the effect of hydrogen, the hydrogen overpressure in the system. This is a little bit more than five, close to six orders of magnitude.

This stood out as the dominant aspect in the model, which is seen also in the experimental work. The hydrogen partial pressure of the dissolved hydrogen, however you like to think about it. That has a primary control and mechanistically it's because it's available to react with the hydrogen peroxide. So it's almost a direct offset. So that's the sensitivities and this is why we want to take a look at some of the electrochemical work and see if we can understand the mechanism that's really driving that. That's all from a process standpoint.

These are kind of the details of Fuel Matrix Degradation Model. It's got, you know, there's Shoesmith, et al, 2003 reference. It's what it's based off of. We modified it. That was purely for reducing conditions. We modified it to be able to go into oxidative conditions with oxygen coming into the system for unsaturated. It's consistent with the other models of degradation and they're under oxygen conditions. It's got an electrochemical transport module. It has surface potentials based on major interfacial anodic and cathodic reactions, shown here. Some here. And all of the reaction in it is going on the surface.

When we developed these models back in, actually over a decade ago these were developed, this was a conceptual piece that was supplying hydrogen and potentially ferric and ferrous ions to the solution. But we weren’t doing process models here. I think there have been some updates where there’s actually an iron material. This is about five millimeters away from the spent fuel surface and it’s used as boundary condition in the way it’s implemented in PFLOTRAN currently. But the process model may actually have an iron source term over here now, a corrosion source term.

It’s the major constraint on hydrogen production is the steel corrosion going on. That’s the primary aspect of this. In the model some of the uranium dioxide it oxidizes in solution. Some of it precipitates out. I think schoepite and studtite has phases for precipitates have been looked at. There is no mechanistic aspect of the precipitates. We did not want to completely occlude the surface, as this would just shut off the material from corroding. And we don’t have enough data to really say that’s what would actually happen. So these are built up as what Jim Jerden used to refer to as French fries on the surface that still allows this degradation to go on, but reduces the surface area that’s available to degrade.

So those are the surface precipitates. So those are the details in the model. And those are a lot of aspects that we’d like to look at in a little bit more detail, particularly the electrochemical testing. But moving forward …

SIU: Excuse me, David, how are we doing, process check? Because we also have to hear about the international collaboration.

SASSANI: I’ll speed up.

SIU: Thank you.

SASSANI: Sure. So these are the surface half reactions. Oops, it went back … I'm not going to speak to these. You can see them on the other plot. There’s some anodic, there’s a chemical reaction with the surface of the fuel and also noble metal particles where I believe the reaction rates of these are put in as catalyzed.

This is a conceptual diagram of how it fits in the total system model. This was the old version. We had this going on here with concept of a steel canister that was breached, groundwater reaction with this. And that’s the instant release fraction over there. Those two pieces go into, they’re inside of cladding, which is breached and waste package internals. And then there’s interaction with the engineer barrier system.

And then this is a more detailed mapping to summarize where this sits for in the GD Safety Assessment Framework. And we’re going to look at some strategic testing activities. But this Waste Form Dissolution Model is over here. The cladding is a separate piece that’s around it that we are putting together a conceptual model for its degradation. And then there’s a Waste Package Degradation, which is sampled currently at this point. Paul Mariner will talk more to the GDSA work.

Then we’ve started developing a strategic testing plan where we wanted to review the conceptual processes to identify gaps, relate them to the existing models and data and integrate it within performance assessment approach, including uncertainty treatments and identifying what’s a fundamental gap versus just better defining the uncertainties. We want to use this in the current approach for prioritizing gaps and new work in the program. We want this approach to be risk informed. This is in the process of evolving from what we had done that ended in 2019 for the road map reevaluation. And it’s evolving back to a FEP based process. So we are in the midst of redoing the prioritization methodology to evaluate those gaps.

So we want to look at what testing methods we have available to address whatever the highest priority gaps are that come out of that. So we pulled the testing mechanisms at all our labs and had those put together into a series of one to two page summaries giving a high level, I won’t call it a technical readiness level, but saying how far along is this, how ready is it to deploy and make measurements to answer questions?

We’re in the process doing this. It is based on our current draft is based on what we did in the methodology for the prioritization for the importance to safety for the road map reevaluation. It had three categories, a high importance, medium and low for importance to safety. This was covered in some detail in the 2020 meeting presentation that I had and links in my first overview on the program. Then there’s another metric, which is the state of the art level, which has five levels, fundamental gaps and data needs. This is, we really don’t know anything about this and we need to go do some basic work. That aspect it tended to be a little bit turgid for some folks as to whether it was the state of the art level existing in the world and the world of science or the state of the art level in what we’ve implemented in the program. So in terms of our discussion about TRLs I think we would break out state of the art level of knowledge in the world versus going into technical readiness level within the program. And that would make things clearer in the next stage.

These get combined. This combined prioritization was put group in Sevougian et al state of the art level across the top, importance to safety here and medium, high and high relate to these boxes over here. So this would be used to say these are things where we really want to get some work going and answer some questions and move forward. These are all in process and so the status is we identified preliminary gaps and defined those. We have this preliminary prioritization based on that road map prioritization methodology.

But we really want to use the FEP tool to map these gaps to the features, events and processes at the detailed level and assess the scoring methodology updates. This bringing in a technical readiness level is one of those aspects. We wanted to have the details of the risk informed bases. In other words, it’s much more important to identify things that mean we’re missing potentially higher releases then it is to get more detail in the uncertainty levels of the range.

And we want to do this review for the state of the art level and revise that prioritization. So once we do that we would reprioritize and identify those high priority gaps and then develop a testing strategy by taking those high priority gaps and our knowledge and understanding of our readiness level for our testing methods and which ones actually answer the relevant gap questions and then lay that out moving forward. But this is all going to be happening probably over the next year or two as we move to this different prioritization methods.

So I'm ready to hand it off to Brady. I don't know if this clock is right up here. I was watching this clock it says I have 18 minutes to go. Oh, I'm sorry, I thought that was the time…

SIU: That’s okay. That’s okay.

SASSANI: I’ll hand it off to Brady and I’ll move the slides for him. Brady are you there?

SIU: He’s unmuted, but he’s not being projected yet. Brady can you continue to talk?

SASSANI: Brady has lots of good details to speak to on these bullets.

SIU: They’re continuing to work on it in the back of the room.

SASSANI: There it is. Brady, does your headset have a mute button on it?

