United States
Nuclear Waste Technical Review Board

Transcript

Spring, 2024 Board Meeting

Tuesday
May 21, 2024

PUBLIC MEETING
In-Person and Virtual

Knoxville, Tennessee

PUBLIC MEETING
In Person and Virtual

NWTRB BOARD MEMBERS IN-PERSON

Nathan Siu, Chair
Ronald Ballinger

Tissa Illangasekare
Scott Tyler,Deputy Chair
Brian Woods

NWTRB BOARD MEMBERS VIRTUAL

Allen Croff

NWTRB EXECUTIVE STAFF MEMBERS IN-PERSON

Dan Ogg
Neysa Slater-Chandler

NWTRB PROFESSIONAL STAFF MEMBERS IN-PERSON

Hundal Jung
Yoonjo Lee
Bret Leslie
Chandrika Manepally

NWTRB ADMINISTRATION STAFF MEMBERS IN-PERSON

Davonya Barnes
Jayson Bright
Kimberly Brown

SIU: Thank you. Hello, and welcome to the US Nuclear Waste Technical Review Board Spring Meeting. I’m Nathan Siu, the Board Chair, and this meeting will focus on the U.S. Department of Energy’s Research and Development Activities related to the geological disposal, spend nuclear fuel and high-level radioactive waste in crystalline host rocks and on corrosion of commercial spent nuclear fuel after disposal. We’re holding this meeting in a hybrid format with a combination of both in person and virtual attendance by presenters. I’ll start by introducing the board members and then describing the board and what we do in very few words. I’ll tell you why we’re holding this meeting and then summarize the meeting agenda. I’ll ask that as I introduce them that the board members who are present raise their hands so they can be identified. We also have one board member who is participating remotely and I’ll ask him to unmute his device and come online and say hello when I introduce him.

So, just to begin, I’m Nathan Siu again, Board Chair. All the board members serve part-time and many of us hold other positions. In my case, I’m retired from the U.S. Nuclear Regulatory Commission. For the rest of the board, I’ll start with Ron Ballinger. Ron is Professor Emeritus of Nuclear Science and Engineering and Material Science at Massachusetts Institute of Technology. Professor Tissa Illangasekare is the Amax Endowed Chair and Distinguished Chair of Civil and Environmental Engineering at the Colorado School of Mines. Scott Tyler is Professor Emeritus in the Department of Geological Sciences in Engineering at the University of Nevada, Reno. And last but not least, of course, Brian Woods. Professor Woods is the School Head and Professor in the School of Nuclear Science and Engineer at Oregon State University. The person who's joining us remotely, a board member, is Mr. Allen Croff. He's a Nuclear Engineer and an Adjunct Professor in the Department of Civil and Environmental Engineering at Vanderbilt University. And I don't know if we can bring Allen up. No.

CROFF: Hello there.

SIU: Thanks, Allen, glad you're here. We have two board members, unfortunately, who weren't able to join us today. Steve Becker is a Professor of Community and Environmental Health in the College of Health Sciences at Old Dominion University in Virginia. And Lee Peddicord is a Professor Emeritus of Nuclear Engineering at Texas A&M University. At present we have eight board members, not the full complement of 11. Our other board positions are currently vacant and we’re working on filling them. Detailed information of our backgrounds can be found on the board’s website.

So, first of all, just to let you know that at all board meetings I want to make clear that the views expressed by the members during this meeting are their own and not necessarily board positions. Our official positions can be found in our reports and letters, which are available on the board’s website.

Okay, so who are we as the board? As many of you know, the board is an independent federal agency in the Executive Branch. It is not part of the Department of Energy or any other federal department or agency. The board was created in the 1987 amendments to the Nuclear Waste Policy Act to perform objective, ongoing evaluations of the technical and scientific validity of DOE activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste. Board members are appointed by the President from a list of nominees submitted by the National Academy of Sciences. And we are mandated by statute to report board findings, conclusions, and recommendations to

Congress and the Secretary of Energy. Meetings like today’s are an important part of the board’s review of DOE’s activities. The board provides objective technical and scientific information on a wide variety of issues related to the management and disposal of spent nuclear fuel and high-level radioactive waste that will be usable to policymakers in Congress and the administration. For example, the board technical and scientific observations and recommendations and letters or reports to DOE following our public meetings. All this information can be found on the board’s website, www.nwtrb.gov, along with board correspondence, reports, testimony, and meeting materials, including archived webcasts of recent public meetings. If you’d like to know more about the board, a two-page document summarizing the board’s mission and presenting a list of the board members can be found on the board’s website. We also have copies of the board’s mission and some recent board reports on the document table outside the meeting room. Maybe the table in the back to you.

Okay. We’ve posted the meeting agenda and presentations on our website and those can be downloaded. We also have a public comment period at the end of each day’s meeting today and tomorrow, obviously. Those attending the meeting in person and 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 just outside. And oral commenters will be taken in the order in which they are signed in. When making a comment during the public comment period, please use the microphone that’s available in the front of the seating area. Please state your name and affiliation so that you will be identified correctly in the meeting transcript. Also, for the DOE staff and National Laboratory participants, if you’re called upon to answer board questions, please use the microphone and identify yourself.

Public comments can be submitted during the meeting via the online meeting viewing platform using the comment for the record form. If you’re viewing the presentation full-screen mode, you can access the comment for the record section by pressing the Escape key. A reminder on how to submit comments will be displayed during the break. The board values these comments and we will read them as part of our deliberations after the meeting. Comments submitted online during the meeting will also be posted to the board’s website shortly after meeting adjournment. The time for each public 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. Comments, as well as any other written materials, may be submitted later via mail or email to the points of contact mentioned in the press release for this meeting, which is also available on our website. These submissions will be part of the official meeting record and will be posted alongside the meeting transcript and today's presentations on the website.

Again, this meeting's being webcast live and is being recorded, so you'll see some cameras around the room and depending on where you're sitting, you might be part of the webcast and the recording. A word to the wise. The archives recording will be available on the board's website by May 30, 2024 and the transcript will be available by June 25th.

Okay, so let's get to the meat of the meeting. This meeting is part of the board's continuing review of DOE activities related to the management and disposal of spent nuclear fuel and high-level radioactive waste. Over the past several years, DOE's been conducting research and development efforts on non-site-specific disposal of radioactive waste. DOE’s objectives in these activities is to develop a sound technical basis for multiple geologic disposal options, such as repository in argillite, salt or crystalline rocks in the United States. The aim is to gather necessary data and perform analyses to support decisions regarding its disposal research program. One of the topics of this meeting is disposal in crystalline rock formations. We’ll focus on laboratory and field scale studies are being used to support the development of numerical methods that represent complex processes in crystalline host rock. Explanation: crystalline host rock is a term for igneous rocks and metamorphic rocks in which a repository would be developed. Our review will focus on, first, DOE’s understanding of the processes that impact the barrier capability of crystalline host rock, and, second, how these processes are represented in DOE’s numerical models to help assess repository performance.

The second topic of this meeting will focus on corrosion commercial spent nuclear fuel after disposal. Our review will focus on the technical basis for DOE spent nuclear fuel corrosion models and radionuclide release and DOE’s approach in addressing the technical uncertainties and data gaps associated with this proposed corrosion model.

So, here's the agenda. We're going to start with the opening remarks by Tim Gunter from the DOE Office of Nuclear Energy. Then we'll hear from the National Laboratory of Researchers who are conducting the work for DOE. Dave Sassani will give an overview of research and development activities related to disposal. And this will be followed by a presentation by Emily Stein and Yifeng Wang on summary of activities related to disposal of crystalline host rock. After a 15-minute break, Pat Dobson will present geophysical techniques to characterize crystalline host rocks. He'll present a laboratory and modeling activities related to characterization of the excavated disturb zone to better understand its impact on flow and transport processes in the crystallin host rock. And then Matt Sweeney will present details regarding the numerical models developed to represent flow and transport processes in crystalline host rock. We'll have a lunchbreak from 12:15 and that will last for an hour. After the lunchbreak, Yifeng Wang will then describe activities related to processes in the bentonite buffer, such as erosion, coagulation, and clogging. And the next presentation also by Dr. Wang will describe laboratory, field, and modeling sties that address buffer behavior when subjected to high temperature and high pH. The final presentation for today will be by Laura Pyrak-Nolte from Purdue University. Her presentation will focus on recent advances in fracture characterization and representation of fractures and fracture networks in flow models. She’ll also discuss insights gained from her research experience. We’ll have a public comment period and adjourn the meeting around 5:15 p.m. today.

Tomorrow, we’ll resume the meeting at 8:00 Eastern Daylight Time, starting with a presentation by Erika Holt from VTT, the Finnish Technical Research Center. And also, Barbara Pastina from Posiva. They’ll provide an overview on current status of the Finnish Disposal Program and their presentation will delve into the flow and transport models that support the safety case for Finland’s deep geologic repository. They’ll also share insights into the technical challenges encountered in lessons learned during the implementation of the Finnish Disposal Program. Following their presentation, we’ll hear from Andrew Carpenter for the Nuclear Waste Management Organization. Andrew will provide an update on the Canadian Disposal Program. He’ll describe the site characterization efforts underway at the Wobegon Lake Ojibway Nation-Ignace site, which is one of the potential locations being considered for constructing a deep geological repository in Canada. After a 10-minute break, we'll have two presentations related to the corrosion of spent nuclear fuel after disposal. The first presentation provides an overview of the R&D efforts and international collaboration programs. That will be by Dave Sassani again and Brady Hanson. The second presentation will describe the implementation of the field matric degradation model and the geologic disposal safety assessment framework and electrical chemical testing by Paul Mariner and Sara Thomas. We'll have a public comment period and adjourn the meeting around 12:15 Eastern Daylight Time. That's tomorrow.

Much effort went into planning this meeting and arranging the presentations, so I want to thank our speakers for making the presentations at the meeting today. We also want to thank the speakers who participated in board factfinding meetings that were held last month in Las Vegas and in DC. The fact-finding meeting presentations will be available on the board website. Thanks to board member Tissa Illangasekare and Scott Tyler, who are board leads for the crystalline rock disposal, Ron Ballinger for leading the corrosion of commercial spent nuclear fuel after disposal. These board members and the board staff, particularly Chandrika Manepally, Andy Jung and Dan Ogg, for putting this meeting together. Finally, I want to give thanks to the DOE Offices of Environmental Management, Nuclear Energy and Science, and the numerous staff at Oak Ridge National Labs who hosted our excellent visit yesterday.

So, if you'll please mute your cellphones, let us begin with what I'm sure will be an interesting productive meeting. It's my pleasure to turn the podium over to Tim Gunter and let's get rolling. Tim?

GUNTER: Thank you, Dr. Siu, and good morning, everyone. Good morning to the board members, the board staff, and welcome to the participants here in Knoxville and also online. My name's Tim Gunter. I am the Director of the Office of Disposal and Research and Development in the Office of Nuclear Energy. Dr. Siu did a very nice overview presentation of what we do and what we're going to discuss today in our research in crystalline host rock and the purposes for why we're doing it. So, what I think

I’ll focus on briefly is our organization, we’ve had some recent changes. Some of them you may be aware of them, some of them you may not be. But we’ll go through that briefly. The first one on the title slide, Office of Disposal Research and Development, is my office. It was formerly the Office of Spent Fuel and Waste Science and Technology. So, you may recognize that name.

So, this is a recent work chart. It kind of just highlights some of the changes. There was a fairly significant reorganization throughout in the...but some of the changes that happened... Oops, let’s see. I’ll start at the top. Our Assistant Secretary for Nuclear Energy, Katherine Huff, recently left the department in early May. She returned to academic background at the University of Chicago, Urbana Campaign. So, she’s no longer with us. But Mike Goff, who is the Principal Deputy Assistant Secretary, is now acting for her. The other recent change you may know about is our DAS, Deputy Assistant Secretary, we had Paul Murray came in from Orano last fall. He’s now in that position permanently. Kim Petry had been acting on the temporary basis. And if you are familiar with our structure, we usually have codes, like the NE 8, 81 and 82 and now 83. Part of the reorganization added a new office NE 83, which is focused on consent-based siting.

So, I touched on the first bullet, what we were formerly and what we are now, Office of Disposal Research and Development. Basically, the R&D activities related to disposal continue on. There’s no big change in that and that resides in our office. Some of you may know or did know Ned Larson. He was my counterpart when we were team leads and he managed the research for the storage and transportation. He retired back in February. And as part of this change, the R&D activities for disposal and transportation... I mean, excuse me, storage and transportation are moving over to the new Office of Storage and Transportation, NE 82. And in general, our current R&D activities are being reevaluated, particularly as we go into planning for next fiscal year looking at the scope of what we’re doing. Paul Murray has challenged us to make sure that we have well-defined activities with trying to meet specific goals and answer specific questions and have specific timelines for doing that.

This is a chart that just kind of shows how things transitioned over. NE-8 at the top, there was a name change slightly from

Spent Fuel and Waste Disposition to Spent Fuel and High-Level Waste Disposition. I mentioned our office that was Science and Technology. We kind of split our responsibilities into disposal research, which is now NE 81, Office of Disposal Research. And the S&T went to NE 82, Office of Storage and Transportation. Kind of similarly, NE 82, which was Office of Integrated Waste Management, they did facilities and planning and also consent-based siting. These facilities were, such as the consolidated interim storage facility that we're working on, and other activities went to the new NE 82. And then the consent-based siting piece went into the new NE 83 Office of Consent-Based Siting.

So, I mentioned that some of the S&T, Storage and Transportation R&D that our office had been responsible is being transferred. Either is being or has been transferred to the Office of Storage and Transportation. So, I just put these... this is a few examples of the things that we had that are being transferred. You're probably familiar with most of them. The high-burnup demo cask project: that's a cask of spent fuel that we instrumented and it's sitting at North Anna Nuclear Power Plant on their pad. We had taken out some of the fuel rods for comparison in the future. They're now sitting at Oak Ridge and are at our PNNL, Pacific Northwest National Lab. The Road Readiness Project at DOE, Idaho, which is a demonstration project to package and prepare for shipment some of the DOE spent fuel and the high-level waste. And we got a Shaker table test going on in those spent fuel storage casks at the University of California, San Diego. That's coming up this summer where it'll be to evaluate the forces and potential changes to the spent fuel during vibrations simulating earthquake.

Other R&D is in transition. I mentioned we will be considering this in our FY 25 planning coming up starting this summer. And most of the S&T R&D will be transitioned to NE 82, Office of Storage and Transportation, by the end of this fiscal year.

This slide is not... I just wanted to mention a couple of things related to NEA, a couple of accomplishments we had recently. First is related to the consolidated interim storage facility. We did get what we call CD-0, Critical Decision 0, just a few weeks back. Which means that we are now authorized by the office... I mean, by the Secretary of Energy's Office to proceed with trying to design, repair, and site an interim storage facility. Now the Project Management thing, there’s a number of critical decisions steps as you go through Capital Asset Project.

The other thing I wanted to mention just as a resource for information is a couple of sites. This basically comes out of Storage and Transportation and Consent-Based Siting, but I thought it worth mentioning. If people are interested in looking for additional information later on, there’s a couple of sites you can go to, curie.pnnl.gov, which is a resource site for different reports, presentations, and general information related to what our offices do. And then specific to Integrated Waste Management, they recently published story maps, which provide... They’re a communication tool and they provide intro level information and visuals on spent fuel, storage and transportation activities again that our offices are responsible for.

So, with that, that’s the end of my presentation. I’ll be happy to answer any questions you might have.

SIU: Any questions from the board members? Okay. And, Allen, if you have any questions, just let us know. Otherwise, I think... Oh.

OGG: Hi. This is Dan Ogg with the board staff. Tim, thank you very much for the overview. My question is directed at the disposal R&D work. You mentioned that for now the disposal R&D work is continuing as it has been. But then you also mentioned that the program is under review. Can you explain a little bit more about who’s reviewing it and what is the timeframe for potentially making decisions about any changes in the program?

GUNTER: Yeah, sure. As I mentioned, our new Deputy Assistant Secretary Paul Murray, he has challenged us to make our R&D a little more defined and trying to address specific problems and identify the timelines. But he, along with our office, are doing an initial review on the disposal research activities. We’re having roughly biweekly meetings with him, depending on schedules, where I and the National Lab is responsible for the different program areas or discussing those activities with him. And he’s providing some feedback and then the actual decision will be made as part of our planning for FY 25. That will start basically next month and we will develop an integrated project list per week, list all the R&D activities and try to rank them based on priorities. And there’s always more R&D than we have funding for, so we go through it like a down select process. And I’m sure Paul will be a part of that too. And at the end of that we come out with the new program planned for FY 25 with funding levels and tasks.

OGG: And what’s the timeframe for that?

GUNTER: Well, I can say it’ll start next month and we always have to finish it before the end of the fiscal year, so late August, early September. And then that gets rolled into our project tracking. I think you’re familiar with it. PICS-NE, as we call it, integrated tracking.

OGG: Okay, thank you.

BALLINGER: This is Ron Ballinger, board member. These programs sometimes get a little nebulous. And I’m curious as to whether as part of the evaluation you’re going to be comparing value against the figure of merit for each of the programs. In other words, what are you trying to accomplish and why and things like that? Wil you be doing that?

GUNTER: Yes, exactly. That’s what Paul has asked us to do and that’s our challenge is to define pretty much for all our R&D. You know, to make sure we really understand what question we’re really trying to answer? What’s the purpose of that particular activity and when it will be closed or completed?

BALLINGER: Thank you.

GUNTER: Okay.

SIU: Okay. Thanks, Tim.

GUNTER: Thank you.

SIU: Next up is Dave Sassani from Sandia.

SASSANI: Good morning, everybody. Glad to see everybody here that I’ve known for a while and glad to see people that I’m just meeting for the first time. It’s always good to have new faces, particularly involved in this kind of work, which doesn’t happen overnight, in a few months, over a few decades, maybe it takes a century or so. But it’s good to be here. I’m Dave Sassani. I’m at Sandia National Laboratories. I’m also the National Technical Director for what was the spent fuel and waste science and technology campaign, which is now Tim’s program of disposal research going forward. I’ll be referring to the structure we have in place currently, talk a little bit to the changes. Tim did a great job covering what’s going on in terms of where we’re going and moving. I’ll mention that Matt Feldman, other National Technical Director for NE 82, is in the audience today. Matt is taking on a lot of the storage and transportation work, so it’s all being consolidated together over there. It’s an ongoing process, as Tim said. It will happen around FY ’25.

So, moving forward, I’m going to talk today about a high-level overview, the Disposal R&D activities, and try to cover putting that in context of where we’re going and possibly how we’re getting to that next stage.

I’ll go through an overview of the program, look at technical coverage, talk about some of the concepts, speak a little bit to the research development and demonstration aspects, cover a disposal program, the conceptual schedule for the program. And this provides the context for where we’re going, how we’re getting there, and how to attempt to assess how far along are we in a generic system? I’ll talk a good bit, spend some time on what capability, development, and demonstrations means. It’s very important to understand we are not doing safety assessments of any repository system at this point, so I’ll go into details there. Processes to assess the activity progress, how far along are we, where do we need to get to, what else is there to do, what’s the status? And I’ll talk about how we do that at a large scale with program planning, a couple of major events. We’re just entering the next one. Our five-year plan, which is a high-level summary guide to the work that’s going on and the technical work for disposal research. And then I’ll go into the geologic disposal safety assessment framework, how that works to track where we are. And our next stage with the roadmap reimagination. As I said, we’re just entering it, which is going back to a detailed features events and processes, bookkeeping for assessing where we are and where we’re going.

So, this is the structure of the program as it was. It's evolving. As Tim said, the Storage and Transportation work is moving along. Fuel integrity testing and analysis, thermal and drying, the dry storage stress corrosion cracking and the canister deposition field demonstration have been replanned. We're closing out their technical work packages this year and they will be involved in the integrated priority list, FY 25 planning, for activities moving forward going into FY 25. And others, we have some external load testing, seismic shake table test at UCSD that's going on this summer. And that dataset maybe collected this year and finalized. And so, we'll move forward as we evolve these moving over into the other area. There's a couple of areas: knowledge management and advance reactor work, that fall at the campaign leadership level because they involve both of these technical subareas or S&T research and disposal research.

What we're talking about today is primarily disposal research, which is now Tim's program in NE-81. So, this will kind of be a good kickoff for this transition we're going through. And in disposal research, we break this down into host rock investigations, argillite clay shale type rocks, crystalline disposal. Nathan did a great job introducing that. It’s both metamorphic and igneous rocks. And then salt systems. These are the host rocks. Then we have what we refer to as cross cutting investigations. These include the engineered barrier systems because they’re involved in each one of these areas. But also our international work, our evaluation of directly disposing feasibility for dual purpose canisters. Some of all the inventory work and waste form performance. Some URL support activities that we’ve been working through. And a key one, the geologic disposal safety assessment, which in all these programs, the safety assessment of the post-closure behavior of the actual system is where you want to get to. You’ll hear a lot of talks today that cover our crystalline work, some that cover engineered barrier systems in terms of the buffer materials and other engineered barriers in the thermal perturbations to those. And we’ll finish up with geologic disposal safety assessment tools and capabilities. Move forward.

So, this is the program’s strategic focus that was in place. And what we’re doing is trying to put together sound technical bases for multiple viable disposal options in the US for both the spent fuel commercial and DOE-managed and the high-level nuclear waste. These are some examples from Germany's program, Sweden's program, and France's program of salt, crystalline, and argillite repository concepts. We want to increase the confidence and the robustness of generic disposal concepts for the US. We are fortunate to have a wide range of geology in the US, so we can pick and choose potentially what types of host rocks work best. And in conjunction with the consent-based sitings program, it gives us lots of options to move forward. And our work is focusing on developing the science and engineering tools needed to support disposal concept implementation. That wide range of geologic disposal concepts means we have to prioritize the generic R&D for each, define complete enough, and utilize the vast international experience. This program that DOE's run has really brought the US up to speed with many other countries in their work areas. And we want to integrate the cross-cutting aspects. And we're focused currently on poising the program to leap into the next stage.

Well, what is that next stage? Where are we currently? This is a conceptual timeline for a repository program. We start with concept evaluations. This is where we are in this concept portion. And then eventually you move to developing siting guidelines, identifying potential sites, do some down selection, and then choose sites to do detailed site characterization on. That happened during the 80’s. We ended up with the Yucca Mountain site here. And once you get there, then you have detailed work that allows you to do repository design, submit a license application for constructing that designed repository in that location here in the US. And that’s where the Yucca Mountain program is still sitting off to the side.

The research, development demonstration initially focuses on analytical capabilities up here. That’s what we’ve been doing a lot. We also do think about site characterization processes. Those characterization aspects and operational demonstrations tend to increase later in a program when you’re at actual sites and particularly when you’re doing site characterization. But you will hear today some characterization methodologies that will be talked to in terms of geophysical techniques and a lot of the process work that we’ve been doing in terms of flow and transport and interactions of chemical and thermal aspects. So, we go from very generic to a final assessment and a final system. Finland’s program is getting ready to operate. Sweden’s not that far behind. The US, we are currently thinking about how do we get from here to the next stage?

So, this is some really basic stuff in our discussions. I know there’s a number of new board members. Not everybody is a geologist, geochemist, just like I’m not a nuclear engineer. But it’s good to learn about how the fundamentals work in a lot of these. So, this is really high-level. And as well as these public meetings, it’s really nice to be able to talk to some aspects that are very high-level. There’s a biosphere up here where we all live. Water goes into the ground. There’s natural barriers in the host rocks. There’s engineered barriers and waste forms that delay aspects. And then fluids can move away with radionuclides and may get back in aquifers. And so, that’s where we want to assess the safety. So, that’s a real nice diagram simplified of a repository system. And then walking through these boxes, this refers to the natural barriers and the engineered barriers basic functions. And we’re going along the waterflow pathway, so this way. And forward in time, starting with natural barriers that can prevent or delay water from reaching the waste form where the radionuclides are. The red boxes kind of indicate kind of the area right in the near-field around the waste package. So, you have engineered barriers that also prevent or delay. And slow degradation of the waste form itself limits its exposure to water and release of radionuclides are limited by that and also the water chemistry in the engineered system after the natural waters come in. And then natural and engineered barriers prevent or delay transport of those radionuclides along those pathways. The overall performance for different disposal concepts relies on these aspects somewhat differently. But the engineered barriers and the natural systems are all orchestrated to combine together to create better performance on the whole.

So, when you go into the details, we refer to the details as features, events, and processes. So, you’ll see the term FEP. A lot of people like to pluralize the term FEP, but these are already all plural. So, I say FEP. That’s just a nip on my part. Features are the physical components of the repository system. These are almost similar to system, structures, and components in a nuclear point type aspect. There’s processes also involved. And those phenomena that act continually over a long timescale. This is waterflow through the system. These are chemical reactions. They’re slow. They happen continuously. Events are phenomena that occur over very short timescale. They are events like a seismic event or an igneous event, something that happens over a very short time, but can have a magnitude of impact.

The FEP are evaluated and screened for either being included into or excluded from the geologic disposal safety assessment model of the system performance. That's our specific term. People refer to it as a system analysis, system performance model. It was the total system performance assessment on the Yucca Mountain project. These are the same things. This is a quantitative assessment of the whole range of potential behavior of the system over the system's timeframe being evaluated. It tends to be about a million years.

So, again, these are all the aspects going on here: features, physical aspects, components of the system, including the engineered parts, the processes and the events. And these are what we have to analyze to evaluate how do we build a model for this whole system to assess the safety of it. We're in the process of doing these. These are conceptual models and the implemented models, numerical models, and explicit models. This is the structure of the GDSA, the safety assessment where you have input parameters. You do uncertainty sampling and sensitivity analysis and there’s computational support to reduce that information and present it. The driving engine is a code called PFLOTRAN. This is the parallel of FLOTRAN, which is a code Peter Lickner wrote at Los Alamos after he was at the Southwest Research Institute where for the NRC, I believe he coded up a code called Multiflo. And so, this involves flow transport, some chemical aspects. And we’ve been building in all these different features, events, and processes into that to be able to evaluate a range of behavior of the system. This horsetail plot shows a whole range of evaluation. These are all capability developments at this point. We do demonstration analyses. And just to assess what’s happening in the model.

So, let’s talk about capability demonstrations. They are not safety assessments. We are not analyzing a specific repository system anywhere in the world. We take pieces from all the repository systems in the world to be able to see if we can represent those processes. Whether we have important features we need to add, etc., etc. But none of these are actual safety assessments. None of these are ready. They’re very early, in the early stages. We went through somewhere on the order of at least

10, 10 to maybe even 12 iterations for the Yucca Mountain project till you got to the point where you were ready to submit something to be assessed against the regulations. We are building the capabilities and process understanding that we need to be able to do this work and to be able to get to a place to assess the safety of a repository.

Some examples that are a little bit more familiar to people. Planning a huge dinner party not just for your family. So, you really want to do something special, right. You've got people coming that aren't the family members who can complain at you all they want if they don't like the food. So, what do you do? Well, you practice meal preparation until it's either enjoyable or at least servable. Right? So, you go to... You figure out some aspects you want to cook. You cook them a couple of times. You get better at it. You're doing that so you can do the actual dinner party. You iterate that cooking, refine the ingredients, your timing, the thermal aspects, the technique. You're building your capability to serve a huge dinner party.

Another example I thought about was sports. Athletics and/or arts, performances, like painting, music, dance. What do you do?

You practice, practice, practice. Not because you're going to this match or you're going to the US Open, but you want to build your skills, your know how, your understanding of what you're doing, your strengths, and refine your technique. This is what we've been doing.

Let's talk about good fortune, another possibility. You hit the lottery, you get a brand-new job with a big raise. You want to develop a new home. You want to plan a new home. You're not sure where it's going to be yet. It could be in the mountains. It could be at the beach. It matters. You might put different siding on those houses, but you don't know where it's going yet. So, you've got to think about where is it going to be? How big do you want it? How many floors and levels? What's the plumbing system need to do? What's the need? How about heating and cooling. Heating and cooling, cooling here in the summer is pretty important because of the humidity. You probably don't want to run a swamp cooler here like you can do in Albuquerque. And you want to think about the roof type. What kind of weather are you going to experience? Big hail? What do you want to do there? You're going to have preliminary, draft, and a final floorplan. Those plans are still not your new home. They are not your new home. You’re not going to live in any of those things. This is what you do in order to be ready to get the new home built. So, that’s our features, events, and processes evaluations we’re doing and also these GDSA capabilities and demonstrations. They’re all demonstrations getting us ready to be some point in the future at an actual site to do an actual characterization and do an actual safety analysis.

So, I talked a little bit about the phases of a repository project and a disposal research program. This is where we are. Starting out at the concept evaluation in 2012, we laid out a roadmap to prioritize the primary aspects we wanted to pursue. Then we had a program that was running for about... Well, these are two-year activities. This went from 2010 to 2012. This went from 2017 to 2019. So, they’re separated by seven years, but they’re two-year long activities to plan and prioritize the work. This roadmap started with a detailed FEPs analysis and prioritized those. And I should say, throughout this presentation, I have pieces where I’ve put links in. I’m not going to talk to a lot of the details of these two pieces. We had an NWTRB meeting, I think, in 2020 and there’s links thee where I did a whole presentation on that and also a whole another presentation on a five-year plan. So, I put links throughout, not just to NWTRB meetings, which are very useful, but also to some of the Sandia sites and some of the international sites where some of his information is readily available.

So, we want to go through to some point be able to start down selecting sites. We don't know when that's going to be. The wide range of disposal concepts reduces the challenges of being able to prioritize across the generic R and D and to find complete enough for getting there. But this is the timeline we want to move along just to keep it in mind. So, in 2012, we did the features, events, and processes gap assessment synthesis. These were detailed prioritization. Professor Ballinger asked about merit, figures of merit. There's a very detailed prioritization in there based on decision points along that timeline for an actual repository program. It's a multilevel attribute tool. It's immense detail. I know the folks that worked on it. We had dozens of people on the program do the prioritization actively. Very detailed to stand the program up. It came out with a detailed prioritization of the features, events, and processes for all these host rock types. Those got synthesized in the high priority topics with the campaign work planning. GDSA was one of them. The safety analysis was a big driver. And there’s a 2012 roadmap report. The 2019 roadmap update, the program had now operated for five to seven years. We had a whole series of activities in disposal research. So, those are what got prioritized for their progress. We did gap analysis. What was missing? And we also considered recent program direction. And program direction is two things. It’s DOE direction, which we’re undergoing right now with our new Deputy Assistant Secretary. And it’s also Congressional funding of the program. Those are the two pieces that make up program direction. They are external to the technical considerations of what needs to get done.

So, we did that update and we began that assessment in 2017. There was a final report. All the details are in there. And then we’ve since then, based on that update, developed a disposal research five-year plan. It updates, incorporates, addresses updated priorities on a two-year schedule. We have short-term primary objectives, one to two years because it’s relatively certain in terms of program direction changes, especially Congressional funding. And then there’s a longer-term vision, which is three to five years, which gives you a general guide of where things will go if no program direction changes. So, if program direction stays constant, this is reasonable. But right now, we’re in the midst of changing a lot. So...

BALLINGER: Is this on? I guess it is.

SASSANI: Yeah, you’re on.

BALLINGER: This is Ron Ballinger, member. I’ll restate the same question I asked Tim Gunter in a different way. Where is there a document going to be that defines what is good enough?

SASSANI: Well, that’s a great, great question, Ron. To me, what’s good enough doesn’t happen until you’re handing your license application to the regulator. But getting there requires a number of things that are essential: an actual site. For generic systems, good enough is we can reproduce other systems, specifics closely enough within the range of behavior that we can go look at other things that are important. I’m not quite sure when we’re going to have a document that quantifies that at this point.

Okay. So, here’s one of these links down here to the 2020 meeting. This is just a picture of the five-year plan cover. This latest one is from 2023. I believe we got that to the board in planning for this meeting. And it does provide progress updates. The first one was updated in 2021 from the 2020 initial because we wanted to add the progress updates. But now it’s on a two-year schedule for updates.

The GDSA framework also tracks information progress and capability progress in it. It’s based, it’s guided by the roadmap, the FEP analyses, the five-year plan, and also the international influences from our program. And the model capability decisions rely on readiness and prioritization considerations and it provides the status of the GDSA model capabilities. And this is just an example of a delta, which has from vaunted all 2012 a whole list of FEP aspects. The red ones have been incorporated at least to some degree into the current safety analysis. And then the black ones are FEP capabilities that are either lacking or excluded so far. So, something like effects from disruptive events, seismicity and human intrusion are not yet built in. And they tend to... The many excluded tend to be chemical, mechanical, and/or disruptive FEP’s, some of which are much more site specific than some of the other features, events, and processes.

So, where we're at with GDSA is we have... These are different pictures from our program: Argillite, salt, crystalline reference case. We also have a deep borehole reference case, which is not for the whole inventory of spent fuel in the US, but for specialized waste that the department may want to dispose of in a different manner. There was a deep borehole field test project that ended in 2017. DOE has funded this concept just to be stood up at a low-level currently. Again, there's some links on here to either the past end of the NWTRB meetings, international areas, and also some of our Sandia aspects for some of these. But that's where we're at at this point. We have these stood up. They're referred to as reference cases. That's nothing special other than we've put together a demonstration of capability with defined parameters. You can go find a report on it. We have a model for it. It's all set. And we have multiple reference cases. You'll hear about two of the crystalline ones later today.

So, back to the timeline. So, what we're doing now is we want to poise the program to enter the next stage. We're in here but we want to get to this point. We'd like to get out there and start doing siting work. Our Deputy Assistant Secretary is pushing on this. We need some go ahead external to the program in some ways, but we’re looking at ways to get there. But primarily to get there, I think, our big piece is to get the features, events and processes set up on the program to actually track these FEP in every instance in all the different generic systems. So, we are standing up a database or a FEP tool. We have lots of historical information on the features, events and processes. We have the reference cases for shale, crystalline and salt defined in earlier reports and possibly others in the future. There’s also a bore hole one that’s not on here. And we want to integrate this information so that a program management team can follow and have status right at hand of where we are at least with the features, events and processes. They’re tied to thrusts defined in the five-year plan. The reports of this pool support decision making by management and the database will provide the documentation of progress as we move forward.

So, the FEP tool is going to be use to organize, integrate, and status those activities. It’s going to be online. It’ll tie work activities to the program thrust and priority, priorities in the project. Each work activity will map to the detailed features event or process that’s being addressed. It’ll document any screening approach we have for including or excluding the FEP from the safety analysis. It will also have the intended approach or the approach for the intended inclusion into the safety and assessment and an estimate of time, effort to complete and an extent complete. This isn’t exactly what Ron is asking, but it is something that will provide a bit more directly viewable aspect for progress. So, that’s what it’s for, demonstrating progress towards the program objectives giving that status. It’s going to be used to continuously improve using updates to the five-year plan. And it will be the basis for our next roadmap reimagination going on. We’ve started early, but it'll be done by the end of FY ’26.

So, it focuses on work activities. The PIs will define their annual work activities via these aspects that are control account, activity name, implementation completion, level of effort. What fiscal year does it look like it’ll be complete? And the PI’s will map these to their thrust areas, to the roadmap update activities, and to the features, events, or process or sub-FEP. We expanded the FEP list. It’s around to the next level of detail, which were sub-bullets. And the results may support inclusion of that FEP into the safety analysis or it may provide the justification for exclusion. This will begin to populate these major checklists for each of the repository concepts. So, you’ll have a better clue about where are we. That may not be... That’ll be adequate to go to a site analysis, but you’re still going to want to modify based on site specific information and any specific repository design.