HANSON: No.

SIU: You are now muted.

HANSON: Now can you hear me?

SASSANI: Yes, we can.

HANSON: Alrightee. Cool. Thank you. Sorry about that. I’ll give a brief and high level overview of the main international collaborations, past, present and future, specifically dealing with spent fuel degradation, which includes cladding performance and storage transportation and disposal. These collaborations are important to us, because they’re both supplementary, where others are doing tests and models that we haven’t done yet and also complementary where their data and models help to validate work that we’ve done.

So we were invited to be what’s called an associated group for the last two major EURAD programs. First nuclides focused on the faster instant release fraction from spent fuel that David talked about. The big highlight of that effort was a significant expansion of the public database for the instant release fraction from boiling water reactor fuels to supplement the database we have in the U.S., which was largely on pressurized water reactors.

Disco focused on the effects of newer fuel designs on spent fuel dissolution. In particular the main conclusion from that program was it found that the addition of chromia and alumina, which are used to increase grain size had no discernable impact on dissolution rates. Under the International Nuclear Energy Research Initiative, which has concluded, but we had two successful collaborative efforts. In the first we worked with leading institutions in Germany and Switzerland. Those two countries tend to have spent fuel with significantly higher burnup then we have in the U.S. So working with them we were able to see the effects of higher burnup, which will help guide the U.S. program, especially as our industry here is now moving in the direction of higher burnup.

We had a second I-NERI where we worked with the Korean Atomic Energy Institute to look at hydride reorientation in different cladding types that they have as well as looking at it as a function of cooling rate during storage. The fourth iteration of what’s called the Studsvik Cladding Integrity Project is actually ending next month. But this program has supplied key, albeit proprietary data on creep of fuel segments that still have fuel in them. And again that will help guide the future R&D efforts of the U.S. program.

And then with IAEA, DOE and the National Labs for over three decades have been part of the program, started as what was called BEFAST and SPAR, Spent Fuel Performance Assessment and Research. Again, looking at fuel and cladding performance and storage transportation and disposal. So seeing all the different fuel types, cladding types worldwide was very important and helpful. Next slide, David.

So we are currently part of what's called a Coordinated Research Program within IAEA on Spent Fuel Research and Assessment. That's a continuation of SPAR basically, although it was split into to look at specific tasks. So we're part of that. There's a new coordinated research program that is starting this fall, which will specifically look at storage transportation and disposal of spent fuel from small modular reactors.

And then as David and others have said EURAD-2 is the big one that we’re excited about. It’s a brand new very large program that just received approval from the European Commission. It starts in October of this year and will run for five years. Again, the DOE and National Labs are participating as an associated partner and we are very thankful to Erika Holt for all of her help and work in getting the U.S. heavily involved in that effort as an associated partner.

When I say big on the European side, there are 52 organizations from 21 member states and then there’s an addition 22 associated partners from six different countries. I believe there’s 15, 16 different work packages specifically for this talk. We’re looking at work package 8, which is the release of safety relevant nuclides from spent nuclear fuel under deep disposal conditions.

The purpose of that program is to improve the quantification and mechanistic understanding of release of safety relevant nuclides, covering a wide variety of representative types of spent fuel and looking at the evolution of fuel prior to and after contact with groundwater. This work package will have four main tasks. The first is looking at instant release fraction again and how it relates to fission gas release. The second, the role of grain boundaries in spent fuel corrosion. Third studies on what they call model materials, including mixed oxides or MOX fuels, the chromia and chromia alumina doped fuels and sim fuels, which you'll hear a little bit more about from the U.S. in the next talk. And then lastly a task on mechanistic modeling, very similar to what David just presented. So we're really excited to be part of that large program.

Lastly this year we will participate in the 32^{nd} International Spent Fuel Workshop, which is obviously been going on for about three, four decades now and very useful. To conclude we use this information, the data, the models that we get from these collaborations to inform and guide the U.S. program and as I said have both supplementary and complementary aspects. And with that, David, next slide. You can cover the summary.

SASSANI: Thanks, Brady. I'm not going to speak to this slide because I was completely off in the time I thought we had left. But I appreciate the attention. And we'll take any questions.

SIU: Thanks, Dave, I apologize for the clock. We’ll make sure that we get it right. Okay. Questions? Ron?

BALLINGER: Too many. Too many to list. At a high level, first off the canisters that we’re going to be dealing with are probably C22, not steel.

SASSANI: I'm sorry, say that again.

BALLINGER: I think the canisters that we’ll be dealing with here are not steel. Not carbon steel. They’re C22.

SASSANI: Yeah, we look at a whole bunch of different kinds of canisters.

BALLINGER: Well, but your models and stuff are based on steel corrosion.

SASSANI: Inside the canisters.

BALLINGER: Inside the canisters. So that’s something to be cognizant of hydrogen. I'm interested in the details. It’s one thing to generate it radiolytically. It’s another thing to get it into the material or have it on the surface. You know, they can be recombination in all kinds of things like that.

SASSANI: Yes.

BALLINGER: So we’ll put that in our letter I'm sure. Let’s see, I took a bunch of notes. I keep harping on this and that is all of these model attributes that you’re going after the question that I keep asking is, how does it affect the dose? What’s your criteria for needing to do research? Is it for the good of the research or is it aimed at some objective criteria that you’re trying to meet? We heard this morning the presentation by the Finnish folks and I'm looking at their slides and they’re a thousand times below any limit and they dump the fuel off and assume no, it’s all dissolved. So I'm just trying to …

SASSANI: Can I address that one a little bit?

BALLINGER: I'm trying to struggle with that. And then I’ll keep going.

SASSANI: So in terms of the performance aspects as I showed we have ranges of values for spent fuel degradation that can be applied. And we have those built into the GDSA for sampling. We can assign fractional degradation rates and that's great. We think that conceptually in these reduced systems you will have very low slow degradation rates, slow release, waste form lifetimes on the order of hundred thousand plus years, maybe a million years, right, 10^{-6} per year. That's a million year lifetime.

You saw how it matters in the case for the Swedish safety assessment. It has a big effect on peak dose out on at long timeframes. So it depends what your regulation is that you're marking, right? We have a couple of different ones. But the question becomes what's driving that. Those are all rates that are derived from hydrogen suppressed degradation of the spent fuel degradation rate. Hydrogen's a key component. It matters over six orders of magnitude in the model. Hydrogen generated from corrosion of the metals in the package, not from the radiolytic aspects.