The system architecture has integration libraries that then speak to the various sub-libraries. These one for the safety analysis activities themselves and various host rocks, the engineered barriers, etc., etc. This is an example table. It’s the GDSA activities. They’re all ID-ed. It says what work package they’re in, what the name of the activity is. It gives a short description. And then this table is too long to fit on this screen for any readability. So, here’s the rest of it. These are the activity descriptions. These are the same rows. And over here, importantly, you have implementation notes for in the safety assessment, what the effort’s like, and how complete it is, and then some notes. The fiscal year that we think it will be done in and whether it’s completed or on schedule or having issues or whatever. So, these will be usable online and then every PI will also be able to get to see what other PIs are working on the same feature, event, or process. So, this should reduce overlap and enhance integration of the work. It’ll become integral parts of the annual planning. It’ll support the updates for the roadmap. It’ll provide the status for the GDSA model and the FEP screening. And this is for all generic repository types. And this is... Each generic repository type has a different set of features, events, and processes. It’s the same set of categories, but the way you treat it in a fractured system, your engineered barriers like your waste package, your buffer material, any backfill that goes in, these tend to be much more high priority to be able to represent appropriately in your safety analysis than would be, say, than in a salt repository system where you’re not that concerned with the source term degradation rate processes because the canister’s in a salt environment. Salt’s highly impermeable. This gets back to the relative behavior of repository concepts and their reliance on the natural barriers versus the engineered barriers for the suite of radionuclides. The radionuclides may rely... Some of them may rely more on the natural barriers than the engineered barriers, etc. Radionuclides that have very low solubility limits, things like the actinides, they’re going to precipitate out in any of these reduced anoxic systems. So, the natural system provides a huge barrier because they precipitate as solid phases, as well as absorb a little bit more readily. But that precipitation fixes them in place a lot. We'll talk a lot more about uranium deposits tomorrow. Some of those are hundreds of millions to billions of years old sitting there happy, stable, not moving. But for other radionuclides like chloride, iodide, selenium, technetium, radionuclides, some of the fission products that are not very low solubility, they transport. And so, they can actively transport. So, there you're looking at some of the natural barriers to prevent or delay that transport much more than the engineered barriers as we move forward. You'll hear some of this in some of the other assessments with the fractured crystalline systems. There are ways to put together a safe repository, but they differ depending on the concepts.

So, it'll give us the status for each one of these generic repository concepts and we'll at least be able to understand how close are we to being able to go and start looking at actual sites? And we'll also be able to identify the gaps, the places where we don't have anything and whether or not overlaps occur in our R&D program that need to be managed a little bit more efficiently and that will help improve the integration amongst all of our principal investigators, all activities will be apparent. And it should help make more efficient use of resources. That’s the hope. We have these FEP analyses in paper reports. But having an online tool where anybody can go in, any PI can go in and see where their piece fits in amongst all the other pieces that are working in that area should make things a lot more efficient.

So, I’m at a summary. And this is kind of important at the top. We have a program that’s shifting to disposal research and development focus. Currently, we’re within generic conceptual disposal system stage. Excuse me, allergies. So, we’re currently within this generic conceptual disposal system stage. The hope is to move to looking at sites at some point again in the future. As I said, we need some external help. Deputy Assistant Secretary Paul Murray is pushing really hard on this. Paul would like us to have something beyond demonstrations, more targeted. We’re not quite sure what that is. We’ve been putting together some large ideas of where to go in terms of the program efforts and integration. But capability, development, and demonstrations for our generic concepts has to move forward to poise the program to move to the next stage in about the next two years. So, we were planning to do this within the program already. The focus and the target, I think, is going to be a little bit different given our new Deputy Assistant Secretary Paul Murray’s input on this. It probably still will take two years to get there. That’s about the timeframe for replanning these in a concerted effort. And then we’ll be ready to go to whatever that next stage of the program is. The conceptual schedule, it covers multiple decades. Our experience from the Yucca Mountain project and the experience around the world in the international community makes our approach to this more efficient, probably cutting about 40% off of that. But the schedule for these programs, they cover multiple decades and the operational period is about a century. These are large undertakings and it needs to have direct public understanding, public support and public buy in and public volunteering for all of this work to go forward. So, we’ll use all that experience to efficiently progress through those stages. We’ll look at the processes to assess our activity progress. This piece to this point we’ve had that program scale roadmap, which occurs every seven years. It’s very detailed. But it isn’t necessarily a highly quantified set of criteria. I think I will talk tomorrow to some of that aspect in terms of the prioritization we’re trying to do for spent fuel degradation testing.

The disposal research five-year plan has the two-year focus and the three to five-year outlook. That gives us some idea of where we’ve made big improvements, but it is not something that statuses every aspect of the program. The geologic disposal safety assessment framework gives us currently great detail on what is the status of capabilities being built into the safety analysis. That’s an actual very key feature. Paul Mariner has done a great job with that. But what about all the stuff that is not going into the safety assessment? It’s still important to lay those features, events, and processes out at some level, even if they’re being excluded, to find those bases and then say, “That’s enough, move on to a different one.” Then that’ll be ready for somebody to pick up when you go to actual sites and say, “Oh, this was excluded. But for this site, we really need to do more to exclude it or we need to put it in.”

So, we want to move to this roadmap reimagination preparing for the next stage. The FEP database tool for the activity status, the prioritization, the integration and program efficiency, I think is something that'll help us get there. A number of folks may disagree with me and I'm sure there'll be some consternation with use and implementation of it. But we're standing up a prototype, hopefully, for some of the PIs to use this year.

And I believe that's it. So, I'll take any questions.

SIU: Thank you, Dave. I think I'll start with the lead organizers for the meeting and then we'll put it to other board members. So, Tissa or Scott.

TYLER: Sure, Scott Tyler with the board. Thank you, Dave, really appreciate it. Kind of a question on the FEP concept. So, some of the... And this may be maybe one step beyond where we are today, but those steps, analyzing them is going to require experimental data or data from the literature that's both generic and site specific. So, we'll focus on the generic side. What in the new FEPs approach, what's built into that to help you define where the experimental data gaps and the tools that you might need down the line for filling in those gaps? And I'm thinking, I know we're going to hear a little bit about some geophysics today.

SASSANI: Yes.

TYLER: So, thinking about what’s the next generation of geophysical tools we need and how do you build that into your process to make sure that gets done five years out?

SASSANI: Yeah, that’s a very good question. I think when we did the initial roadmap, the characterization tools were either a medium high or a high priority. That was one where we haven’t gotten a whole lot done. When I did the assessment before we did the 29 roadmap reevaluation, we did pretty good on a number. Safety analysis was one of them. Some of the engineered barriers and some of the site characterization tools, those we were behind a little bit on. So, when we went into the next roadmap reevaluation, we didn’t focus on the features, events, and processes. We focused on the activities we had. And this is collaboration amongst all the program PIs. We had meetings in Vegas over a couple of days to talk through what are the gaps. We did them by disposal concepts individually and then we came together as a whole group to walk through everything. So, the way we’ve addressed that in the past was the expertise of the

PIs saying, “Here’s what’s available that can be done now. Should we be using it or what’s the priority to start applying it?” So, I don’t think we’re ever going to get rid of that because the topical coverage in these areas is vast. And given the different actual concepts we’re looking at, you don’t necessarily use all the same tools in all the same places. So, we try to bring everybody together to talk through it and then come to some kind of consensus on where does it sit in terms of its usability versus what do we need to do and what’s the priority to do that now versus five years from now? Our Deputy Assistant Secretary Paul Murray has talked to me about is this something we need to do something in the next five years or the next two years to get somewhere in the next five years? Or is it something we can do 10 years from now? So, we’re looking at that timing aspect in terms of the prioritizations. The features, events and processes aspect once we get it stood up, will give us a direct indication of, you know, we did this on the Yucca Mountain project in ’97. A performance assessment group polled the science-based folks and asked, “What models are you developing and where do you think they’re going to be used?” And at that point in time, it was the first real specific and broadscale integration question from performance assessment to the technical bases. And one example was we got back 15 thermal hydrologic models that were being developed and every one of them said, “This is being developed to go into the TSPA.” And in performance assessment we said, “Well, that’s really interesting because we use two thermohydrologic models in TSPA and we don’t know what these other 13 are.” It wasn’t to say they weren’t needed to be done. It was just even the PIs were not sure where their work was going to get used. And it was fine to have a thermohydrology model to analyze and experiment in the field or in the laboratory. It was never going to be built into the safety analysis.

So, we’re hoping to see with this FEP tool whether we have... Here’s one feature where in the process it has 17 contributors working on the same thing. Well, how do they all fit together? What are they really doing? Are they really doing the same thing? Or how do we then figure out where to put those and where do they go? So, that will help us identify aspects where we have too much going on and not enough in other places. But we also will have them bring...and I’ll talk a little bit of this in the prioritization for SNF testing. What techniques do you have? Give me a one-page summary. It ended up being two pages. But a one-page summary of what questions are you answering? Why is it important to answer those questions? How does your approach answer that set of questions? Is it ready to go? When will it be ready to go? How long does it take? And how much does it cost?

We're actively starting to try to get definition of those capabilities that exist and whether or not they can be applied now or it's under development for two or three more years. So, putting together that list, I think, comes right out of the FEP list. It's still going to be interactive amongst all the PIs, but it will be more of an online effort that can go on all the time. And once we stand up the first round of everybody doing it, then going in and modifying and changing it should be very directly assessable.

TYLER: Thanks, Dave. I guess, yeah, somehow building in this capability that says, "I need to be able to measure this in the future across all the four different types of repository conceptual design or the repository environments," would be helpful. Throughout the process, always asking that question at this point. What can I measure and how am I going to make sure I can measure that in the future? The ones that are generic across all disposal systems would be the ones to start with, I would think.

SASSANI: And that would... That aspect is something we hope comes out of this, so that we can have it actually documented and usable as opposed to we're finding in our knowledge management, not everybody wants to go poll a bunch of big reports and read them anymore. So, we're trying to get a little bit more accessible in terms of all that information.

TYLER: Good. Thank you, appreciate it.

BALLINGER: This is member Ballinger again and I'll expand a bit on member Tyler's comment and beat a dead horse to some extent. And that is nowhere in the conversation we've had so far has anybody had to defend an inclusion and then ask the question, "What's good enough?" You see what I'm getting at. It's we know that corrosion's an issue, for example. Near and dear to my heart, I never met a corrosion program that I couldn't like. But how good do I have to be for the endpoint? That's the key question. And to ask a PI to defend that as part of the discussion process opens a lot of debate sometimes.

SASSANI: Yes, although I agree with you completely. It’s a little trickier to do it for a generic system because you don’t have all the other pieces built yet potentially.

BALLINGER: True. But member Tyler said that we can do it for each generic repository.

SASSANI: Right.

BALLINGER: Because the different... What’s good enough may be different for a different repository.

SASSANI: It absolutely will and what I tried to hit on was salt repository canister lifetime is not a big concern. For deep borehole, three to five kilometers down in the crust, we didn’t have any canister lifetime other than operational lifetime. Just to emplace it. Don’t even think about the canister. No waste form lifetime either. Because of the degree of isolation for the types of wastes. So, you’re absolutely right. We think about those all the time and we try to define them for those conceptual models. But you got to go dig to see it. And there are actual repository systems out there that are defining copper corrosion...copper outer canisters that have very long lifetimes because that’s what’s needed to have the safety confidence in the concept where you have fast fracture flow pathways. So, they’re out there and that gets to these different systems relying differently on the engineered versus the natural barriers or relying more on natural barriers for specific aspects...or engineered barriers for specific aspects.

BALLINGER: But, for example, in one of the repositories in Scandinavia, let’s say, they just make an assumption on the dissolution rate, period.

SASSANI: They’re not...

BALLINGER: For them that’s good enough.

SASSANI: Yeah, but they’re not complete assumptions. They’re based on data that have been measured. But I agree, yeah. And you can do a sampling like that. Unless you want to think about things like how does the chemistry of the system impact the changes to that rate, then you need to be a little bit more mechanistic. And I’ll talk a little bit about that tomorrow.

SIU: Tissa…

SIU: Do you want to use another mike?

SASSANI: Is it not turned on?

SIU: It’s on. It’s on. It’s on.

ILLANGASEKARE: Thank you for your summary. I understand your process you are trying to follow now is you are building all the tools and you are looking at this capable demonstration. But at the same time, you mentioned that US is in a way fortunate to have diverse possibilities. So, the approach you are using is basically to build the tools and when the time comes, then you are going to use these tools to look at getting away from generally looking at specific sites. That’s the process. So, my question is that while you do that, there are a lot of... Conceptually, you should be able to say even without models, conceptually, you should be able to say that certain things is not going to work. It’s like your example of the dinner. You know, certain guests never will eat this type of food. And so, I’m taking the example of the climate. For example, the climate will become a major factor. So, in a way when the time comes for the select real size, can you start eliminating, at a conceptual level, based on the experience of an international experience, to be able to say that certain areas may never work? So, that day you narrow the type or size which are available to you purely based on conceptualization as well as possible consent-based type of selection? So, is it too early to jump into that stage or are you going to wait for all the tools to develop, all the processes are there... When the time comes I'll go into these sites and do the analysis... But that's going to be a very large... You know, you have to look at various geologic conditions. That may be very challenging.

SASSANI: Okay. Well, I think what you're referring to is that next stage of siting guidelines. And I like to talk about guidelines. There are some things that are showstoppers potentially, you know, that a site would not work. You're not going to go put it in a pile of sediments out in the middle of Missouri. National parks, you're not going to put it in there, but that's by law and regulation. There's some consideration of population density. So, there are some narrowing ideas. And you said it, the process for consent-based siting, we don't necessarily want to overly constrain what doesn't work until we have an idea of where is it possible to put it. We know in these generic systems, and one of the things about generic systems is they always work really well because we think we wouldn’t be analyzing a system that didn’t work, right. So, generic systems by definition work really well. They have all the features, but they don’t have any “disqualifying feature”, which might be what you’re referring to. Working to identify those, you want to do it a little farther into the program and you would assess sites, volunteer sites and say, “This doesn’t look good because of X, Y, and Z.” And it would be based on the natural system. “And this one looks really good because of X, Y, and Z.” But I don’t know, in terms of eliminating sites right off the bat, you want to be very careful with this because until you go look at a site, you don’t know what its aspects are and it may have something you haven’t thought about, either good or bad to it. The conceptual aspects, you know, the deep borehole concept is a good one. The main concept part of it is it’s three to five kilometers deep for disposal. You have an enormous transport length scale, which is all diffusively driven. Looks fabulous. But if you go to a site and there’s fractures that are down in that location that could do fast transport to aquifer depths, that site doesn’t work. So, you have the aspects of what the site relies on for performance, the generic concepts. And if you saw something that impacted at an actual site, one of the major relied upon safety elements, you'd have to think long and hard about whether that site is acceptable or not. But I don't think you would do that until you get to the sites and start looking at them against the concepts. You'd have guidelines that would say, "Here are the things we're looking for that are positive aspects." You might have some disqualifying features, but I don't think you're going to come up with a litany of disqualifying features and just say, "Yeah, none of these sites work." But I mean, there are some out there. But I mean, there are some out there. I can see Bret wants to add. No?

SIU: Actually, I have a question first, but I think we're running out of time. But I'll get to mine and I think they're very quick. Dave, I think you mentioned that I think you're going to have the FEP tool fully implemented by end of Fiscal Year 2026. Is that correct?

SASSANI: Yeah, the FEP tool, we're trying to get a prototype set up for this Fiscal Year so people can...we can get a small group of PIs using it, so we can take care of all the issues with using it and then move forward and stand it up over the next year for all the concepts and start using it. So, by the end of FY ’26 was our planned goal. I think it’s in the 2023 five-year plan to get the whole roadmap reimagination done so we’d have another big report that documents all of that. So, the FEP tool we’d like to get complete next year so we can use it and get it populated by all the PIs in FY ’25 and into FY ’26 so we can use it as the basis for what are we missing? Where do we want to refine our understanding of capabilities being applied?

SIU: Okay. And so, that big report will be the public documentation of progress?

SASSANI: Yes. Well, I don’t know if you mean the FEP report.

SIU: Yeah.

SASSANI: The FEP tool is documented currently in the GDSA framework. Report that Paul gets done every year. So, its progress is in there. Then the actual roadmap reimagination will have a full report on all the prioritization that done, including how the FEP tool is used. And the FEP tool will be populated by that point.

SIU: The other question: on the excluded FEP, some of them looked like potentially big players, like human intrusion. When is that actually going to be addressed?

SASSANI: So, human intrusion is not necessarily excluded currently in these because human intrusion with our experience with Yucca gets kind of defined in a regulatory sense and the same with WIPP. So, that may be imposed in terms of the regulation. Human intrusion considerations are looked at a broad scale. And this is kind of how much does it matter that Ron’s asking about and what do you need? For sedimentary hosted repository concepts – clay, shale, salt, they tend to be drilled a lot for resources, for things like oil and gas. That gives you a tenfold increase in the likelihood of human intrusion occurring. So, it’s not the human intrusion scenario, but it is certainly the probability aspects of it. I don’t know... We know that we carry that forward with these concepts. Whether or not that would disqualify a site at this point is unclear because you need to define the scenario for human intrusion.

LESLIE: Yes. Bret Leslie, Board Staff. Just a quick question and it might be too long for the Q&A part. But how are both you and the FEP tool and DOE in its reprioritization looking at our recommendations from the generic repository 2020 meeting? We had four recommendations and yet I haven’t heard anything of how those board recommendations have played into how you prioritize what you’re doing.

SASSANI: Well, that’s a good question, Bret. And I’m going to have to go back and look at the recommendations and make sure that we do include consideration of those in that. To this point, you’re right. We haven’t been doing that. We’ve just been trying to put together the structure to do the reprioritization.

SIU: Chandrika?

MANEPALLY: Hi, Dave. Thank you for the nice presentation. I was wondering your thinking about this concept of digital safety case that other countries are considering and how it kind of plays into your capabilities building at this stage.

SASSANI: Sorry, I missed the part after you said “the concept of.”

MANEPALLY: Digitization of safety case or digital safety case.

SASSANI: Official safety case?

MANEPALLY: No, no. Digital. It means that you make everything on a digital platform so that other people can, you know.

SASSANI: Oh, gotcha.

MANEPALLY: Like for example I think Posiva is looking at it and I think even SKB. So, there are a couple of other countries.

SASSANI: The digital safety case.

MANEPALLY: Yes.

SASSANI: Sorry, my ears are slightly clogged up from my allergies. We’ve started talking about those. It’s, you know, we’re finding out standing up that this FEP tool is a large piece of work. When you’re doing all the generic concepts, it’s at least three times the amount of work of an actual repository program. But you’re doing it at a much higher level, so it’s a lot fuzzier. We’ve started talking about that. You know, we want to build a library of reference cases that could potentially be public facing that would allow people to look at a high level and then others to drill down if they needed to or wanted to. But that’s likely going to be one of the considerations moving forward in terms of having some of the R&D program develop tools that are a little bit more accessible, not just within our actual technical work, but externally as well. So, we’ve talked about it internally about that much.