There’s also hydrogen generated in the radiolytic aspects. So all of those questions go to is there at the technical basis level, not the PA level, but the technical basis level how do you support selecting amongst the various ranges of rates that can go to very high rates of degradation. So everyone of these programs has done it, right? But we don’t have the same inventory in our canisters, the same canister size, the same temperature variation. We don’t have any of those things. So you got to develop the basis for those fundamental aspects. That’s why that other model exists.

BALLINGER: But these folks are considering that there’s no cladding… it’s complete dissolution instantly. The Finnish folks are saying we’re going to dump it all out in the repository without any time period before you get, you start to get dissolution. And there’s still a factor of a thousand below their dose limit.

SASSANI: No, they’re using a range of degradation rates as well. It was in the table that I showed.

BALLINGER: Okay. I have to go back and look at the … I'm looking at this cone looking thing where at the bottom there’s the dose.

SASSANI: Right. And their safety assessment. So if you have a full safety assessment you can get to a dose estimate. We don’t have a full safety assessment, because we don’t have a site. And if you recall Erika and Barbara both said you start doing all your specific design aspects after you start collecting your site data. So we’re looking at generic systems, so we’re looking at a much broader range of potential variation. Not just in the geology of the system, but also in our spent fuel inventory.

BALLINGER: I don’t doubt that for a moment. What I'm wondering about is what’s the effect on the dose?

SASSANI: It’s scales virtually directly. If you just think about iodine 129, which is what drives the dose. The iodine 129 released from the spent fuel directly proportional to the degradation rate.

BALLINGER: Yep, I saw that yesterday. And that to me said that at least for their analysis that the time at which you breach the canisters is important because that’s when you get the instant 10 percent.

SASSANI: Yes.

BALLINGER: You get the iodine release, which tells me that the canister itself is very important to the barrier.

SASSANI: Absolutely.

BALLINGER: So making an assumption that you don’t have any cladding has a big effect on what’s going to happen.

SASSANI: It can. Yes.

BALLINGER: And you’ve got a … we’re getting into the weeds here … you’ve got an area ratio between the cladding and the breach of probably 10,000 to one. And so not considering the zirconium cladding in the modeling just to me makes … it’s a big gap.

SASSANI: It is. And you know the Yucca Mountain project had no cladding barrier in it. And it met the regulatory requirements.

BALLINGER: And it met the regulatory requirements.

SASSANI: Completely different system though and completely different degradation rates.

BALLINGER: I better shut up.

HANSON: David, if I may …

SASSANI: Go ahead, Brady.

HANSON: Professor Ballinger, thanks for the question. I did want to note Barbara has posted in the Chat that the Finnish and Swedish programs do have fuel degradation rates of the 10^{-6}, 10^{-8} that David talked about. But you are absolutely correct that the programs do not take cladding credit and as David alluded to in the U.S. program we're actually putting together a test plan right now to look at what would it take in order for us to be able to look at cladding credit.

BALLINGER: Yes. Good idea.

SASSANI: We started that a couple of years ago, both based on a direct disposal of DPC work where cladding matters in a different manner. But also for post-closure performance.

BALLINGER: Again without including the cladding your electrochemical model just doesn’t work.

SASSANI: Well, there may be an electrochemical aspect there, but you know all the data sets measured for spent fuel with and without cladding do not separate out into two groups of degradation rate. So that’s my understanding of that.

SIU: For the purpose of the meeting can we make sure that we get the information that we need. We’ll discuss, write the letter … By the way before you go on, does Allen have any questions? No? Okay. You have more Ron? Or can we go to Andy? Andy do you have any questions?

JUNG: No. I'm fine.

SIU: We'll take a couple more minutes for Ron if you have anything.

BALLINGER: I don't want to dig my hole any deeper.

SIU: Okay.

SASSANI: I just want to say I'm happy to have the questions. I'm happy to talk about it.

TYLER: And Scott Tyler, Board. And this is not my area of expertise, I apologize for my ignorance when it comes out as opposed to if. But on the model of the fuel degradation model you're bringing in water through the breach in a diffusive manner I assume, which is causing … which is the source for the iron oxidation. So you have this balance of sources of hydrogen coming in. You'll have a reducing environment in the groundwater system, which may be far less reducing than what the fluid may look like inside the canister as it's oxidizing. How are you dealing with the advective transport of water coming in and then potentially the advective transport of water out given perhaps buffers, erosion and things like that?

SASSANI: That’s a good question. In terms of actual evaluation of flow in and out of the package at this point I don't know that we do a whole lot very mechanistically. It’s at this point in the saturated systems, the packages will fill up with water relatively quickly, because once you saturate the bentonite and/or degrade it, you’ve got a pretty good fluid pressure around the canister so if it breaches the water’s going to go in, potentially even some of the bentonite could go in, but the water’s going in. And so once there’s water in the canister the metals are way below the lower limit of the water stability, so corrosion goes on, hydrogen gets generated.

You might be asking well, does it use up all the water that comes in so that there’s no water? But a 30 micron water film can form on the surfaces of these fuel pellets. It doesn’t have to be a completely saturated system. So those are kind of conceptual assumptions at this point. But the flux of water into one of these canisters is relatively quick on a geologic time schedule.

BALLINGER: I feel compelled. Does the model consider … I look at the radiolysis effect and alpha radiolysis versus beta and gamma radiolysis is very different?

SASSANI: Yes.

BALLINGER: And so let’s say for argument purposes that you can increase the concentration of metal ions in solution because of radiolysis. When it gets out and starts migrating away from the package you’re way above the solubility for those metal ions, which is typically around 10^{-6}, several ppm. So does it allow for precipitation? Does it allow for the fact that once this high saturated, super saturated solution ends up away from the canister, now away from its source of super saturation?

SASSANI: Yes. In fact, the system model does do solubility limits and those elements, like uranium, plutonium, they all precipitate out. They’re not the issue. It’s things like iodine 129 that does not precipitate that just transports and can get into a fast fracture pathway. So there are other elements that are not solubility limited that are the issue. And that’s why the degradation rate matters for those elements and their release.

BALLINGER: Thank you.

SIU: Okay. Thanks, David. And we will continue now with Paul Mariner and Sara Thomas. And could we make sure our clock is set to 40 minutes. No, no, no, no.

MARINER: Alright. Hello. My name is Paul Mariner. I'm with Sandia National Labs. I am one of the leads on the development of the performance assessment modeling capability for repository safety assessment. I'm going to be giving this talk with Sara Thomas. She’s from Argonne National Laboratory. And the name of our talk is Fuel Matrix Degradation Modeling and Electrochemical Testing.

For the first part of this talk I'm going to talk about the fuel matrix degradation models that we’re using in our repository reference cases. And then I'm going to talk quite a bit about the surrogate models that we’re using to represent the fuel matrix degradation process model in our reference case simulations.

In Part 2 Sara will talk about electrochemical corrosion testing of simulated spent fuel and in particular how they help support the fuel matrix degradation process model that David was just talking about.

There are two general approaches that we use in the GDSA reference case simulations that the two approaches that Dave has talked about, one is the fractional degradation rate. We also call that the FDR model. The other is the fuel matrix degradation model, which is the more mechanistic model we were talking about earlier. When we simulate the fuel matrix degradation process model in our reference cases we do that with surrogate models.

The fractional degradation rate it’s a fixed rate model. The rate does not change over time. The rate is sampled usually from a range like what is shown here, the 10^{-6} to 10^{-8} per year. And what that means is that is the fraction of the remaining fuel in the waste package that degrades in a year.

For the fuel matrix degradation surrogate models, because it’s based on a more mechanistic model, we can get rates that change with time in our reference cases.

We have two different surrogate models that we’ve developed for representing that mechanistic model. One is a neural network surrogate model and the other is a K nearest neighbors surrogate model. We’ve developed them and we’ve implemented them and we’ve tested them on two different reference cases: the shale case and one of our crystalline reference cases. What I'm showing on the right here are two different results. I mean, two results from one of our shale case studies. In that shale case we in one application we used the fractional degradation rate model and in the other we used the neural network surrogate model. And they are both shown, one above the other.

The fractional degradation rate model, as you can see is just a constant rate. The waste packages fail and then they … the rates are expressed here are in terms of uranium dioxide flux, in terms of moles per meter square per year. And that doesn’t change over time. But when you simulate the … you know, some of the mechanistic processes in the fuel matrix degradation model you do see a change in the fuel matrix degradation rate. It starts off quite a bit higher at earlier times and then decreases, the rate decreases and then eventually levels off at late times. This simulation that is demonstrated here is for a shale case with 2,000 failed 4-PWR waste packages.

It would be very nice if we could directly hook up the process model to our reference case. But we can't do that, because it runs too slowly. When we have probabilistic simulations we may have thousands of realizations we need to simulate and we will have thousands of waste packages in each simulation that are breaching. And so we just cannot run the slower process model in the PA reference case. The surrogate models run thousands of times faster. And so that's why we've developed them. The fuel degradation rates from the fuel matrix degradation process model they're sensitive to temperature and dose rate and they're also a function of the concentrations, the environment concentrations of dissolved hydrogen, oxygen, iron and carbonate. Our surrogate models are also a function of those same set of inputs. And that's why the surrogate models can do a really good job of emulating the process model. It uses the same set of inputs.

Here is a slide that talks about the two different surrogate modeling approaches that we've implemented so far. They're two very different surrogate approaches. They are both developed using machine learning techniques. The one on the left is the k nearest neighborhoods regression model. And what that does is it basically averages the nearest data points weighted by distance. In this very simple example you can think of the green points there as the true values. Those are the values that we get when we run our process model.

The surrogate model point is that yellow point there. We know what the input is, we look for data points that are in our database of results from our process model that are near that input value and then we average them. And we average them and weight them as well. So the closer the data point is to your interrogation point, the more you weight the value of that data point. So now imagine a database of millions of training data, millions of these green dots in six dimensional space. That's what we have for our fuel matrix degradation model surrogates. There are six different input parameters. So that's why we have a six dimensional space.

So what is happening here is that you find your values of your six inputs and you look in your training data set for the data points that are nearest to that interrogation point and you pull the nearest neighbors and you average them. So basically all this is really is just a very sophisticated multi-dimensional look up table.

The artificial neural network surrogate is very different. What we do there is we take all the training data sets, all the training data and we basically fit a response surface to it all. The way it's done in the artificial neural network is that it has neurons in a hidden layer that it uses them in order to optimize equations to fit all of the data. And so what ends up happening is you generate a whole bunch of coefficients that fit equations that fit all of your data.

This slide compares the training data, actually it doesn't compare training data, it compares test data from the process model to the neural network surrogate model. What it shows is the degradation rate on the Y axis, has a function of time. Both are in log scale. The solid lines in this graph are directly from the fuel matrix degradation model. And those are generated from random tests. So we're showing ten random tests. Those particular tests were not used to train the surrogates. The training data set was a completely different set. So that helps make this a fair, a more fair comparison.

So as you can see the surrogate model does a pretty good job of predicting what the process model would calculate. I'm sorry I didn't include also a plot like this for the K nearest neighbors regression. It also does a good job of predicting the trends and the magnitudes that you see there. But what it looks like, it's a little noisy. And that's just the nature of that approach versus this approach. The neural network approach produces very nice smooth curves.

In the upper right table that shows the range of input values that this surrogate was trained on. The temperature range is 300 to 400 degrees Calvin, fuel burnup between 40 and 65 gigawatt days per metric ton. And you see there the ranges of environmental concentrations of carbonate, oxygen, iron and hydrogen.

In the lower right is an analysis of how well the surrogates did against the training set. So in other words these are aerometric for the entire training set that was generated over the entire ranges of the parameters that are in that upper figure.

And what you see on that last slide there is the mean absolute percentage error of 29 percent for the K nearest neighbors regressor and 14 percent for the neural network. Those values are actually pretty respectable considering that these surrogate models are predicting degradation rates over five orders of magnitude. You can see on the left side. It’s predicting rates over five orders of magnitude. So to have mean absolute percentage errors that low is pretty good.

So for future improvements. We’re actually going to be improving the process model in a way. Not mechanistically, but we are going to add a feature so that we can change the chemical conditions over time. And then we’re also going to continue to work on surrogate models. We are now exploring a new surrogate model called the neural ordinary differential equation surrogate approach. The slide there shows kind of how that works. What that approach does is it fits a neural network to the time derivative of the process model data. We think that might be a really nice way to do it for our particular application. We'll see.

The other thing we're working on right now is a method for calculating the surrogate error for a specific repository reference case simulation. When we run our repository reference case simulation we are not pulling values from the entire surrogate training space. We're only probably pulling it from a very small section of that training space. So we want to know what is the error from the … in the data values that we pull. And so we're developing a way to actually look into that.