MANEPALLY: Thank you.

SIU: Brian, I think I passed over you. Did you want?

WOODS: Yeah. I think I maybe have a real quick question. So, the GDSA, so you talked about your analogy about tasting a meal for folks. So, for the GDSA, what does that taste test look like? Are you going to wait until you know when you know you’re going to move from demonstration of assessment? Is it once we have a site, we're going to move to assessment? Or do you have like a non-sites kind of criteria that you're going to use for when it's ready to move over to assessment space?

SASSANI: Well, one of the better slides that shows that was the slide from which FEP from where 2012 assessment were actually built in. There are still pieces that are getting worked. So, I would say we want to use the FEP tool to then move the GDSA to the point where you would say this is pretty much for this concept, generic as it is. Good enough to move to a site. And you're still going to have to make modifications, but I think we would do that with each of the concepts moving forward. I view this next change, although we're in the process of a bigger scale change as well as the reprioritization. I view this as the next stage that gets us to the point where we can go and start looking at actual sites using the tools. Those tools still wouldn't be safety assessments because when you do site evaluation, you walk through the FEP process for that site. Generally, if you're looking at multiple sites, you'll start with just literature data about the site. And then you'd narrow down the sites. You'd high grade them and say these look the best. Then you'd go and maybe do some safety analyses and build the model for that site at a high level. It would be a part of a larger set of decisions for down selecting to an actual site where you'd do a characterization program. But we want to get to this next stage, get the program to the point where it could go and look at sites. That won't happen at the end of the reprioritization. There'll still be some work to do, but probably over the next five years. So, we would do it to the point where we would have a number of different reference cases. Once we start looking at actual sites, you would build, then you would think about the actual inventory the US has. Some of our reference cases look at different inventories. But it's, again, to do the capabilities. So, we would get these pieces to the point where you could go ahead and do it. I mean, you could start doing it at any point in time. You'd just have a little bit more work to get it up to speed, up to that point. And you'll see some of the analyses that get done. We generally use the readily transportable radionuclides or "fictive" tracers because those are the ones that really kick the peak doses in safety analyses. So, but we're building in all the other pieces as well to look at all the processes that make those the actual important ones.

SIU: Okay. Thanks, Dave. Emily? You’re up. And Yifeng. I apologize. We took a little of your time. We’ll see if we can make it up.

STEIN: Okay. My name is Emily Stein. I’m a Manager at Sandia National Laboratories. And I am the Control Account Manager for the Geological Disposal Safety Assessment Area in DOE’s Disposal Research Program. Today I am partially here in that role and partially also standing in for Chris Camphouse who is my colleague at Sandia and the Control Account Manager for the crystalline host rock R&D. This presentation will be split between me and Yifeng Wang, who is the Principal Investigator for crystalline host rock R&D activities.

So, I would like to begin with just a little bit of an overview of the context in which the crystalline host rock R&D activities are conducted. I will then talk about how our generic repository reference cases are used to demonstrate safety assessment capabilities and methods. And then I will hand the mike over to Yifeng who will give an overview of the objectives and R&D activities. So, R&D context first.

Crystalline host rock is one of the natural barrier systems studied in the disposal research program. As you have already seen, shale-rich rocks and salt rocks are the other two. Crystalline rock is a rock type that was identified early in the US Repository Program as a potential host rock. It is also a rock type that has been chosen in other countries as the host rock for spent nuclear fuel disposal. And those countries include Sweden and Finland, where Finland is in the process of constructing a repository and Sweden, their program has actually been granted a constructed license, but construction is yet to start. So, concepts for disposal in crystalline rock are well developed and let me tell you just a little bit about the characteristics of crystalline rock. First of all, you can see it in that picture there at the right. The closeup of that one fracture cutting through a very durable looking rock. So, crystalline rock has high mechanical stability. It has very low permeability where it is not fractured. And compared to the other host rock types, it has a higher thermal conductivity, which helps, of course, conduct heat from the waste packages.

There is also widespread occurrence in the US that are definitely multiple areas of crystalline rock. And those are some of the advantages of crystalline rock. The fractured nature of it poses perhaps the primary challenge in working in a crystalline rock. It is not possible to know where all the fractures are, so characterization of fractured media is one challenge. Those fractures present high permeability fast transport paths. And so, there can be a high reliance on the engineered barrier because of that. And then related to the fractured media characterization and the impossibility of knowing everything there is to know about any particular fracture network that will introduce uncertainty into your flow and transport calculations. And it can make model validation tricky as well. And when we speak of model validation, we're not speaking really of the total system model, but of models that are subsystem process models on a much smaller scale. So, possibly looking at inflow into a drift or the behavior in a single fracture when subjected to differing stress fields.

So, Dave has already introduced the idea of the disposal research five-year plan. On the right, you're looking at the cover of the 2023 revision. And this report is publicly available. It has not made it to OSTI yet due to an administrative glitch, but I'm working on that. And the crystalline R&D priorities are described in this report. And over the next couple of years, those priorities include improving the statistical sampling and representation of fracture networks. You will hear something about the methods for characterizing fractured rock from Pat Dobson later today. Investigating new generation of engineered barrier materials, particularly resilient types of clays and Yifeng Wang will speak about that this afternoon. And this idea of improving the representation of coupled thermal hydrological and mechanical processes affecting fracture transmissivity. And Matthew Sweeney will speak about this this afternoon. His talk will touch on that.

But to a large extent, the safety assessments that have been done for crystalline rock repositories have kind of made the simplifying assumption that the fracture network doesn’t change too much over the regulatory period. But, in fact, when you subject that system to glaciation, to isostatic rebound, to any other thing that could cause a seismic event or even just to the heat load of the waste packages and the potential for fluid overpressure, it’s possible that the transmissivity of your fracture network can change over time.

In this next five-year R&D segment, there will be a reduced emphasis on developing discrete fracture network models and that’s because we have a fairly robust capability for creating the fracture network models and for simulating flow and transport on that. And that is through two pieces of software: DFN Works, which Matthew will talk about some this afternoon, and PFLOTRAN, which is also the software that we use for safety assessment. So, the focus is shifting from that model development aspect to model validation and demonstration with field data. And, again, those model validation attempts are on the small scale from core and laboratory scale up to drift scale. And they rely very heavily on our international collaborations. And so, I’ll hit on just a couple of those in a couple of slides.

The crystalline R&D and, in fact, all of the R&D that we do in this program is really grounded in a very healthy and robust international collaboration program, which you may have heard about at previous NWTRB meetings. The international collaborations are a really important part of the program because they provide firsthand access to decades of experience from international partners. They provide our program with access to experimental data, both from past testing and ongoing in situ, that is underground research tests. They provide a framework for active peer to peer research participation with a whole variety of international groups. And you will hear about some of that international collaboration in the GDSA talk later this afternoon. Rosie will tell you about an international collaboration that we're part of there. They enable us to take part in underground research and facilities all around the world where we would not be able to carry out tests like that here in the US. And last bullet, really leveraging what has been a substantial and financial time and human resources commitment in other countries to development of these research facilities.

So, specifically, here's just a list of a few of the international collaborations that have benefited the crystalline R&D program. And they include a couple of full-scale heater and placement tests at the Grimsel test site in Switzerland. The first of those this Febex test, the full-scale engineered barrier emplacement experiment, which really demonstrated the possibility of emplacing the large, of emplacing the large waste package-like heater and the full engineered bentonite backfill around it that was fully instrumented to measure temperatures and water saturations. And it ran for 18 years. Right now, there is a new heater and placement test called HotBent. This one has been largely driven by the US, in order to look at bentonite performance at higher temperatures, as high as 200 degrees Celsius. And that, of course, is important when you start thinking about the large inventory of spent fuel in the US and the convenience of disposing of that in larger waste packages.

Another international collaboration has been with the Swedish Spent Fuel Management Company, SKB. There are a couple of taskforces that they set up specifically to look at process modeling. The first, for groundwater flow and transport of coelutes in naturally fractured crystalline rock. And the second, looking at the bentonite rock interactions. So, I know a couple of years ago, Hari Viswanathan spoke about the long-term diffusion experiment looking at fracture matric interactions and that came out of this SKB taskforce, the first one. And then the program has also participated in an experiment looking at the saturation of bentonite buffer placed in the fractured crystalline rock.

Another one, which I think Pat will touch on today is this deep drilling characterization project. So, this is for whole characterization looking at methods for identifying the open flowing fracture zones and the quantity of flow that occurs in those systems and also estimating the stress state in the subsurface. Another example is this DECOVALEX 2023 Task G, which is like belonging to a secret society. So, DECOVALEX stands for Development of Coupled Models and their Validation Against Experiment. Task G is an experimentally based task where a variety of research groups are running lab experiments to look at the effect of imposed external mechanical stresses, thermal stresses, and hydrological over pressuring stress on single fractures primarily. And the response of the transmissivity of those fractures to the applied stresses. And then finally listed on here is the Nuclear Energy Agency Crystalline Club, of which we participate. And that is largely a venue for exchange of information.

So, this slide kind of summarizes that context within which the crystalline host rock R&D occurs. At the top of the slide, we have the Disposal Research Program. Dave earlier showed you a slide with a blue list of all of the control accounts that exist in that program. This slide has plucked out just three of those control accounts that work very closely together to develop the technical basis for disposal in crystalline rock and that is the Crystalline R&D work packages that you’re hearing about today. The engineered barrier system R&D area because of the reliance of the fractured rock systems on the engineered barrier. That’s a very important collaboration. And then the international work that I just described to you. So, these three control account areas together provide the underlying fundamental science and the underground and other field testing that then allows us to develop process models and parameterize them. And ultimately inform the development of our safety assessment capability and the GDSA framework.

Okay. So, I will go on to tell you...just give you a very high conceptual understanding of what those safety assessment capabilities and methods are. And then Rose Leone and Paul Mariner will tell you more about our reference cases and simulation and analysis capabilities this afternoon. So, you have already seen this slide. I will perhaps spend a little bit more time on it than Dave did earlier. And what you’re looking at is a diagram of the software capability that we use for post-closure safety assessment. It sits inside of this big blue box labeled NextGen Workflow. And that is just representing the idea that we can automate the workflows in order to make them traceable, reproduceable, and more accessible to new people who joined the program. And then in this lower left, the biggest box, the simulation engine, is PFLOTRAN, which is a multiphase heat and fluid flow and reactive transport simulator. It is highly parallel, massively parallel. And we generally run it on supercomputers, but it also scales down. You can run this on your laptop or a local work station.

This is the piece of software that in addition to the flow and transport simulation capabilities, that it kind of came with, we have also implemented a number of capabilities related to source term and evolution of the engineered barrier system, specifically for use in post-closure safety assessment. It also has a simple biosphere model in it, which is just a well model with dose conversion factors. And it couples also to a more complex biosphere model that’s being developed at Pacific Northwest National Lab.

Up at the top, the piece of software that we use for uncertainty sampling and sensitivity analysis is called Dakota. This is an open-source piece of software. And I should have mentioned that PFLOTRAN as well is an open source and generally speaking all of this software, we're driving toward a completely open-source framework and that is for the purpose of making this both transparent and accessible to others. So, Dakota is the uncertainty sampling and sensitivity analysis software. We use a variety of tools, including DFN Works that you will hear about later for pre- and post-processing and visualization. And then in the lower right here's just an example of some of the results that you can produce using this software framework. And you can see in the upper left that you could do a single run and look at the 3D distribution of solute in the model domain, for instance. You can also do multiple realizations resulting in this horsetail plot on the right where you're looking at concentration at a point over time. And as well, you can look at plot- the values of input parameters versus your output of interest to understand to understand how those input parameters influence the output. And we'll come back to look at example results for the crystalline reference case at the end of this presentation.

So, what do we mean when we say reference case? This is a simple pictorial depiction of what a reference case is. In the center you’re looking at a model domain for one of our early crystalline repository reference cases. This model domain, I think it’s three kilometers long and about a kilometer and a half wide. It’s just over a kilometer deep. So, to give you some sense of the scale. You can see the repository is the square figure sitting towards the center of the model domain. And the components of the system that we’re modeling include source terms, both heat and radionuclide source terms. We look at actinide series decay chains as well as fission products in those source terms. The engineered barrier system is incorporated in there. So, we’re looking at primarily uranium oxide spent nuclear fuel, but sometimes other waste forms as well. The waste package, any buffer or backfill and the disturbed rock zone surrounding the excavation. And then the natural barrier system, which would include the host rock and any overlying or underlying lithologic units as well. In this case, it is a fractured crystalline rock as represented in that image in the lower right. And then as well, we need to consider what processes we’re going to model. So, all of our reference cases will include basically the processes that are shown on the right there, coupled heat and fluid flow, waste package degradation, and waste form dissolution, radioactive decay, and ingrowth solubility and absorption of radionuclides and advective and dispersive transport. And then this center image is replicated a few times to represent the fact that we’ll run multiple realizations propagating uncertainty to be able to quantify uncertainty in the outputs and also do a sensitivity analysis looking at which uncertain inputs affect the uncertainty and the output the most.

So, looking then at each of those three pieces of the reference case, the first is the natural barrier system. For the crystalline reference case, the concept is that you would choose an outcropping or sub cropping crystalline basement. You would want to find rock that is sparsely fractured and with a low topographic slope. And the reason for that is you will have a free water table and a flow within that water table would be driven primarily by the topography. So, lower slope means less driving force for flow. And that concept is consistent with concepts elsewhere in the world, particularly with the repositories that are going to be built in Sweden and in Finland.

On the right, you’re looking at what this might look like in the numerical model representation of the system. So, this is a model domain that Rosie will tell you quite a bit more about later today. And in it, you can see that there are both these large deterministic features that could be mapped in the field and you would have a pretty good idea of where those are and what their extent is, as well as a whole number, a very large number of smaller fractures that are described using probability distributions and then generated, sampled from those distributions to create multiple realizations of the system.

The engineered barrier system is drawn here very simply. And that’s because although there are many engineered pieces, for instance, inside a waste canister, there are only a very few primary pieces of the engineered system that we are currently modeling within the safety assessment. So, that includes the spent fuel itself, the waste package overpack, the bentonite buffer and the disturbed rock zone. So, a couple of important processes that we model include the rate control degradation of the uranium oxide spent fuel. And you will hear quite a bit more about that tomorrow, as well as rate control degradation of the waste package overpack. When that fails, we assume the canister is breached, radionuclide release into the 3D model domain can begin. And then, of course, for modeling radionuclide transport.

So, a little bit more about the rate control degradation of the waste package overpack. We have a fairly simply model in there for that, which mimics a general corrosion or could be kind of considered to be a general corrosion model. And that depends on this base rate or C, which is a canister material constant and temperature. We sample R from this truncated log normal probability distribution so that each waste package in the model domain actually has a different degradation rate resulting in a different breach time. And this kind of generalized model allows us to examine the effect of different waste package mean lifetimes on the behavior of the overall system. We are working toward implementing a bentonite erosion model in our safety assessment simulations and Paul Mariner will tell you more about that later. Bentonite erosion is a mechanism that, in the Swedish and the Finnish cases, can lead to canister corrosion. So, it’s kind of a special case because bentonite erosion occurs when fresh water infiltrates a fracture. So, you’re probably looking at a system that would experience glaciation in order for that to occur. But when the bentonite erodes, it then allows corrosive hydrogen sulfide to reach the copper canister and that can initiate erosion of the canister. So, this bentonite erosion model is tied to a mechanism for waste package degradation.

Okay. And then the final part of the reference case is this heat and radionuclide source term model. And this slide is just explaining some of the assumptions we use in creating that source term. For instance, this is not the only assumption that we’ve used, but for instance, assuming an initial enrichment, a burnup and number of years out of the reactor, you can then calculate both the radionuclide inventory and the heat of decay associated with each waste package. And so, on the left, you’re looking at a plot of decay heat versus time. And that arrow is pointing you to the decay heat at 100 years out of the reactor for a waste package containing 12 pressurized water reactor assemblies, which is one of the waste packages that we have used in a crystalline repository reference case. And then on the righthand side, you’re looking at output of our radionuclide release model. Commonly, the radionuclides that we will include in a reference case simulation are listed down there. Some actinides, including the decay chain starting with Americium-241 and also fission products. When we want simulations to run faster, we have, like Dave said, frequently taken the shortcut of only simulating Iodine 129 because with its very long half-life and mobility in the environment, that is the radionuclide that's mostly going to come through and contribute to dose at a down gradient receptor point.

So, up there on the top, the very top, you're looking at the canister breach model. So, in this case, the canister degrades and breaches at a thousand years. At that point, the waste form starts to degrade as well. And that green line in the top plot is tracking the remaining waste form volume. And then in the bottom plot, you're seeing radionuclide mass fractions remaining in a waste package over time.

And I think this is my last slide before Yifeng takes over. And I just wanted to give you some examples of what the output is from a GDSA reference case. This diagram... The picture at the bottom is just the top half of a sliced through the crystalline reference case model domain. These simulations were run in 2016.

You can see the repository is a series of little white dots down toward the bottom of that image. There is one...it’s colored by permeability. So, everywhere the permeability is a warm color, those are higher permeability areas. Those are the fractures. This red one is a deterministic feature and we’ve put an observation point marked by that yellow star at the top of it. And pictures on the left are showing you, first, the results for iodine concentration at that point as the function of time. With parameter variations, things like porosity of the buffer or waste package degradation rate variations. And then in the middle, you’re looking at a variation in iodine concentration at that point depending on the stochastic realization of the fracture network. And then finally on the right, you’re looking at a sensitivity analysis. So, these are rank correlation coefficients relating that maximum iodine concentration to various uncertain input parameters. And what you can see here is that the uncertain input parameters that in this set of analyses had the greatest impact on the iodine concentration at that point including the rate of the spent fuel degradation. And the permeability of a very thin sedimentary aquifer at the top of the model domain.

Okay. So, that was a quick overview of what a reference case is and the types of information that you can abstract from it. And now I hand this over to Yifeng.