And I think that's my last slide there. And it's onto Sara for Electrochemical Corrosion Testing of Simulated Spent Fuel.

THOMAS: Okay, I'll figure it out. Good morning. I'm Sara Thomas from Argonne National Laboratory. And I'll be presenting on electrochemical corrosion testing of simulated spent fuel or SIMFUEL.

Okay, so just a reminder on what the fuel matrix degradation model really does. It's an electrochemical model that calculates the dissolution rate of the UO_2 matrix fraction of the fuel as a function time since groundwater exposure. And it was developed as an electrochemical model because the dominate pathway for radionuclide release from the UO_2 matrix fraction of the fuel is an electrochemical process. So it's the oxidation of uranium four oxide to much more soluble uranium six species. So I've just included the generic UO_2 oxidation half reaction on the slide.

So in order to address the knowledge gaps on the factors that affect UO_2 matrix dissolution kinetics under repository relevant conditions, so these are the gaps that Dave Sassani briefly discussed in the previous section, the gaps on the fuel matrix degradation model, we're running an electrochemical corrosion test using SIMFUEL. And the gaps were specifically focused on are related to the effect of fuel chemistry, galvanic coupling to cladding and also certain environmental conditions, so how those affect UO_2 dissolution kinetics.

So this slide just covers some of our rationale for using SIMFUEL and electrochemical testing. So one nice thing about SIMFUEL is that we have composition control. So we can exclude the beta and gamma emitters from the composition to represent aged fuel in a repository. So this would not be possible if we were to be testing with actual irradiated spent nuclear fuel. And we're doing that because the fuel matrix degradation model assumes that the fuel has aged sufficiently prior to the waste package breached by groundwater. So only the alpha emitting fission products remain.

And another one of our main goals with this testing is to elucidate mechanisms. So we do that by conducting highly controlled electrochemical experiments in a laboratory. So some examples of the mechanisms we can better understand with our testing, and this is also something that was discussed in the previous session, is the role of the noble metal fission product particles or also known as the Epsilon phase in protecting the UO_2 matrix from dissolution.

So there's two proposed mechanisms by which these noble metal particles can protect the UO_2 matrix from dissolution. One is catalytic protection, because the noble metals are known catalyst. So they can actually catalyze surface reactions that donate electrons to the fuel surface and lower the surface potential protecting the matrix from dissolution. There’s also galvanic protection where the molybdenum in the noble metal particles will actually preferentially degrade or corrode and do it instead of the UO_2 matrix. So another protective mechanism.

And then finally the nice thing about these electrochemical measurements that we run is that they can be conducted on a relatively short term timeframe. So we can generate valuable data to actually validate model predictions and calculate model parameters in a matter of weeks or months.

So our electrochemical tests. We systematically controlled single variables. So the variables under the first bullet point, those are already take into account in the fuel matrix degradation model. So we can perform our testing to just validate how they are incorporated into the model. So, for example, we can control the noble metal content in our SIMFUEL by preparing SIMFUEL with different concentrations of noble metals. We can control the dissolved hydrogen concentration in solution by purging the electrolyte solution with different hydrogen argon gas mixtures. We can control the carbonate concentration in the electrolyte solution and also the system temperature. And also we can control oxidant concentration. And by oxidants I just mean those produced due to alpha radiolysis. So mainly hydrogen peroxide. We can control that by either directly adding hydrogen peroxide to the solution or we could use the SIMFUEL doped with alpha emitters like U-233.

But our testing might also indicate that we need to include additional parameters or processes that are not currently in the model. So currently the model does not consider different noble metal alloy compositions, it just assumes one composition. It doesn't consider fuel composition and compositional changes over time, with the exception of considering the presence of noble metal fission product particles. It is calibrated to only an alkaline pH, meaning the rate constants in the model were determined from experiments that were conducted in alkaline solutions. It doesn't consider the effect of catalytic poisons that may inhibit catalytic effects of the noble metals. And also it does not include galvanic coupling between either the UO_2

matrix and the noble metal particles in the fuel or the UO_2 matrix in the waste package allies.

So this slide just covers some of the details on our SIMFUEL synthesis in electrode fabrication. So our SIMFUEL is composed of UO_2, lanthanide oxides and different amounts of noble metal surrogate fission products, because we’re interested in quantifying the effects of the noble metals that are present. To date we have made four SIMFUEL materials, each with a different noble metal concentration. And the compositions were inspired by depletion calculations in the literature. So the UO_2 L material that is to represent the composition for a burnup of three atom percent uranium and the UO_2 M material is to represent the concentration of noble metals expected for a fuel with a burnup of 6 atom percent uranium. And then the H material we just doubled the amount of noble metals present compared to the UO^2 M material, just to see if we could measure an affect.

So we prepared the SIMFUEL materials by mechanically mixing the reagent powders, pressing them into a pellet and then centering under vacuum. So that’s just a picture of one of our pellets. It’s about the size of an actual spent fuel pellet. And here I'm showing back scattered electron microgragh of the polished UO_2 H surface where I’ve identified the UO_2 matrix reaction and then different noble metal phases. And in order to use the SIMFUEL as an electrode we make an electrode by taking a section of the SIMFUEL pellet, embedding it in electrically conductive epoxy and attaching lead wires. And we do polish the surface of the SIMFUEL so it’s pristine and flat before every test that we conduct in order to have a nice surface for measuring surface reaction rates.

So this one I included to just show how our electrochemical measurements relate to some of the electrochemical parameters in the fuel matrix degradation model. So the model includes 11 half reactions that occur on the fuel surface, either on the UO_2 matrix fraction or the noble metal fraction of the fuel surface. And it calculates the corrosion potential or the E_{CORR}, the current densities of each half reaction simultaneously, such that the net current at the fuel surface is zero. So another way of explaining that is at the corrosion potential E_{CORR} the sum of the current densities of all the anodic half reactions occurring on the fuel surface plus the sum of all the current densities of the cathodic reactions or the reduction reactions occurring on the fuel surface is equal to zero.

And these current densities of half reactions are important because that’s how the UO_2 dissolution rate is actually calculated. It’s from the current densities of three surface reactions that involve the dissolution of UO_2. And that’s calculated with Faradays Law.