WANG: Okay. I’m Yifeng Wang from Sandia Lab and technical lead for the crystalline work packages. And so, what I’m going to... Let’s see. Okay. So, we starting again with the list of the key characteristics of different media. So, Emily already talking about some of these characteristics for granite. So, I just wanted to highlight two key characteristics. So, one is the crystalline rocks, if not fractured, have usually have very low impermeabilities, almost impermeable. But in most cases, the rock usually is fractured to a certain degree so that make the modeling work or the characterization work for fractures quite interesting. And then second, we usually call the crystalline repository either harder rock in repository. That’s because the rock itself have very high mechanical strengths. So, that created a high stable cavity. And then inside of the cavity you can maintain the integrity of engineering system for long, long time. So, which is very important because in crystalline repository there is a possibility for a fracture intersect the waste packages. So, in that case, engineering barrier system will play very important role in waste isolation as natural barrier system.

So, basically, a high level repository system will consists of a near field engineered barrier system and also then is surrounded by far field. Another key process considered will include waste form degradation and waste package degradation and then the radionuclide transport across the EBS into the fracture far-field and then all the way to the biosphere. So, the whole purpose of the crystalline work package is to an advanced understanding of the long-term disposal of spent fuel in crystalline rocks, which includes granitic or metamorphic rocks. And the develop mostly experimental and the computational capability to evaluate various disposal concepts in those media specifically so those will package develop detailed process model to support GDSA teams to developing a robust repository system level performance assessment code. And also to provide the model input parameters to GDSA. And then for this work package, we have to leverage the international collaborations. And also, we closely coordinate with work packages for other media just to make sure the data used like thermodynamic data used will be consistent across other work packages.

So, the current activity heavily focused on two areas. One is just to better characterization understanding of fractured media – the flow and transport in those media. And then second, to providing technical basis for designing effective engineering barrier system for waste isolation.

This is the list of process models we wanted to develop. This process model included the innermost barrier, which is the waste form degradation. And then waste package degradation and then include the buffer material in performance. And also, the radionuclide transport through the backfill layer. And then into the DRZs. And then eventually this radionuclide release was transported into major fractures in natural media, in natural barrier system and then all this will be put together and then to predict the radionuclide release in biosphere. So, this model will be developed for different level of fidelities to the underlying physical processes. Those arrows basically indicate the coupling of the data feeds between the different process models. And, of course, to incorporate this process model of course, to incorporate this process model into a GDSA system is sometimes is quite a challenging because sometimes it’s not computationally feasible to incorporate it in the high-fidelity model into a GDSA. So, what we usually do is to streamline those process models to simplify them as much as we can and then to incorporate some key aspects of this model into a GDSA. So, eventually, we hope we can build energy in the GDSA model and then to predict the performance of all disposal system as presented in horsetail plot.

The next two tables kind of are a chart. So, this is the list... So, to support the development of process models, we formulated our tasks into 16 or 17 tasks. So, those tasks are formulated and based SFWST roadmap and also based on five-year R&D plan. So, just to help you to get the feeling about the status of those tasks, I color coded them. Sorry, the label for the yellow one is missing. Yellow one means that's insufficient. Then we wrap up activities and some of these results can be directly available for incorporated into GDSA. So, we have two areas which we already completed most of the research, which is fracture matrix diffusion and the colloid transport in fractures. And then we also made quite a significant kind of progress. For example, in discrete fracture networks and also the flow and the transport in fracture networks. And we collected quite a significant amount of data through international collaborations. For example, through the DECOVALEX project from different URLs from different countries.

And, again, this is also we make significant progress and evaluate the spatial heterogeneity of radionuclide transport. And also, we're making quite a bit of progress in evaluating the thermal limit of buffer materials and then develop a new buffer materials for high temperature in harsher environment in applications.

So, this is just the highlight of the work I just show you. So, we developed for fracture modeling fracture inflow and transport. We're developing whole workflows, starting from the field data and then we synthesize the flow of the data into fracture distributions. And then we generate fractures from those distributions. And then we can calculate if we need like the effect of permeability for the whole physical domains. And, again, we complete the work related to the matrix diffusion. So, a team at Los Alamos tested their model with the SKB data. So, this part of the model or data can be already available for incorporation into GDSA. And then similarly for colloid-facilitated transport model, I think, the model is already available for GDSA incorporations. And then for buffer material and development, we will talk more in this afternoon. Basically, we show maybe there’s a good chance that we can raise up the thermal limit for the bentonite and buffer materials. And also, we find in a new material that it maybe performs better in some disposal environment. And also, another interesting work that then at Lawrence Berkeley Lab. And they found actually bentonite swelling and extrusion into fractures that can significantly reduce the fracture permeability, which is very important for waste isolation. And then we’re also developing a modeling approach based on machine learning to predict some dynamic properties of chemical speciation and surface sorption. And here for chemical speciation use this approach. We hope we can move beyond the current approach, which is approach, which is Pitzer model and more that we can move beyond that in Pitzer models. And then we have also significant understanding has been obtained for fluid flow in compacted bentonite. That is in low permeability deformable media. We’ve made quite a significant progress there. This is just a plot showing the column experiment data with crushed Grimsel granite rock. So, this is the breakthrough for different radionuclides for the colloid and then the solid line is the multiple site model developed by the team at Los Alamos. You can see the model can fit the experimental data very well. So, this model is already available for GDSA implementation.

Okay, so, to summarize. So, crystalline is one of the natural systems that has been studied in spent fuel waste disposal research program. The crystalline repository reference case is we demonstrate the safety assessment method and then drive the capability development and then advance our understanding of the whole generic system behaviors.

So, basically, the crystalline rock R&D and integrates host rock and the engineering barrier system studies to advance process understanding and then to inform development of safety analysis capabilities. I think that’s the last slide. Yeah. Both Emily and myself are happy to take questions.

SIU: Okay, there we go. We ran a bit long on the questions to Dave, but we’ll try to... We’ll give you guys a few more minutes, get lots of a few more minutes honestly. And maybe we’ll eat into the break or maybe we’ll start a little bit later in the next section. Tissa and Scott, I guess you guys have –

ILLANGASEKARE: Yeah, in your GDSA safe framework there’s no task in trying to determine the data value. The reason I’m asking this question is when you go to the field, especially you will find situations where the model has to be validated to some extent. So, in theory you could do everything within your reference cases. You can in theory do some analysis to determine where is the data value. For example, in a fracture system the main challenge is in finding the information to validate the model. Have you thought about that idea? And which state of this process you bring in this idea of data in validating modeling the field system? And really because you’re using field data for the larger system models now. But I know in the GDSA framework you don’t have that. But where does this fit in your thinking in the long-term?

STEIN: Okay. So, that’s a great question. And I will basically answer it with to the extent we’ve thought about it. So, you’re correct that we are using field data now to develop those crystalline repository reference cases. And the way in which we’re doing that is basically borrowing the statistical descriptions of the fracture networks from both the Swedish and the Finnish programs. Those fracture network descriptions were developed from field data. And largely, they were developed from the down hole flow logging techniques that Pat is going to touch upon later this afternoon. But in translating that type of measurement into a description of a very large-scale fracture network, there is a modeling step involved. And that involves basically generating different fracture networks and optimizing them until you are doing a good job of matching the flow data. So, that is the type of data incorporation exercise that we could be doing with our GDSA tools. In fact, when we started the DECOVOLEX performance assessment comparison task four years ago, there was somebody in the group who insisted that was exactly the type of exercise they wanted to do. And I resisted that because I wanted that task to be about comparing different modeling approaches when you already know what the underlying system description is. So, the idea has come up. It would be possible to pursue it. It isn’t something that we’ve done yet.

ILLANGASEKARE: Just a comment that up in carbon sequestration, for example. They don’t have any data on site which has leaked.

So, what they are looking at this data models like you have pretty sophisticated than lot of many things and see that they can get a hypothetical scenarios, so a possible design of monitoring systems. I don’t know where in your process this comes in, but eventually that has to be done. I was just asking the question have you been thinking about it. It seems like you have been thinking about it. Thank you.

WANG: Yeah, I just want to add to what Emily just said. For the larger scale model validation. So, we did a test of a larger scale fracture network flow and transport model against the data collected from Japanese Mizunami site. I think that give very good. Actually, we show we can predict the tracer or inflow and behavior as the excavation proceed. So, yeah, so just added to that.

SIU: Scott

TYLER: Yeah, Scott Tyler, member of the board. Just maybe a higher-level sort of question and comment. This meeting is about crystalline rock repositories and I think it would be helpful for all of us and to the public also to have a definition of crystalline rock. We are all engineers sitting at this table, but I happen to be in a geologic sciences department at home. And there are a range of crystalline rocks out there, both volcanic and igneous rocks, metamorphic rocks. And yet we sort of talk around and I've seen in some of the presentations granite. I think it would be helpful to the public and to us and to all of us to think about what are the range of crystalline rocks that we are interested in studying, that we think are appropriate? And there is a wide range of them out there and just being clear that they're low porosity, high strength, low fracture density rocks is kind of what we're looking for. So, it's just a kind of a comment from the geological sciences side. And I'd be curious to hear if you agree, disagree, that's fine, but just a thought.

WANG: Yes, yes. So, there's like a wide range of igneous intrusions. So, first of all, we need to look at the igneous intrusions. For those like volcanic rocks. I mean, that's high in fractured, so maybe not, is not a good choice for repository. So, we look at the granite rocks. And also, I think another possibility is highly metamorphic rocks. That I think may be even better because of the structures. It's really harder to develop kind of continuous fracture through metamorphic rocks.

So, that’s maybe a good lithology to look at. Yeah. That’s in a wider range of igneous rock, but mostly like granite or something closer to granite. Intrusions, massive intrusions.

STEIN: And I just want to agree with both of you. Your description is low porosity, is sparsely fractured, and it’s competent. It has high mechanical strength. And when you go look for what rock that is, it’s what Yifeng discussed.

TYLER: I would agree, but there are igneous intrusive rocks that are not granites. That are also gabbros, diorites. And they are also low fracture density, low porosity. So, just thinking a little bit broader, I think, helps all of us understand what a crystalline rock repository would look like and opens up the map of the United States and other places where these kinds of environments are, as opposed to any rock.

STEIN: Yeah. And I think we’re using granite in the non-technical (unint.). We did not define it based on silica content.

SIU: I have questions I think maybe I should put off till later because they are not necessarily crystalline rock specific. But, for example, Emily, your slides show the next gen workflow. And I’m wondering for this decades-long enterprise, there are definitely going to be technological developments, changes. And the extent to what you’re thinking about and you’re planning, what tools you have now, what tools you will have maybe later anticipating these kinds of changes.

STEIN: Yeah. So, I think that’s a great question. And it is definitely a thing that we are constantly thinking about and aware of. So far, our approach to kind of remaining current in simulation analysis methods, also in software and hardware tools is to use these two pieces of software, PFLOTRAN and Dakota, that have very active development communities with people who are constantly driving new capabilities and new approaches. Because we’re also keeping up with the high-performance computing changes occurring at Sandia, we’re kind of in a position of being forced to keep up with kind of modern computing hardware. But you’re absolutely right. There may be a point where instead of doing these incremental updates to keep up with state-of-the-art, that you’re suddenly thrown into a place where maybe you’re doing quantum computing. I don’t know. And a completely different piece of software. But I think that’s why it’s important to have an ongoing active kind of vibrant development community to always be pushing the boundaries in order to attract new staff, right, who are excited about the next big thing and new technologies. I would say that one example of that is incorporating machine learned surrogate models into the safety assessment. And I’m sure there are others. My brain is going blank right now. I have heard other people in other programs speak about using digital twins in the same way. Like in the 80’s, the 90’s, WIPP was certified without any digital twins. Yucca Mountain didn’t use them. But in order to keep the kind of up to date with where your reviewers or your stakeholders might expect you to be and in order to attract kind of best and the brightest, it’s really important to keep up with advancing technology.

SIU: Any other board questions?

CROFF: None from Allen Croff.

SIU: Great. We are only five minutes behind. Let’s take a break and reconvene at 10:45. Thank you.

[BREAK]

SIU: Okay. Our next speaker is Pat Dobson from Lawrence Berkeley. Pat?

DOBSON: Okay, thanks very much. I’m a Research Scientist at Lawrence Berkeley International Lab. And one of the other hats that I’ve been wearing over the last number of years is also working as a geologist for our geothermal research program as well. So, I think that there’s a lot of overlaps between the work that we do, characterizing the subsurface for looking for geothermal resources and also for evaluating the appropriateness of crystalline rocks for nuclear waste repositories. I just want to call out thanks, special thanks to Liange Zheng, who’s the lead of our nuclear waste research program at Berkeley Lab, Chun Chang who some of his work I’ll be showing today, Chris Doughty’s work at the CO2 Portal, and our EGS collab team looking at geothermal research. This is a team that had 10 national laboratories and 8 universities participating in that effort.

So, some of the key questions that we wanted to sort of address in today’s session was looking at what are the challenges for and what are the opportunities of using geophysical techniques for characterizing subsurface repository rocks? And we’re really trying to deal with these rocks. As we’ve mentioned, there’s a variety of different rock types. They have different types of geometries. They’re not nice layer cake sedimentary sequences. And so, how do we evaluate their nature and their distribution? And then also can we image and characterize fractures, which are really a key component as we heard from previous presentations that are critical for developing the safety case? Are there lessons learned that we can apply from other investigations, other uses of the subsurface. And they could be for carbon sequestration. They could be looking at geothermal resources, looking at oil and gas expiration of the subsurface. Now we’re looking at hydrogen. A variety of different uses of the subsurface. Can we use tools that have been applied by these other groups and apply them for evaluating crystalline repositories? And geothermal is really a good analog because in many cases, it’s also looking at resources that are hosted in crystalline rocks.

And then the final question is what are the scales that we really need the data? And I think some of the questions were posed earlier. What is enough? And what level of detail is needed for the types of modeling and assessments that we’re going to be doing? So, we can look at large-scale features that are pretty easily resolved using surface-based geophysical techniques or we can look at really small-scale features. We’re looking at fractures, the damage zone in excavation areas that are going to be more easily detected using approaches that are closest to what we’re actually investigating. Those will be using borehole techniques or techniques within an underground research laboratory.

So, there’s a wide range of different types of tools and talking about technical innovation. Some of these tools are currently being approved and developed upon. We have lots of seismic techniques that are used, both active and seismic techniques. We have traditional reflection seismology that’s used often in the oil and gas industry for looking at the different sedimentary strata and looking at structures. We can really use these to capture big scale features, such as major faults and basins types of features. We can use, if we have a borehole, we can use vertical seismic profiling, crosswell seismic as well between multiple boreholes. A lot of techniques we can use are also passive in nature. We don’t have to apply a seismic source signal. We’re using sort of natural seismicity that’s present using acoustic emissions. We can be using ambient noise sensing and just seismic monitoring of natural seismicity within a region. A lot of other actual techniques are very helpful as well. These are looking at contrasts and the electric conductivity of different materials such as brines or of rocks. And so, we can use a couple of different techniques: time-domain electromagnetics and magnetotellurics. And then at a project, the EDS collab project, we used electrical resistance tomography, both as sort of a characterization and as a monitoring tool. We can use potential field methods, such as gravity and magnetics for assessing changes in rock properties that are going to be able to help map out the distribution of these different bodies. And then fundamentally, one way to look at it is small scale, we use borehole logging techniques. So, we can measure changes in temperature, changes in resistivity. We can look at the porosity and using neutron density, we can look at changes in the rock composition using gamma logs. We use televiewer logs for looking at identifying fractures and stress indicators. And then we use full waveform sonic logs as well, for getting the changes in rock properties. And then the more modern techniques that we’ve been applying are different fiberoptic sensing techniques. And these include looking at changes in moderating temperature looking at DTS. Looking at acoustic sensing using fiberoptic sort of as seismometer and we can also do strain sensing as well.

And this cartoon that you see on the righthand side is just a cartoon that was developed by a research team led by Pacific Northwest National Lab for one of the earth shots that DOE has funded. This is focusing on the enhanced geothermal system earth shot and it’s really looking at the fundamental differences in scale for different types of processes we’re looking at. And there we’re trying to look at fluid flow and fractures for being able to transmit and extract heat from hot rocks in the subsurface. So, we’re looking at from the pore scale to the fracture scale to the reservoir scale and trying to identify, you know, what levels of information do we need to put together to build a comprehensive model to properly assess the potential for developing these enhanced geothermal systems?

So, going back, I’m just going to go through each of those different types of geophysical techniques that I highlighted in the opening slide there. And this is looking at seismic methods. And these are looking at some concrete examples from the US Department of Energy’s Frontier Agency, the FORGE site, Frontier Observatory for Research and Geothermal Energy. And it comes off the tongue like that. But it’s a site located in Milford, Utah. It’s located in a Mesozoic granite that is tertiary...and there’s tertiary volcanic rocks in this area as well and quaternary volcanism in this area. There’s an active geothermal system, the Roosevelt Hot Springs Geothermal System. But on the other side of a fault, you have basically no evidence of active hydrothermal circulation, but you have hot rocks. And so, what has been done in this area is to tap into those hot rocks and to develop a geothermal resource as a testing facility.

And so, the upper image on the right is a reflection seismic profile and it sort of delineates two different things. One is just looking at the basin sediments. And then the yellow line is depicting the lineation between the sedimentary rock sequence that’s overlying this older granitic intrusion. The bottom figure is a VSP survey that was done at the Utah FORGE site where they were looking at changes in seismic velocity. And you can see that that contact between the overlying tertiary and quaternary sediments to the older granitic rocks is gradational in nature. So, you have basically upper maybe weather or slightly different velocity behavior in that upper granite that’s probably telling you something about the nature of fracturing and weathering in that upper part of the granite.

So, we can use these types of examples as a very useful way of trying to sort of get an idea of the location of where these intrusions are, but also to tell us something about the nature of the degree of fracturing that may be present. So, we can use cross-well seismic and vertical seismic profiling for getting these changes in seismic velocity. We can also be more aware of where their active seismicity and measuring seismicity looking for active faults as well.