So I’ve provided a current density equation for a single half reaction at the bottom of the slide. And I just want to cover some of the important electrochemical parameters, not all of them to show how our measurements relate to the model. So the parameters in red we determined from our electrochemical measurements either directly or indirectly. And then there’s the purple sigma term. That’s the fraction of the fuel surface area that contains the site where the reaction occurs. So we can control that by our SIMFUEL compositions. We know that the relative surface areas of the UO_2 matrix and the noble metals. And then the concentration of chemical reactants at the fuel surfaces in blue. So that’s … we can control that through the composition of our electrolyte solution.

So our electrochemical tests they use the standard three electrode system with SIMFUEL as the working electrode and they mentioned this method allows us to control the solution pH, chemistry and temperature. And when we determined the effect of one variable it actually involves multiple types of measurements. It’s not just electrochemical measurements, because sometimes the electrochemical responses aren’t enough to identify a mechanism. So the electrochemical measurements that we run are open circuit potential measurements where we measure the surface potential of the SIMFUEL over time. There’s potentiodynamic scans where we scan an applied potential at the SIMFUEL surface and measure the net current density and then there’s potentiostatic tests where we apply a fixed surface potential and then measure current density over time.

And we do characterize the SIMFUEL surface during the electrochemical measurement using electrochemical impendence spectroscopy just to see how the electrichemical properties of the surface change throughout the measurements. And then we do scanning electron microscopy coupled to energy dispersive x-ray spectroscopy or SEM-EDS analysis on the SIMFUEL material before and after we test in order to see how the microstructure changes. And we also look at the solution composition after our electrochemical tests. So we take samples and we measure the dissolved metal concentration. So we’re interested in dissolved uranium and also the noble metals. We do that using ICPMS.

And I just have one example of a type of electrochemical measurement that we run and I'm showing just one example of some interesting results, so it’s the open circuit potential measurements. And I like these because they’re relatively easy to understand and they provide insight into the stability of the SIMFUEL surface under the known exposure conditions. So I have two plots measuring open circuit potential which is just potential over time and it’s the same SIMFUEL material UO_2 which is the material that does not contain noble metals and it’s in air saturated solution or a hydrogen purged solution.

So as you can see in the plots the data kind of reach a stabilized value. So we run until we see that stabilized value. And you can compare that value to the threshold potential at which uranium-4 is known to oxidize to uranium-6 for the specific exposure conditions. And we can gain insight into the thermodynamic stability of the UO_2 under those conditions. So in the hydrogen purge solution the OCP stabilizes right on the boundary for U4 oxidation to U6. So that indicates that the UO_2 matrix of the SIMFUEL is actually stable under those conditions.

And in contrast in the air saturated solution that has dissolved oxygen the stabilized OCP is much higher than the threshold potential for U4 or oxidation to U6. So we know that oxidation is actively occurring. Also this OCP measurement is nice, because we can directly compare it to the E_{CORR} parameter that the fuel matrix degradation model calculates. And, finally, we use this OCP measurement to select surface potentials to apply when we run potentiostatic tests. So those are the tests where we apply a surface potential and derive the corrosion I guess. So since we're interested in oxidation processes because the UO_2 dissolution is an oxidation process, we select applied surface potentials that are above the stabilized OCP value. And these potentiostatic tests actually provide insight into the surface reaction kinetics.

Alright, so just to summarize what I presented we're running electrochemical experiments using simulated spent fuel and our goal is to quantify the effect of individual variables on surface reaction kinetics so we can identify mechanisms. And we do that by controlling the SIMFUEL composition, the solution chemistry and temperature and also the surface potential and some of our electrochemical measurements. And looking to the future. So our near term future electrochemical tests we aim to determine the effects of the concentration and composition of noble metal phases in SIMFUEL. So that’s why we made SIMFUEL materials with four concentrations of noble metals.

And then the effect of the presence of catalytic poisons in solutions. That’s related to the first bullet point, because noble metals are known catalysts, so what happens when you have a catalytic poison in solution? How does that effect UO_2 dissolution kinetics? Also dissolved hydrogen concentration in solution. So that’s what we’re actually looking at this year. And then the galvanic coupling between the cladding and the UO_2 matrix and noble metals in the UO_2 matrix.

And then we also have a capability to look at the effects of system temperature dissolved carbonate concentration pH and other solution chemistry parameters. But these four bullet points are the near term priorities.

Alright. So we would just like to acknowledge the other people that work on our projects. It's not just Paul and I. There's Bert at Sandia who's involved with the FMD surrogate modeling and Vineeth at Argonne National Lab who actually runs the electrochemical tests that I presented on. And then the references for the presentation. And we'll be happy to take any questions.

SIU: Thank you. Ron?

BALLINGER: The microstructure that you're showing on slide 12. How does that compare … that's for SIMFUEL?

THOMAS: Yeah, that's the SIMFUEL.

BALLINGER: How does it compare with actual UO_2 microstructure?

THOMAS: Yes, I knew this question was coming. It is different. First, we see the noble metal particles are like embedded in the

UO_2 matrix. And that does occur in actual irradiated spent nuclear fuel, but you see them also in the grain boundaries too in the actual irradiated spent nuclear fuel. But for this they are embedded in the UO_2 matrix. But it's useful for us, because we know that they're electrically connected. So we can see the coupled effects. And I know the grain size, you can't really see it in the SIMFUEL, but it's approximately the same as in actual spent nuclear fuel, like one micron diameter. And I'll note that they are a little less dense than the UO_2 matrix is a little more porous than actual spent fuel. But we do make all the materials the same way so we can compare relative effects.

BALLINGER: Because that little purple sigma makes a big difference.

THOMAS: Yeah. We have a good way of estimating the surface area of the noble metals, because they're nice and compact and flat. But we don't have a great way of estimating or measuring the solution exposed fraction, their surface area of the UO_2 matrix yet.

BALLINGER: Good work by the way.

THOMAS: That’s Vineeth. Vineeth does it too. It’s not just me.

BALLINGER: Tough work by the way.

THOMAS: Have a degree, yeah.

SIU: Other questions?

WOODS: Brian Woods, Board. Just to follow up on that question beyond like the porosity. Also there might be a lot of cracking and some irradiated fuels. Is this something that you may be potentially will look at, you know, SIMFUEL that doesn’t look a nice annullus or a nice cylinder?

THOMAS: I mean, right now we’re just focusing on those chemical methods that I presented on with the materials that we made. But I'm not really sure if it’s appropriate to use electrochemical methods to look at cracking effects.

SIU: Just to … so I understand the game plan here. At this point you’re not changing the number of parameters, particular parameters in the FMDM, but you would upgrade the values of those parameters, which would change your surrogate models. Is that correct?

THOMAS: Right now we're just validating how the parameters are already incorporated in the models, see if they're capturing what we see experimentally. But we are making a list of processes that could be included in the model. And I think the metric for inclusion would be having like orders of magnitude effect on the dissolution behavior.

SIU: That would again conceivably lead to more parameters which then now in your surrogate modeling you'd have to accommodate. Is that fair?

MARINER: Yeah. She is actually more of an expert on this model than I am. She's really gotten to know well the fuel matrix degradation model. So if she sees some ways we can improve that model she'll bring it up and we will look at it.

OGG: Dan, Board staff. If we could I'd like to ask a question of Dave Sassani. And also if possible could we bring up his presentation and go to slide 21? This is all related. But really this question is sort of addressing the big picture perspective on how this fuel matrix degradation model fits with everything the U.S. program is doing. And I don't know if we can get that previous presentation slide 21. Let me set the stage … and this gets some of Ron Ballinger’s question, again, getting big perspective. So the U.S. doesn’t have a repository so we’re not yet doing a performance assessment. We’re at the stage of developing the tools that may be able to do a performance assessment. So we heard yesterday as you’re developing your tools, you’re exercising them and you’re doing these reference cases. Yesterday when we asked about the crystalline rock reference case we asked what are you using for fuel matrix degradation. And it was basically a constant rate degradation, correct?

So now looking at your slide here you say fuel matrix degradation model at the top, the third sub bullet says the model is implemented into GDSA as an alternative to the fractional degradation rate sampling. So my question here is do you expect and plan now that FMDM will be a part of GDSA or are you just doing R&D now to evaluate the value of this model to see if, in fact, it is a good alternative to the fractional degradation rate model?

SASSANI: The answer is yes. And I'll break it down. So the safety analysis, the original intent of developing this model was for it to provide a mechanistic model for the degradation rate for these saturated systems. When we coupled it … it actually has been coupled as a FORTRAN code to an earlier version of the safety analysis. But when you do a system model, particularly the larger ones that are being done now it is the long pole in the tent. It's very slow to run it for every waste package in the system.

OGG: Understood.

SASSANI: So that initiated the surrogate modeling. But we also have the fractional degradation rate sampling. The real purpose of the model is to get after the mechanistic processes in various systems we're looking at with our expected evolution of those systems at higher temperatures under different conditions with very active potential corrosion once your canister fails as an alternative to assess these other variables, because in the literature and there are repository programs out there that have selected a range of rates and sample those and analyze those. They all reflect this very large effect of the hydrogen overpressure in those systems from the experimental work.

So we wanted a model that would span both the saturated systems and be able to go to oxidizing systems, because we were still looking generically, so we're still looking at things at a low level for like unsaturated alluvial systems where DPCs could have heat removal go on. So that model goes across that whole range. But it ties it to those chemical input parameters. So we're using it to evaluate the technical bases. It's not so much to evaluate the performance of the systems at this point, although the surrogate models reproduce it very well and are much faster.

But to do the detailed chemistry in an engineered barrier system we have some background work going on with like a 2D reactive transport model that represents the EBS components. So if you were going to do that to get ranges of locational performance, you might use this model as well.

OGG: Back thought to my bigger question for perspective, if and when this would really be used in a future performance assessment. My understanding is you still have a lot of uncertainties about this model. There are a lot of gaps in applying the model. There’s a lot of research to be done in order to prove that this can really do what you want it to do. And so do you expect there’s still a lot of filling in the gaps needs to be done before you really could apply this model in a performance assessment package?

SASSANI: There are gaps and then there are gaps in the barrier models. There’s gaps in this model and there’s gaps that are outside of this model that would be relevant to build in. But those are all like the cladding degradation model. We don’t have one.

OGG: Right.

SASSANI: That could help. But that’s not part of this model. It’s something that would go around this model.

OGG: Well, I thought the question of the cladding is one of the gaps associated with FMDM.

SASSANI: It’s one of the gaps we’ve identified. But it’s actually a separate model in the safety analysis and it would be done as a separate model, unless there was a strong coupling chemically, which Professor Ballinger has raised as an issue.

OGG: Right.

SASSANI: We don’t see that in the datasets that have been measured in the literature where cladding is in some of them and it’s not in others. We don’t see any discrimination there. So we think it’s mainly a physical barrier to flow into the fuel pin. Also with unzipping aspects that were evaluated in the Yucca Mountain project if you’re oxidizing the spent fuel you generally have a volume expansion, because the precipitates are much larger volume and this tends to unzip your cladding. So if you fail a fuel pin … so maybe the model of cladding would be when do you expect the first failure to occur. But if it unzips over a hundred years that’s essentially instantaneous on a geologic time scale.

OGG: Okay. This helps to understand the big picture a little bit better. Thank you.

SASSANI: Sure.

SIU: Bret?

LESLIE: Bret Leslie, Board staff. I'll too go to the big picture. So you primarily have developed GDSA, the fuel matrix degradation model using commercial spent nuclear fuel. If you were to include DOE spent fuel, which is quite a bit different and currently there's really no basis other than … simultaneous release. Would you develop different models, different technical bases? If you look at some of the radionuclides in DOE's spent fuel and you can go to our 2017 DOE spent fuel report, appendix two. It lists which radionuclides in the DOE spent fuel inventory, even though it's a small fraction it's 40 percent of the total inventory in commercial spent nuclear fuel. So you might come up with different things to do. So have you done that and is that a plan for, as you reevaluate the FEPs? Dave?

SASSANI: Thanks for the questions. These are good questions. So we have … when we were doing work on a defense only waste repository we actually talked about what the models for the DOE managed spent fuels would be. For any of the metallic fuels the models would be instantaneous degradation. It is … there's data sets out there and I've seen reports form within DOE's program that say, oh, well, it's not quite instantaneous, so maybe we should do more R&D on it. Well, a hundred years is instantaneous on a geologic timescale. It's highly reactive and it's because these metals are way below the lower stability limit of water. So they decompose water, rip the oxygen off it and degas hydrogen.