Another technique that’s very commonly used in the geothermal industry is looking at electrical methods. And the reason why we do that typically is to look for zones of clay alteration where we get a nice electrical conductor. And there are a couple of different techniques that are used primarily in tandem. We use electrical resistivity...time-domain electromagnetics. And this is just a cartoon showing here where we basically put out a loop. And we have a transmitter. We basically send a pulse of electrical energy into the earth. And we will look at how that electrical energy decays and is being conducted out into the subsurface. And this provides us with a fairly good picture of changes in electroconductivity in the rocks in the upper one to two kilometers of the earth’s surface. However, for geothermal, we’re also interested in a much deeper electrical structure and so we use basically the natural currents that are present in the earth and that can get us imaging all the way down...all the way through the crust at a slightly lower resolution. And so, what we’re really looking at is trying to build a picture of changes in electrical resistivity or the conductivity of rocks and of fluids that are in the subsurface and sort of identify what those are due to. It could be due to differences in lithology. It could be a difference in hydrothermal alteration. It could be due to the presence of highly salinated conductive fluids as well.

This is just a 2D cross section that was produced based on a 3D magnetic... Sorry, MT survey that was done at the Medicine Lake

Volcanic Center in Northern California. And what I wanted to highlight here was... This was a very young volcanic center where we’ve got evidence of hydrothermal alteration. And the zones that are warm in color are zones where we have abundant hydrothermal alteration forming clay. So, the clay’s surface is good conductors and basically form a clay cap that seals the underlying hydrothermal system below. So, it basically serves as an insulator and it serves as a permeability barrier for the hydrothermal system that’s underlying this. You can see a number of boreholes that were drilled into this system that reached temperatures of greater than 250 degrees C. And so, this is a way of sort of delineating the extent of the hydrothermal system and identifying potential places that you would target wells for capping into the geothermal system.

Another method that is very commonly used in geothermic exploration is used for characterizing crystalline rock is just looking at potential methods, field methods and these would be gravity and magnetics. And so, for the case, once again going back to the Utah FORGE site, we have sedimentary rocks that are basin fills. Sediments that are basically draping on top of this older granitic intrusion. And so, in this case, we can basically use the gravity signature to map out that 3D structure of that contact between the sediments and the underlying granite due to the density contrast, the density difference between the sediments and the granitic rock. And this is just showing on the left the Bouguer anomaly map and then the granite basic model is basically an iso surface or where the granite is located at the subsurface and we have been able to drill into this and basically confirm that this is in agreement with the seismic profiles that we've seen before. So, you can use a variety of different techniques and basically do joint inversions to get higher resolution and higher confidence in the interpretations of these datasets.

So, as I mentioned before at the beginning of my presentation, we want to be able to not only look at big picture characterizations of these sites, but also looking at smaller scale types of features, such as fractures. And so, a lot of these techniques are going to be used in conjunction with having boreholes that basically get to the depths of where we're really interested in getting better details in terms of characterizing the rock system. And so, one of the key tools that we use are optical and acoustic televiewers and these provide images basically of the walls of the borehole that we’re created by drilling into this rock. And so, on the righthand side we should see some borehole breakouts that are associated with providing us with indicators of the stress regime of this particular system, where we’re getting rock failure occurring can tell us where the orientation of SH Max and SH Min are located within this borehole.

It also gives us images of where fractures are located and their orientation, their strikes and dips. And so, that’s really important in terms of developing a discrete fracture network model that you’re going to hear more about in the subsequent presentations.

We can also look at characterizing the different rocks by looking at changes in resistivity. We can look at the nature of the permeability by looking at the porosity by looking at neutron density logs. As mentioned earlier, gamma logs can tell us changes in some of these different rock types if we have variations in the different basement lithologies. These can be very helpful. For example, at the COSC borehole. We had gneiss. But these are both felsic and masic gneisses and so, there’s a really big contrast in terms of the gamma responses based on the minerology of these different rocks.

We also look at fiberoptic sensing eyeballs, just focusing on those techniques alone. And then also, you can do...a lot of these techniques have been applied to characterizing the systems. And I’m sure that when you hear the presentations tomorrow from the work that’s been done in Finland and Canada, that the folks from Posiva and Andy Parmenter from Canada will talk about some of the borehole logging that they’ve done to characterize the subsurface geologies of their different sites.

So, one of the methods that we’ve used is not only are we interested in where are the fractures and where are they located. We’re also interested in trying to identify which of these fractures are actually flowing because we have a lot of fractures that are basically tied and sealed. And so, what we found at the COSC borehole, which is drilled near Åre, Sweden in the central part of Sweden. This is a research borehole that went down two and a half kilometers and was drilled to try and penetrate what is known as the Sevey Knot. And they were really looking at sort of fundamental research and tried to identify the sort of structural setting for this part of Sweden. We were using it as an opportunistic borehole as it penetrated two and a half kilometers of high-grade metamorphic rocks, these gneisses. And it had complete core recovery from this borehole and a whole suite of different types of borehole logging methods were applied to this idea, this location. So, hundreds of fractures were mapped based on descriptions of the core and of the borehole logging from the acoustic and televiewer logs. However, when we went through and were using this flowing fluid electroconductivity logging method, we noticed that only less than a dozen of these fractures of the hundreds of fractures that were mapped were actually transmissive fractures. And the way this test works is as follows-is that we have a borehole. We have saline fluids in the host rock. And we fill up our... We can basically pump out our borehole and put in fresh water from a local stream that’s very low...total dissolved solids. So, there’s going to be a contrast in electroconductivity between the fluids that are in the host rock and the fluids that are in the borehole. So, any of the fluids that are in the host rock that leak in there are going to basically make that zone more saline. And we can detect that by putting in a conductivity log tool into the borehole.

We can monitor or change the way that the borehole is interacting, the fluids are interacting with the host rock fluids by changing the hydraulic head of the borehole by basically putting a pump down the hole and lowering the water table level, the water level in the borehole. And so, by doing that, we change the inflow rate of those saline fluids into the borehole. So, we can do it at this test of a variety of different water levels. Then the borehole. And we can then model as we bring our conductivity tool, we can model both...and calculate both the salinity of the fluids that's coming in, as well as the rate of the fluids in. So, it gives us an idea of that are coming in. So, it gives us an idea of the transmissivity of the fluids and the salinity of those fluids. So, it's a really nice technique that you can apply to get a better idea of which of these fractures that we...countless fractures are actually flowing and what their salinities are.

So, what's really important is that we've got a variety of different tools. You know, we had to question which tool should we use? My suggestion is you want to use multiple tools to increase the confidence. And also, some of the tools only provide part of the answer. So, for example, the borehole tools tell you the fractures are there. It doesn’t tell you how far that fracture actually extends. Seismic methods can tell you, “Hey, there’s a reflector here. What is it really indicating to us? Is it telling us the presence of a fracture? Is it telling us a change in lithology?” So, this is from the Forsmark site in Sweden where they did a reflection seismic survey and they came up with a series of what they interpreted to be reflectors that might be infractures. And then they were able to supplement this with the borehole logs that they had in the subsurface. And they were able to constrain. And the outline in the bottom box, that green outline, is basically denoting the location of the seismic survey. They were able to identify which fractures in the boreholes correlated with those seismic signatures. They were interpreted as fractures in the reflection survey. But it was able to tell you the extent of how far those fractures actually went out. So, that’s an important part of the DFN is not only estimating the fracture distribution, but the fracture length. And this provides using these two techniques together gives us much better constraints in building a more robust and more accurate model of these fractures.

So, we’ve been talking mostly about the characterization of a site, but geophysical tools can also provide you information in terms of monitoring how the site is performing over time. And so, this is just some information that I wanted to share from our EGS Collab project. We were using the old Homestake gold mine in the Black Hills of South Dakota as a test bed for doing research focused on geothermal resources. And where we were located, we had two different test beds. One was at the 4850 level, so it was located about 1.4 kilometers below the subsurface. And then another one at the 4100 level, which is located at the 1.25 kilometers below the ground level. Great location for doing these types of tests. These are in 1.8-billion-year-old rocks, It’s a suite of amphibolite, old meta basalts, and also of phyllites and schists that are old metasediments that are highly folded. What was known as the Poorman Formation, so no gold there, aptly named. But it was a really nice place to be able to go in where it was well characterized from a geologic standpoint over the decades of work that had been done by the goldminers in the past. And so, what we’re really looking at is developing a way to assess how do we identify permeable fractures? How do we go about creating a distributed fracture network to be able to extract heat from the subsurface.

And so, on the righthand side is a figure showing the array of boreholes at one of our testbed sites. And this is at the 4100 level where we had electrical resistance tomography and we also had a series of fiberoptic sensors. We had a whole suite of temperature measurement sensors as well and seismic sensors in addition to that. And so, we would be injecting fluid into some of these boreholes and we’re looking at the response of where the fluids are going. And so, we could actually inject fluids that are tagged based on different salinities that we’d inject. We’d inject fresh water or salt water. And we could evaluate the movement of these fluids to this subsurface by using the electrical resistance tomography sensors.

On the lefthand side, we were able to use the DAS tool from the fiberoptic network to look at when we were doing the stimulation which fractures are actually responding to the stimulation, not necessarily in terms of having fluid flow through those fractures, but actually having some sort of mechanical response. And so, that was also a really useful tool for identifying which of these fractures are actually going to be important in terms of being potential pathways for fluid flow.

So, another topic that I wanted to touch based on really briefly is just looking at can we use geophysical techniques for evaluating the excavation damage zone that’s associated with creating zones where we have under repository, where we have drifts, where we’re going to be placing the waste? Just the act of creating a drift is going to cause some zones of damage along the walls of those drifts. And we wanted to get an idea of how extensive are those potential zones and what impact they might have. And these are some examples that were published by Chinese researchers at the Beishan Underground Research Laboratory where they were looking at a zone in granite. And they created a test drift where they excavated it using different blast technologies and then they used a variety of different techniques. And so, they use ground penetrating radar and that’s on the upper righthand side. And they were seeing a series of reflectors that were indicating that the penetration or the damage done was really restricted to less than about half a meter from the walls of the excavated drift. And then they also were using acoustic emissions technology. They basically were hearing snap, crackle, pop as the rocks are sort of responding over time to the effects of having that excavation occur. And they were seeing a zone and this is on that image on the bottom right, a zone that basically stands out about half a meter where they're getting sort of fairly extensive amounts of acoustic emission responses to that. Another thing that we did, I'm not showing here, is when we were working at the Homestake Mine, we were looking at the effects of ventilation. The mine had been there for decades and so you have a cooling effect that basically penetrates about 50 meters from the margins of the drift into the wall rock. And we saw as a response to that cooling effect, and it was only looking about 15 degrees C, that there was a significant change in the stress regime locally. And that caused when we were creating hydro fractures, those fractures were instead of creating penny shaped fractures that would propagate out evenly around the borehole that we were using for injection and creating that fracture, they had propagated preferentially towards the drift due to that stress perturbation that was caused not only from excavation but from the thermal stresses that were imposed as well due to the ventilation. So, if we're putting in a waste package that's going to have a fairly significant thermal gradation, that's also going to impact that zone around the borehole.

So, we’ve also combined some laboratory experiments to sort of give ourselves some additional insights as to what the nature of heterogeneity in these crystalline rocks might play in terms of how it could affect flow and transport. And we’re looking now at the grain scale. And these are some samples that we obtained from the Grimsel Granite in Switzerland. And these are just core sized samples and what we can see is that these samples are not just homogeneous, equi-granular crystals of quartz and k-feldspar and plagioclase and a few mafic minerals, but there may be some foliation in these granites. And so, because of these variations in the grains on the core size sample, we’re looking at a few centimeters where we have millimeter-size grains. When we impose in the laboratory, pressure and temperature to the samples, we can see that these samples are going to respond in different ways. In this particular experiment, we see that some of the samples experienced rock failure where you get changes in permeability associated with the creation of new fractures. And so, it’s going to be important to understand at what scale are these heterogeneities important and where are they going to lead to potential fluid flow and transport? How do we incorporate this into our GDSA model?

So, just a few takeaway messages from this presentation. One is that we’re really focusing on characterizing fracture in the crystalline case and we really need to understand how do we get good information in terms of the orientation, distribution of fractures, not just any fractures, but fractures that are more predisposed to flow and transport.

One of the things I didn’t really touch on was looking at the stress orientation...the orientation of the fractures relative to the stress regime really matters. We can do calculations to look at the tendency of fractures to either dilate or to slip. And those are going to be fractures that are more likely to have flow along them. The techniques that we’re going to apply are really dependent on the scale of the types of features that we’re going to try and image. If we’re looking at really big scale images if we’re looking at really big scale images, we can measure these things from the surface. If we want to look at smaller scale features, we’re going to have to have techniques that are closer in investigation. They’re going to be mostly borehole related techniques. Some of the techniques that we have are going to be non-unique solutions. For example, most of your electrical methods are going to come with a series of responses. They’re not going to be unique. You’re going to have an inversion. You’re going to get a best fit. So, you’re going to have multiple techniques that you could jointly invert. You’re going to end up with a lower level of uncertainty and a higher degree of confidence in those results.

And I think there’s a lot of opportunity for collaboration for characterizing the subsurface between different types of investigators. Many of us at National Labs, we’re not only working on nuclear waste related research, we do things with CO_2 sequestration, with oil and gas, with geothermal. And so, we’re constantly putting on different hats. But used in these same suites of tools to investigate very similar types of processes. And so, on the righthand side is from a previous DOE initiative called the subTER Program where we’re looking at how could all these different programs within DOE share information and collaboration on different types of research projects? An earlier version of a research project that was done at the Homestake Mine called Kismet was part of one of these subTER efforts. And so, the idea was really getting a better handle on what they call these different pillars that they’re looking at where we’re trying to identify zones that with permeability, how do you investigate the distribution of permeability. For geothermal, we want permeability. For nuclear waste siting, we want to avoid high permeable features. So, we’re still trying to identify these features, but for different purposes.

So, I think that’s it for my presentation. There’s a whole series of references that go along with the images that I shared in the previous slides. I’ll be happy to take any questions you might have at this time. Thanks.

SIU: Thanks, Pat. You really brought us ahead of schedule. So, that’s great. We have more time for questions. We’ll start with Scott or Tissa.

TYLER: Thank you, Pat. Thank you for an outstanding presentation. I just want to reiterate I think what your last bullet point was is that the similarities and characteristics between an enhanced geothermal system and a crystalline rock repository are amazingly parallel in that it’s a low porosity, high heat, high stress environment, with very few fractures. In your case, you want to make some fractures with EGS and in a repository, if you don’t. But I think those collaborations and the advances that are going on right now at EGS from the geophysical standpoint are really going to add to the repository work that you’re doing at crystalline rock. So, outstanding.

DOBSON: Sure, thanks.

ILLANGASEKARE: Thank you. Very nice and informative presentation. So, I start off the discussion earlier, but toward the end you talked about the Chinese example. So, my question is so there are two issues of monitor. You have to monitor a large-scale system and the more focused. The more focused system monitoring techniques are fairly advanced, but you are suggesting that it can be used in the disturbed zone, within the drift, in that area. So, in the drift area there will be stress distribution as time goes because that will be open for a while. So, are there any geophysical techniques where you can monitor the changes as you go? For example, when the site is open, with time, it’s going to redistribute the stress.

DOBSON: That’s correct.

ILLANGASEKARE: So, in the acoustic case, it seems like the acoustic signals can be used to see whether things are changing. But are there any other techniques where you can monitor in the long-term how the system is changing?

DOBSON: Yeah. So, I'd say that the fiberoptic monitoring using DAS and DSS would be very helpful. At Berkeley Lab, we've developed a couple of different tools for monitoring, sort of, real time stress indicators. This is the SIMFIP tool and the DORSA tools that we both used at this particular site. And those acronyms are almost impossible to remember what they are. Basically, using fiberoptic sensors that can measure submillimeter types of deformation that are occurring. And we can monitor not only when we're doing stimulation. We can record the different the different amounts of movement that are occurring on the facture itself. We can also monitor sort of more sort of subtle long-term types of effects that are associated with, as you said, things that are happening once you excavate the drift or you change the thermal regime. How does that impact the surrounding rock mass? And so, by putting in these types of sensors, we can make those types of measurements.

ILLANGASEKARE: Okay, the second question is like some of the characterization methods... I like the idea of using multiple methods. That make a lot of sense. But at the same time, like in some cases you may have long fractures. You know, they have been modeled as individual fractures. So, that case, in other techniques develop enough to identify like a long fracture? Are there methods to say that during the... Ideally, you're going to locate... the location which is selected based on not a lot of fractures, but there may be fractures as you get the shallow zone. So, if something gets connected, are there methods to identify a single long fracture?

DOBSON: So, I guess it depends on like what sort of signal that fracture might have. And so, if it's got a fairly significant aperture to it, then you're going to probably see that in terms of a change in seismic velocity. If there's a damage zone associated with that, you know, like a fault, that also would be something that's going to be easier to identify. If it actually is a transmissive fracture, you can basically do a tracer study where you're injecting a fluid that's going to be a contrasting agent and be able to see that particular feature fairly distinctively. What we can... Also, if you have a network of boreholes, you can map these fractures and basically see does this fracture...do I intersect that same orientation fracture in multiple boreholes that it’s telling me that it’s one continuous feature? So, there’s sort of a number of ways you can sort of going about trying to map that. That’s one of the biggest challenges is getting out how extensive, how long do these fractures go? Are there offsets to these fractures? And then the other thing is we typically use...oh, the cubic law. We put in an aperture, a representative aperture, and we say it’s got this transmissivity based on... the permeability is assigned based on the aperture. Well, we know that the fracture apertures are not uniform. There’s going to be some variability and we get channelized flow paths. So, one of the things that we did from the COSC project is we brought home actual pieces of core that correspond to those fractures that were transmissive fractures. And even at the core scale, there’s some degree of flow channeling within that core shaped fracture piece itself. The fracture apertures are not uniform throughout. And so, the question is-is that level of detail really important for the model or does it give you some information that is going to be useful in terms of trying to identify the rates of flow?

Another aspect, getting back to your monitoring point, is that, when we’re doing our experiments at the Homestake Mine, we notice that the system behaved dynamically. That you started off with a fracture. Here’s a fracture that we’ve mapped and here are the flow paths. And then all of a sudden over time, the distribution of where flow is going changes. And so, that’s due in response to changes in stress. And so, the models that we develop have to be dynamic in nature. They can’t be static. They’ve got to take into consideration the changes that occur, you know, due to heating, due to excavation, due to long-term changes with glaciation or with seismicity in the area that are going to reflect the changes in permeability and fracture flow.

ILLANGASEKARE: Yeah. So, one more last question. So, eventually when you go to modeling, we’ll hear what the equivalent porous media versus the discrete fracture models. Any of the geophysical techniques allows you to get the equivalent porous media parameters, in the sense, that you will be able to... in the electrical resistivity methods, do they give you the equivalent value, like somehow in an equivalent porous media model, does parameters can be related to your geophysical characterization?

DOBSON: So, I’m going to defer to the presentation that’s going to... where it’s going to talk about the discrete fracture network model and how they’re able to transform a discrete model into an equivalent model. They’ve done a lot more work on that. But I think that geophysical techniques are sort of useful for identifying the fractured network. And then where you go from that in terms of the modeling work, I think, is something that’s going to be addressed in the next.

ILLANGASEKARE: So, my question is there are no geophysical techniques you can use to get the equivalent porous media parameters?

DOBSON: I don’t, I don’t, I don’t know for sure.

ILLANGASEKARE: Thank you.

DOBSON: Sure.

SIU: Eric, I’m going to... Emily talked about the impossibility of identifying all the fractures. And I understand that’s why you go to a stochastic model. But for the GDSA. But can you envision a future 10 years from now or 20 years from now, whenever the detail site characterization actually has to be performed where we could actually get to that point where we do know where all the important fractures are? With the way the field is progressing.

DOBSON: I would say that that’s the ultimate goal. I mean, we’re still having issues like we have earthquakes on faults that we didn’t know existed. And it’s not for a lack of trying. And so, I think that we’re improving our ability to image the subsurface. And so, by being able to improve that, we’re able to image things that we couldn’t identify 10 or 20 years from now. So, I think that’s still the sort of the ultimate objective is to develop better imaging techniques. One of the things that I think is being developed is the use of smart tracers where you’re injecting tracers that are going to record what they see when they’re underground. And so, being able to have that type of technology will, I think, go a long ways in terms of identifying. Right now, when we do tracer studies, we have a starting point and an end point. We have some information that we imply to our model where we say that we think this is the fracture pathways that it’s using because we know it takes this amount of time. We have first arrivals and later arrivals. Then when we do another model, the things move in a different way. So, trying to understand the dynamic nature of these fracture networks, I think, is an ongoing challenge.

And I think Laura’s going to probably talk a little bit to that later in her presentation. She’s been working on this area of research for decades. Okay.

BALLINGER: This is Ron Ballinger, a member. I think Nathan, your answer to his question was pretty much overlapping mine. And that is, I’m saying what techniques are there available? And I guess the tracer technique is the one we’re talking about where you can determine not only whether there’s fractures there in the distribution, but the inner connectivity. Which is really what controls the permeability.

DOBSON: Right.

BALLINGER: So, is tracer techniques the only way to do it?

DOBSON: No, so, one of the other techniques that we use, we’re looking at micro seismicity and that’s where we’re creating fractures. That’s obviously not what you want to be doing for this type of repository. For geothermal, it’s very much one of the techniques we use. And one of the questions is it really indicating where fluid flow is occurring or is it just telling us where rocks are cracking? So, there’s a distinction between those two processes that we have to be aware of that one is not necessarily indicative of another. So, just as I mentioned, just the fact that we have a fracture there doesn’t mean it’s a flowing fracture. And so, if we can inject...if we use, for example, showing the electrical resistivity tomography, we can actually see the effects of putting in a contrasting fluid into a fracture network. We can actually image where that fluid is going. So, that technique is something that’s pretty novel, that’s giving us better insights as to actually what’s happening in real time. Because we can do this not as just sort of tracer study, we have to start at the beginning and end. Here we’re seeing the fluid flow dynamically.

BALLINGER: Thank you.

DOBSON: Sure.

MANEPALLY: Thanks, Bob, for a lovely presentation. I have two questions. Oh, I’m Chandrika Manepally, Board staff. The first question kind of relates to the topic we talked about in the morning, which was how much is enough or good enough? I was wondering based on the other industries and your experience in either geothermal or carbon dioxide sequestration, is there an idea about in terms of fracture characterization, if there is a limit or kind of an idea as to how much is good enough for that particular applications? Do they have an idea about how far they go about characterizing the fractures and where do you stop?

DOBSON: So, yeah. When people are developing geothermal systems on a commercial basis, the cost of how much it takes to do something is really brought into play. So, people typically don’t do 3D seismic surveys for geothermal systems because it’s just not a cost-effective way of interrogating the subsurface for them. What is really done is to understand the sort of network of fractures. Trying to get what are the different fracture systems that are there. So, if you start with mapping outcrops because they’re easy to access. Then if you have subsurface data, you would really look at characterizing using borehole image logs. That’s a very effective way...challenge for geothermal as many of those tools are temperature sensitive. So, developing high temperature borehole image tools is something that’s important for the geothermal industry. In geothermal, if you hit heat but you don’t have permeability, if you’re not looking at EGS, then that’s not so good. So, identifying permeability is really important. So, understanding the stress regime and understanding sort of the local structural geology, I think, is really important. So, those are things that are not that high cost, that are easy to do. So, just basic field mapping and structural mapping and stress identification is sort of first order. Next order would be doing borehole imaging and then other things that are not that expensive are gravity and magnetics. Those are fairly straightforward, easy to do for sort of characterizing the extent of your system. But more detailed things like an ERT, those are done easily when you have easy access to the subsurface, working in a mine. Not so easy to have that type of system if you have to drill from the ground surface all the way down. So, it just depends on looking at how much is going to cost and what you’re going to get out of it? So, valuable information is a tool that’s applied a lot in geothermal and I think it could be applied here to identify what level of detail do you need in order to build a model that's going to tell you what you need to do.

MANEPALLY: Thank you. I had another question. This is regarding, you know, the difference in terminology. Some people use excavation damage zone and there's also the excavation influent zone or the disturbed zone, which is larger than the excavation damage zone.

DOBSON: Right.

MANEPALLY: So, all the techniques that you showed here, are they able to distinguish between these two zones? Can you get a good idea?

DOBSON: So, I would say that looking at... What we're showing there was really the near field, that small scale damage zone that's only, maybe extends a meter or so around the excavation. Whereas you were referring to there's a broader zone that's probably going to need to be taken into account as well. And I think the importance of that is... Here's an example as well. We were drilling...looking at bore holes at Homestake. Our first set of boreholes were near vertical and we had very few fractures. Ah, great, we building in unfractured rock. The next set of boreholes were near horizontal and we hit lots of flowing fractures. So, you have to make sure that you investigate, take into consideration that your investigation, the way you investigate is going to be...is not necessarily going to statistically cover this. So, if you're walking on a drift wall that's sort of going north-south, if our fractures are north-south, we're not going intersect very many fractures. If our borehole's vertical and our fractures are vertical, we're not going to hit any vertical fractures. So, making sure that your area of investigation is distributed so that you capture the full capability of identifying those features is important.

Getting back to your other question. Looking at crosswell seismic, if you have a couple of boreholes that go out from your excavation zone, you'll be able to see changes in seismic velocity that are probably going to give indications of how far that disturbed zone goes out that might give you a way of creating sort of enhanced permeability. And that's what we're really interested in is how far do we enhance the permeability away from our excavated zone, from our drift, that's going to allow you to make easy connections with larger transmissive fractures in that host rock. So, from the far field... It’s basically how far does that connection go to connect the near field to the far field? And I think that’s really looking at...so, looking at changes in seismic velocity might give you a sort of indication of where that disturbed zone might extend to.

MANEPALLY: Thank you.

DOBSON: Sure.

TYLER: Pat, the more I was thinking about this... I often try to look and see what are the differences in research needs for the different kind of rock repositories that we’re talking about. And I think what you brought up toward the end there is the issue of, in fractured crystalline... crystalline rock where we’re going to see these stress fields propagating during characterization, during construction, during closure that will be quite temporal in nature. And thinking about then ways that we can measure that as we’re doing it in the field, in order to be able to predict, what’s going to happen. So that there aren’t these surprises out there as we drill the last drift and suddenly there’s rockfall in five different places. So, thinking about the R&D program going forward as to what tools can we begin to develop that would be specific for crystalline rock looking at this distribution to disturbed zones as they move out, I think will be an important area going forward.

DOBSON: Yeah. And so, just monitoring changes in strain using fiberoptic sensing, I think, would be one technique that could be useful in terms of long-term evolution and changes in a repository area.

TYLER: Yeah. And quite easy to do.

DOBSON: Yeah.
TYLER: Okay, thank you.

DOBSON: Yep, low cost.

TYLER: Yeah.

DOBSON: So, I guess one last thing. There are technical challenges. Where we’re using fiberoptics sensing and other techniques, we’re getting terabytes of data. And so, just being able to handle and interpret and deal with these large amounts of data, I think, is an important challenge. That’s it. Thanks a lot.

SIU: Thanks, Pat. Excellent. Okay, our next speaker is Matt Sweeney from Los Alamos.

SWEENEY: Okay. A nice segue into talking more about discrete fracture network models and the physical and geochemical processes that impact flow and transport in crystalline host rock. So, again, to reintroduce myself, my name is Matt Sweeney. I am a scientist on the subsurface flow and transport team within the Environmental Science Division at Los Alamos National Lab. The work I’m going to be presenting today is very much a collaboration between my colleagues Jeffrey Hyman and Hari Viswanathan. Hari’s the PI at LANL for this work. So, the way that this talk is structured is to give you largely an overview of a number of the projects that we’ve worked on... to give you some background on the modeling strategies for fractured rocks and development of those models.

So, we wanted to start with a really high-level motivation looking at some of the range of problems that we look at LANL as well as the broader DOE complex, many of which are in the subsurface. And these problems range on length and timescales of many orders of magnitude, going from the very short timescale to the very long timescale. So, things going from underground explosions and gas seepage from underground explosions all the way up to things we've been talking about related to spent nuclear fuel waste and things in between. The unifying theme between these problems is the presence of fractures and fractures are important because they often dominate the flow and transport behavior. Because typically, but not always, they've higher permeability in the surrounding rock. So, they tend to provide fast paths or conduits for flow. Although in some cases as in the previous talk, often fractures are filled so they can also be barriers. That's also something to consider.

Going back to these problems then, they not only vary in time and length scales, but they also vary in terms of the physical process, principal processes that govern the systems. So, in the case of underground explosions, were dominated by a mechanical regime where we're actually fracturing rock. And then we could have more coupled systems, so hydromechanical, thermal hydromechanical, and then combining all of that into thermal hydrochemical systems. Typically, if we want to understand these systems in greater detail, we use what we're calling physics-based models to model these systems. Physics-based models meaning, we have some idea of the underlying physics, maybe some idea of the equations that govern the system. We have some idea of the geometry of the system. So, we can take all that information, develop computational domain, discretize set equations, solve those equations on that domain, and hopefully get a better understanding of what we're after. In our world, we often talk about the quantity of interest, which is our modeling goal. And that can be something like, as simple as understanding the effect of permeability out of a fractured block of rock, the arrival time of solute, things of that nature. The thermal breakthrough in an EGS system. We just heard a lot about geothermal.

Physics-based models range in both how much they cost from a computational perspective and how complex they are. So, oftentimes, we augment our physics-based models using machine learning models. We can accelerate the physics-based models using machine learning models. And then we get a natural description of uncertainty quantification doing that. I’ll touch a little bit more on uncertainty in fractured systems in the following slides. I’m not going to talk too much about machine learning but I just wanted to mention it because it is an area of active research that we’re working on.

So, getting more into the physics-based models, what are the actual strategies we use when we’re talking about modeling flow and transport and reactive transport in fractured rocks? So, there’s generally four classes that we can think about and I’ll go into brief details on each one. And they range in complexity and they range in the descriptions of how we represent the fractures, how we represent the rocks, as well as the coupling between them.

So, on the top left, we can look at the channel network. Sometimes you’ll see that it’s called pipe network, graph network. This is the simplest expression of a discrete fracture...of a fracture network where we are not representing the fractures explicitly, we’re just distilling the system to its base components, which is really the topology of the network or the connectivity. And we’re just hoping that by capturing that, we’re getting most of the behavior, the most important components of behavior of the fracture network. So, we’re not actually modeling the full geometry of individual fractures, we’re just getting maybe the volumetric flux between factures and are estimating that. The advantages of doing something like this is that it’s quite cheap. So, if we have very limited information about our natural fractured rock, we might choose a model like this because we can run many hundreds, thousands, even more of these. And by doing that, we can then describe, develop uncertainty bonds of our potential behavior. The disadvantage of this might be obvious. It’s that we don’t have the surrounding rock in this case that we can use analytical models for that. They’re not as good as something I’ll show in a second. And we were losing any sort of in fracture variability, in fracture gradients, which turned out to be important in many cases.

Moving down then to discrete fracture network models, we’ve heard a little bit about them. I’ll just refer to them as DFN’s from now on. These are a quite popular group of methods and models. They differ from channel networks or pipe networks in that we’re explicitly representing the fractures as two-dimensional planes in a three-dimensional space. So, each fracture in this case would be individually meshed and then the fractures would be sort of stitched together in such a way that we could run flow and transport using a tool like PFLOTRAN on these systems. These are sort of in the intermediate class of models in terms of how much they cost computationally speaking to run. We usually are doing this in a stochastic way. You can do it deterministically. In many cases we’ll run these models in ensembles to describe the ranges of possible behavior. One of the advantages of doing DFN’s is they’ve been around for a while. There are many groups that have worked on them. There’s good user support. And many existing flow solvers, like I mentioned PFLOTRAN work on these models. The main disadvantage, which might be obvious looking at it, is that we don’t have the surrounding rock. So, any sort of problem where we might expect a contribution from the surrounding rock or the matrix, you’re probably not going to want to use a DFN model or you’re going to have to incorporate some sort of a semi-analytic or analytical description of whatever that behavior is. For instance, if you’re working on an EGS problem, you need that thermal reservoir around it to describe the evolution of the system.

So, moving up into the right, we then have a class of methods called continuum methods. And these also include things like single continuum, multi continuum, effective continuous porous media. Those are all saying very similar things. The idea with the continuum methods is that we're in a class of problems where we need to describe the surrounding rock, the matrix. But we also need the contribution from the fractures. So, what we do is that we upscale the fracture network. So, maybe we start with the DFN. We upscale that into a mesh using effective properties. So, effective properties meaning, there'll be an effective permeability and an effective porosity on the continuum mesh. So, the mesh is all one dimension and that simplifies the flow and transport because we can use existing solvers then.

The downside of this, historically, is that you smooth out much of the behavior, much of the geometry and topology of the underlying fracture network. And I'll touch on that in the next slide a little bit more. And then moving down to the bottom right, we have discrete fracture matrix models or DFM models. I'm just going to touch on these really briefly. These are really the highest fidelity model we have, in that, it's probably the closest representation to the true system in that we explicitly resolve the fractures and we explicitly resolve the matrix. So, this is a multi-dimensional method where we have a three-dimensional matrix mesh, and a two-dimensional fracture mesh and those are typically conforming. And these are kind of at the forefront or cutting edge of what we can do, very much an active area of research, very expensive to run. We're kind of at that limit of current solvers, in that, the computational geometry perspective gets really difficult to make these meshes, but it's also really difficult to solve the equations of flow and transport on them because you have a big disparity in length scales between the two domains, the fractures and the matrix. So, I won't mention those again.

So, moving and sort of comparing the models and getting into some more brief history of their development. So, say you have a system that's dominated by fractures, but you also need to model the surrounding rock. So, we don't want to use a DFN model because we don't have the surrounding rock. We can't use the simplified pipe networks or channel networks, because we need the surrounding rock. We're not going to use DFN's because they don't really work at this point. So, what we turn to is the continuum methods. So, historically, they’ve shown sort of only modest success at reproducing the behavior of the underlying fracture network. And what I mean by that is, if you picture a continuum model and the surrounding rock in the model and you dial the permeability down close to zero or as low as you are comfortable going with your solver, you should reproduce the behavior of the underlying fracture network. What I mean by that is if you say, for example, you solve a flow, steady-state flow problem, and then you send a pulse of particles through your domain, the results from the DFN and the continuum method should be the same. Typically, that was not the case. We started getting better a handful of years ago. This was a study that Sandia led that some of my colleagues from Los Alamos were on. And so, on the left is the DFN. On the middle panel you’re seeing the continuum model, the effective continuum model. The left figure is showing the permeability distribution. The right figure is showing the porosity. So, you solve flow and transport on that. The flow is not shown in this particular slide. But what you’re seeing on the right is the breakthrough curves of particles going through the system. And so, the idea was exactly what I just said, was to compare from the DFN and the ECN. So, you’ll see on the plot on the right, these are breakthrough curves, CDF’s not PDF’s. The axis is showing time. The Y-axis is showing the cumulative normalized breakthrough. The light blue lines are from the DFN breakthrough and the green lines are from the continuum breakthrough. You can see that the green lines are consistently to the right of the blue lines. And this is on a large scale so those differences aren’t insignificant. And so that basically means that the particles are taking longer to get through the continuum model than the DFN. So, they’re not in quite agreement though they are quite close.

We took that study one step further a few years later and discovered the reason why that was the case is when you upscale the fractures into the continuum model when they’re not aligned with the grid, they turn into basically like staircases. And so, if you think about the path line through a staircase, it’s longer than the path line on a plane. And so, we figured out a correction for that based on that geometry, based on the angle of the normal vector of your fractures. And what I’m showing here is just three somewhat random examples of different fracture orientations defined by the normal vectors, the components of the normal vector, n_x, n_y, and n_z from the title of the plots. And, again, we ran into the same problem. These are just in single fractures. So, flow, steady state, send the particles through. And what you’re seeing is a comparison between the breakthrough from the DFN in the solid line. The stars are showing the breakthrough from the original no correction continuum model. And then the X’s are showing the corrected model. And you can see that we get quite a bit of improvement when we correct this geometrical behavior. And so, this is exciting because it really allowed us and other groups to use these continuum methods with more confidence that they’re actually reproducing the underlying fracture behavior that we’d like to see.