So for those models we pretty much know what the degradation rate issue is. But they would need to be looked at in FEPs more for the other impact of processes of gas generation very rapidly and how that would affect engineered barriers around canisters where you need a bentonite backfill around them. That may be a local effect. It may disrupt the barrier. And in such a crystalline system that's a different mechanism for taking out the bentonite barrier other than just corrosion from influx of very low saline waters, very fresh waters. So we would look at those. They are a small inventory. In fact, N reactor fuel is about 85 percent of the DOE managed SNF by mass. It’s a metallic fuel. So all the rest of them are kind of cats and dogs. But I know there are some ones that have particular radionuclides in them that don’t necessarily get thought about directly in some of these safety assessments.

So they’d be important to look at and think about. I don't know that they would be prioritized, and this is my speculation, not the Department of Energy’s, I don't know that they would be prioritized until we started going to actual sites and down selecting. But it’s certainly something that would need to be done.

SIU: Andy Jung?

JUNG: This is Andy Jung staff. I have two quick questions. The first fuel matrix degradation model still I'm not quite confident why do you need it? Because this is fundamentally for in corrosion area. Many researchers agree the theory itself. But there are lots of experimental data and have this try to study by utilizing the constant, the field degradation rate model already in Swedish or Finnish and other countries. And also this current FMDM only can apply to clay base and granite crystalline, not prototype on Yucca Mountain could be possible. But the long term prediction you may need some mechanistic theory. But still in the … Dan has already asked it, this model could be an alternative to fractional degradation rate sampling. So in your GDSA framework still their fractional degradation rate model is the conceptual? So FMD is kind of alternative process model and then … so I'm still … because this is the probably I'm guessing just the first attempt to use FMD for repository, the safety assessment, actually they applied it in this case. So I'm still not confident, because there’s a lot of the extent of work is required to prove.

And the second … for the experimental, the SIMFUEL because the actual, the high burnup fuel. The surface area is not very smooth. It’s very rough and have a microcracks and the void. So utilizing this simulated spent nuclear fuel, Sara said that actual the surface area ratio, which is not actually … is not quantitative yet. But surface area quantification is one of the key factors to apply to the actual … the dose consequence analysis. So is there any plan to how you can quantify the fractional release rate for considering surface area?

THOMAS: So there is a way to measure surface area using EDT analysis. But that's just gas expose, not solution expose surface area. We can look into it. But what we're really doing with the SIMFUEL testing is trying to identify mechanisms using SIMFUEL prepared the same way. We're just one variable is changed. So that's the motivation for the testing with SIMFUEL.

JUNG: Yeah. Another one is like if you have the rough surface… some locally deep area it has the solution to be stagnant, kind of some crevice effect could be another mode of the acceleration of the fuel dissolution too. So maybe you may also have consider how you can reflect some surface … to simulate actual spent fuel.

THOMAS: That's a good point.

SIU: Yes, please.

SASSANI: Dave Sassani, Sandia National Lab. So when we started putting safety analysis models together taking distributions out of the literature that were developed already and then sampling them within the safety analysis that’s very straightforward. We can do that. That’s what we’ve done. So there’s bases out there for those. In terms of the generic system and you’re right there, these are applied really only to granitic systems and to clay shale type systems. And that’s primarily because in salt systems they’re much higher ionic strength, they’re brines. But the reliance on the waste form lifetime is much lower because in impermeable salt things like iodine 129 are not going to transport as readily through very minor impermeable areas.

Now that’s a generic description of a salt system. If you get to an actual salt system you might have other features that could be transportable pathways and in an actual system you might want more performance from the waste form. But it’s not a priority for the generic salt systems. Just like waste package corrosion lifetime is not a priority for the salt systems either. The reliance is very much so on the reconsolidation of the salt around the canister and then having very impermeable salt as your transport pathway.

As far as what’s this in there for? It was after we looked at ranges of degradation rates and pulled some from the literature from some of the other programs we also went to the literature and looked at the datasets that those were based on and they primarily are driven by the delta in the hydrogen overpressure in the experimental work. But not in any fashion that anybody can identify the mechanism to. There’s papers out there that identify the epsilon particles, the five metal particle, noble metal particle phases in the spent fuel as catalyzing hydrogen reacting with the spent fuel and with the radiolytic oxidants.

Other papers identify it as a cathodic protection. Other papers indicate that you don’t need the epsilon phases at all. That it’s just simply the reduction in the electrochemical potential because of the hydrogen overpressure. We went and found Shoesmith’s work, which developed a mixed potential model, which is mostly what the fuel matrix degradation model is. It’s an implementation of Shoesmith, et al’s model with a coupled radiolytic model and it’s coupled in as an expansion polynomial of the radiolytic production rate of hydrogen peroxide.

It’s also developed so that it can go to much higher oxygen potentials. So those two modifications are what differentiates it from the mixed potential model developed by Shoesmith, et al back in 2003. So there wasn’t an enormous amount of work that went into … it took a while to figure out how to make them all couple together, but eventually we got there. And what drives the U.S. program in terms of heterogeneities or spatial variability depends enormously on the thermal loads and how those perturb the system and our perturbation tends to be much higher, that’s why we’re looking at much higher temperatures for bentonite stability and/or other higher temperature mineral buffers.

The U.S. program has much hotter canisters to consider much higher thermal loads, much more active perturbation to the geologic systems than most other repository systems in the world. So we thought about how does the degradation rate potentially vary due to those heterogeneities as driven by our engineered materials and these thermal perturbations. And if you wanted the couple in some kind of perturbed chemistry to the degradation rate of the fuel this is something that captures most of the major, if not all of the major chemical constituents that can affect that and the mechanistic aspects when we developed this back in 2011 to 2013 indicated that the hydrogen overpressure is absolutely the largest driver of variability to the model results.

So that identifying whether or not we could figure out electrochemically what the mechanism was, so that you could understand how to use it over long timeframes in these systems was the priority. And in about 2014 there was a program direction change, most of the work shut down. There was about a 100K a year that was going on for model tweaking and development, but no testing. And this only really started back up I think after FY 2017 when the budgets went back up. So we've been grappling with what is it that we want to do. Is there a series of tests that we can do that could definitely answer the mechanistic question?

We're not spending enormous amounts of funds or energy on this. But it's the only thing out there that we've seen that allows one to consider coupling it to the potential chemical variability of the waste packages in the system.

SIU: Okay. Thank you very much. And I think we don’t have any public comments. So thank you all presenters. Really appreciate the time and the valuable information. We will be meeting ourselves in cogitating over what we’ve heard. So with that, I think we’ll call the meeting closed. Thank you again.