And so, to get more specific in our actual models and the ones we use, we have two different sort of classes of DCN or continuum models. We have the UDFM, which is the one we developed at Los Alamos. This is based on an octree-refined representation of the underlying fracture network. And what that means is shown in this figure where this domain...this is a computational domain. This is the continuum mesh and it’s colored by the distance from the nearest fracture. And so, you can see as you get closer to where the fractures or where they used to be, I should say, because they’re upscaled, the mesh elements get smaller. And so, we do this in hopes of preserving the underlying geometric geometry and topology of the fracture network. The downside of doing this is that it’s an expensive meshing procedure because you have to loop through for each fracture and resolve the mesh in that zone.

One of the other classes of continuum models that are being used in this project is this mapDFN, which was developed at Sandia. And this is a more simple meshing strategy where they overlay a uniform hexahedra mesh. So, think boxes over the fracture network and do the same upscaling in terms of the hydraulic properties. So, the advantage of this is the meshing is quite simple, but it’s a finer mesh because they’re not...it’s not a variable mesh resolution. And this was used in DECOVALEX Task F1.

Regardless of what you do in terms of a continuum model, the mesh resolution can greatly impact the flow and transport. And this was a recent paper we did. So, we’re often thinking about, you know... Depending on your fracture spacing, there’s going to be points where you can’t resolve your mesh to the point where you can preserve the true fracture spacing. So, what are the effects of those artificial connections? And that’s what we looked at in this paper where I just pulled this schematic figure from. So, consider an original DFN. This is shown in 2D, but everything was done in 3D. The gray lines are a hypothetical fracture network. So, we’re going to overlay that fracture network with a computational mesh in two cases. We have a fine mesh and a coarse mesh. And then where you see the gray-shaded boxes would be our fracture cells in the continuum model. And so, on the top line you can see that when we have a fine mesh, we preserve the true connectivity structure of the fracture network. Whereas in the bottom one when we have a coarse mesh, we induce what we call the false connection and so we’re actually changing the activity construction of the fracture network. How important this is really depends on a number of things: what your quantity of interest is, what your observation is. It turns out it’s really important if you change, say, the global percolation nature of the network. So, if you have a section of the network that didn’t percolate before, that may have cut off a big chunk of it or maybe reconnects a chunk of it that was not connected. That can matter depending on where your observation point is, that could matter. So, say, if you had a well or something right in that bottom left where the red star is, your behavior in the continuum model would be off compared to what you'd expect the true nature to be.

Okay. So, I'm going to pivot a little bit now and talk about DFN models. So, hopefully, you got a little background on the continuum models and how to use those. This is our most recent work looking at how dissolution in fracture networks affects flow channeling. And I want to stress before I get into this that we do not expect this to be... We did not plan this to be a true chemical system. It's a capability development working toward more realistic chemical systems. This is very much a young field in terms of doing reactive transport in complicated three-dimensional DFN's. So, in this paper we did an ensemble analysis where we ran flow and transport using PFLOTRAN through, I think, 30 networks that in this case the fractures in the network were initially filled with quartz. And the quartz dissolves as the system evolves to produce aqueous silica. And so, one of the new things that we did was in PFLOTRAN. We developed this ability to dynamically update the hydraulic properties as a function of time. So, the system is evolving as the quartz dissolves. The permeability gets updated. The porosity gets updated. The mineral surface area gets updated.

And then so we have eventually sort of quasi steady state system. And then once that happens, we simulate particle tracking through both an unreacted network and its dissolved counterpart. So, the purpose of doing this was to understand how permeability evolves in such a system, how flow channeling evolves in such a system, and to understand how transport might be affected. And I guess I didn’t define flow channeling like how it’s being used in this context. What we mean by flow channeling is thinking about the percentage of the active surface area of the network. So, how much of that surface area is actively flowing in the network? So, if you have a low percentage of surface area in the network, that means you have a high degree of flow channeling because less of the network is being used.

So, I’ll go through some results quite quickly here. So, this is showing the effective permeability through these systems before and after. So, we have the dissolved in orange, the unreactive networks in blue. The histogram count are just counting individual realizations and systems. And so, we can see almost uniformly that in systems where we allowed the dissolution to occur, we see a two to three order of magnitude increase in the effective permeability. And as expected, we see then a decrease in the amount of active fracture surface area percentage in the dissolved networks, which means that there’s a higher degree of flow channeling. And if you think about it, this makes sense. There’s sort of a feedback between as you’re dissolving parts of the network out. Those parts of the network are becoming more permeable, less resistance to flow. So, there’s a feedback. It’s sort of a worm-channeling, worm-holing effect.

And then lastly, we can look at the breakthrough of particles in the system. So, on the x-axis we have time. On the y-axis, we have the probability density breakthrough. And we see a two order of magnitude increase in the time, and a two-order magnitude decrease in the time of breakthrough in the dissolved networks. And so, I just want to stress again that this is really the first of its kind of this type of reactive transport modeling in this complicated of DFN’s and it’s a capability that we’re quite excited about and working on developing.

So, moving onto the next study. I’ll go through these ones a little bit quicker. We touched on it briefly in one of the previous talks about how fractures are not perfect planes in rocks. So, we wanted to understand how infracture variability in networks at the fracture scale affects global flow and transport properties. So, this is a study where we use data from our lab colleagues on where they actually measured aperture fields and we projected those on discrete fracture network models and then ran flow and transport simulations before and after. So, doing a constant aperture baseline and then an infracture variability final suite of ensemble of simulations. And so, this bottom left figure is just showing an example where we’re zoomed in on one of this fracture intersections and on the left is a constant aperture case. On the right are the lab data of fracture variability or variable apertures. The contours are showing streamlines and a velocity. And so, you can see in the constant aperture, it’s quite homogeneous. Well behaved is what I would call it. On the right, we can see that they’re quite irregular. They’re connecting points of high apertures. There’s pinch off points and things like that. And so, what we were interested in understanding was how did these changes at the local scale impact flow at the global scale? And so, this top right figure is a really cool figure from Jeffrey that he made. So, we’re representing the fracture network as a graph structure. And each node in the graph is a fracture in the DFN. And the thickness of the edge connecting nodes is the relative percentage of particles that pass through that intersection in the particle simulation. So, a thick line signifies that many particles went through there.

So, what you see in the constant aperture case, we see a kind of uniform thickness across several for different flow paths connecting the inlet and outlet. But as we include the infracture variability, we get much more heterogeneous behavior. We see in some cases there are just a few really thick flow paths and in between these different realizations, these were all generated with the same statistics, they're quite different. And so, that really speaks to this idea of how uncertain the behavior in these systems is. So, even with the same statistics, we're changing the flow channeling behavior and which parts of the network are being touched with the same. I'll move onto the next one then.

So, this is also quite recent work. For a while, the radionuclide tracking capabilities and the high fidelity DFN capabilities sort of existed in these separate silos. And so, we're working on sort of combining or integrating those capabilities. In this particular case, it’s with MARFA, which is a code called the Migration Analysis of Radionuclides in the Far Fieldes with our code DFN works at Los Alamos. And so, taking some of the capabilities of MARFA, which are quite advanced for radionuclide support, things like decay chain and different types of dispersion and diffusion and combining that with some of the capabilities we have in DFN works like I’ve shown like in fracture variability, we have analytical matrix diffusion that Jeffrey developed in his 2019 paper shown on the bottom right where he matched theory with semi-analytic implementation in DFN works. So, in the top figure, you’re just seeing an example of this integration where the path lines are shown in purple of the radionuclides through this network. And our variable aperture field is shown plotted on the fractures. And then the group, the MARFA group, just published a paper outlining these capabilities, I think in WRR, in this 2014 paper, where they showed the effects of toggling diffusion on and off. And so, this is very much a work in progress between these groups.

But someone asked recently why I have this Lagrangian transport capability at all if you have the Eulerian models. Having both of those models together is really good for verification purposes. Lagrangian models themselves are really great because they’re not as prone to numerical diffusion as Eulerian models. So, they sort of achieve different needs, but are also sort of symbiotic in that way.

So, the last science project I want to talk about is looking at the inclusion of background stress in a fracture network. So, during my postdoc, Jeffrey and I were noticing that there was a lot of mechanics and geomechanics studies on single fractures. And looking at the flow channeling, how you can induce flow channeling in single fractures by, you know, changing the asperities in the fracture and things like that. And so, we were wondering how those results at the single fracture scale might translate to the network scale. And so, what we did was develop quite a simple mechanics description of how fractures close and open depending on the magnitude and direction of the stress tensor relative to the fracture plane. And we did this using a Barton Brandis type model. And what we did was we fixed the network so we didn’t run ensembles of different networks. The network was the same in this paper, but we changed the direction and magnitude of the stress. And then looked at things like how did we change the flow and transport behavior as the stress behavior changes? What happening was it was pretty interesting, not totally unexpected but definitely interesting is that when you change the direction and the magnitude of the stress and very much in anisotropic way, you change which fractures close and open in the network. So, you can imagine if you have a static network and there’s some insitu stress field and you change that, you might activate fractures then that were previously closed, likewise or anti-likewise, you might close fractures that were previously open. And that completely reorganizes the flow field and changes the transport behavior considerably. In two dimensions, there was some work that showed almost uniformly that if you did send particles through these systems before and after, they would always arrive early because you tend to open big fractures that are aligned with the flow directions. And we showed in 3D that that almost is never the case. Well, I should say almost never. It did happen. But in a lot of cases, you just develop these really tortuous transport pathways through the network. So, this is definitely something that we’re still working on in trying to link some of these observations that we found back to the actual fracture network characteristics. So, things like, you know, the mean orientation, the lengths of the fractures. Big fractures tend to respond to stress in different ways than small fractures. So, thinking about the length distributions. So, thinking back to crystalline rock repositories, it’s definitely something to keep in mind since stress changes could impact the flow around the repository if that stress regime changes during its lifetime. So, thinking about, Emily mentioned glacial changes, you have changes along fault zones, things like that.

So, to summarize, the model choice for reactive transport and flow and transport, in general, in fracture networks needs to be made with the problem and quantity of interest in mind. I think there’s probably a whole discussion to be had about the merits of even doing high fidelity discrete fracture matrix models given how complex and time consuming they are, given the uncertainty in the subsurface. The subsurface is opaque. I mean, we’ll never have a perfect description of every fracture. So, it’s sort of finding that balance of managing the uncertainty with our expectations and our quantity of interest in mind. And then thinking about a couple of processes. So, the thermal, the hydro, mechanical processes. As we add more of those processes in, the complexity increases our ability to really bound behavior from a simulation standpoint decreases.

The relationship between field core and lab measurements in generating numerical representations is very much an active area of research. I didn’t get into it too much. We like to think about it as sort of bridging the gap. Like what measurements do we need from the field? What can we even use and how much can we use it in our representations of our fracture networks? That’s an evolving area that we’re still working on. We’ve seen a lot about continuum models in crystalline disposal for a good reason. I think they’re to me one of our most powerful tools because they can reproduce much of the flow and transport behavior of the high resolution DFN’s. But we get the surrounding rock as well. But of course, then we can’t resolve the high fidelity in-fracture scale processes. So, the one study we did looking at the in-fracture variability and how important that can be in certain cases. So, we don’t really have a description of that for continuum models.

I touched on the integration between MARFA and DFN works. So, Lagrangian particle tracking can be used in conjunction with most of our Eulerian models, PFLOTRAN advection-dispersion type models to understand repository performance. And then we talked a lot about flow and transport, a little bit about reactive transport. I just want to stress from my own personal perspective that mechanics can't be ignored either. And how the stress changes can really impact the flow fields in these types of rocks. With that I'll take any questions, thanks.

SIU: Thanks Matt. Okay, Tissa?

ILLANGASEKARE: Okay, so Tissa Illangasekare, Board member. So, this question more has to do with, actually, you touched on some of the questions that I had in mind. But these are more thinking-in-the-future questions. So, one of the issues is that do you anticipate any multiphase flow in fractures? For example, during the gas formation. So have you done any work, or have you been thinking of issues of multiphase flow?

SWEENEY: That's something we're working on right now in my group at Los Alamos and in Amanzi, not in PFLOTRAN right now. Jeffrey Hyman and Phil Stauffer did publish a paper using FEHM for CO_2 in multiphase, but I would say it's definitely something we're looking at and it's important.

ILLANGASEKARE: The second question has to do with the validation. So you mentioned in your discrete fractures, you were using some experimental data. But eventually this type of models that validate that much larger scale. And I think if I remember during the fact finding Hari mentioned that you are doing some experimental work at UT Austin or something. Are there any type of experimental validation going on at the scale eventually this problem will be solved?

SWEENEY: So I think what Hari was referring to was we're trying to use field data from UT Austin on sedimentary rocks looking at, the previous talk mentioned on sort of lots of times fractures aren't open in the field. And trying to understand, relating back to diagenesis and things like that, trying to understand how incorporating closed fractures, using the field data, would affect flow and transport. That doesn't come from lab data. But ideally what we would do is take lab data on sort of mechanical properties of these rocks at the core scale. We have lots of triaxial core experiments and understanding permeability and how mechanical permeability and hydraulic permeability are related in the lab scale. Take those data, combine it with the field data and integrate it all together into our models. And that’s kind of the high goal of what we’re working towards.

ILLANGASEKARE: So, within each fracture, you mentioned in your presentation that the asperities and all that changes. Eventually in the fracture network model, you are using some effective transmissivity term. That effective transmissivity had the fracture apertures and, I don’t know, if it relevant in this case. But when the fracture opens and closes, then the asperities get readjusted and there is a shift in this pattern.

SWEENEY: Yes.

ILLANGASEKARE: So have you thought about those issues of the equivalent, within the fracture network itself, the equivalent, effective transmissivity of the fracture, and on top of that, you have, you mentioned the stress changes. That permeability can change. Have you thought about those types of issues?

SWEENEY: Yes. We’ve thought about combining, so like a study like this, where we looked at the in-fracture variability and then combining that with our stress model. That would be a logical next step in seeing how that affects things. I think that makes a lot of sense. Just to touch on how we calculate the permeability. It’s not a parallel plate model for the whole fracture. We were calculating the permeability at a cell-based level. So it’s still a cubic law, in a sense, but it’s variable across the fracture.

ILLANGASEKARE: So the last question. So you, so you are looking at the, basically the cell size to the effective behavior, that sort of is obvious and clear. But have you looked at the orientation of the network in respect to there is a natural fracture, there are certain fracture patterns. But then if you look did you look at the sense, the orientation change, orientation affecting the orientation with the aspect of the -

SWEENEY: In the context of the continuum models?

ILLANGASEKARE: Yes.

SWEENEY: Yeah, so that’s what I was showing here is that when you change the orientation of the fracture and you upscale it, it turns into a staircase in the three dimensional mesh. And because of that sort of artificial length increase and the path line, as you send particles through it, they have to traverse that staircase. So, the way that we got around that was we basically bump up the volumetric flow or the permeability in those cells based on the geometry, the orientation of the fracture to account for that to make sure we get the correct flux and the correct transport time.

ILLANGASEKARE: Thank you.

TYLER: You hit the slides that I wanted to talk about, also. So just a quick question on this. This is in a single fracture, so one dimension. So, can you do the same kind of correction in a three dimensional fracture network?

SWEENEY: So, we do it in a by fracture basis in the network.

TYLER: Oh you do, okay.

SWEENEY: And the scale is, I think, Rosie’s going to show a network example of this, but it does scale almost perfectly. So, if you correct one fracture and you correct this fracture and you put them together, they're correct together.

TYLER: Okay, good. And then the slide you had up before which gets to Tissa's question, which is kind of the understanding the large scale behavior of these fracture aperture distribution or in-fracture variation. An area you may want to look at is in enhanced geothermal industry right now. They're doing large-scale fracturing events, much larger than at the scale that you're looking at here. And they're injecting two sets of tracers. One is a chemical tracer which would follow the path lengths, and the other is heat which is going to reflect much more the bulk properties of the fracture whereas the chemical tracer will affect the fast pathway. So, there may be some really interesting experimental data and theoretical data coming out of EGS in the next five years that may fit very nicely into what you're doing here and at length scales of tens to hundreds of meters.

SWEENEY: Right, this was core scale. So yeah, that would be great.

MANEPALLY: Hi Matt, this is Chandrika Manepally, Board Staff. Could you go back to the slide five please?

SWEENEY: I think the numbers fell off the slides, which?

MANEPALLY: Yeah, this one, thank you. So, in your second bullet you say that it depends on the quantity of interests. So, this correction factor, will it change, say here you are looking at breakthrough curves. So, if my quantity of interest changes to say those, will it change?

SWEENEY: Can you repeat? So, your question is if the quantity of interest changes, will the correction change?

MANEPALLY: Yes, the correction factor.

SWEENEY: No. No, this is agnostic to what you’re actually after in a problem. You want to do this no matter what because it’s capturing the correct physics.

MANEPALLY: Okay. And here what you’re showing, it was a flow model, right?

SWEENEY: This was – so it’s steady-state flow on a single fracture at different orientations and then a pulse of particles through that network. And the plots are showing breakthrough curves of the particles.

MANEPALLY: Okay. So, but if you run, say, the reactive transport case, in the future you tend to do that. The flow model, what you’re saying, is just the physical aspect of having representation of the fracture. But in a reactive transport, you have to look at the surface area and all of that will change.

SWEENEY: Right.

MANEPALLY: So you think, you think that this correction factor will get more complicated because you are looking to count all of the surface area changes?

SWEENEY: I think you’d have to correct for the surface area in a reactive transport model and continuum. Because I know we do a correction, not really a correction, but for instance in the DFN our initial attempts, we have to consider both sides of the fracture, even though we’re only, the mesh is only a plane. It’s only two-D. So, I think if you did it in a continuum scale, you’d have to account for the surface area, which would be difficult to do, because you’re talking about, in this particular case, I’m showing you the dual, or the primary mesh. We compute on the dual mesh, which is a Voronoi mesh. You’d probably want to go to this model which is a pure hexahedral mesh because then you could probably get a decent estimate then of the surface area, because they’re cubes. Whereas the Voronoi mesh are uneven, computationally speaking and geometrically. Something, yeah, a really good point, though.

MANEPALLY: Thank you.

WOODS: Brian Woods, Board. Thanks Matt, for the presentation. I was just curious, you talked about using dissolution for a dynamic kind of updating of your flow model. And then you also talked about then looking at background stress. Maybe right now, maybe there’s not enough computational power per se, but I mean, is it something in the future to maybe be able to, are you all thinking about maybe like literally dynamically updating your fractures as you go forward in your models? Or is that a little too –

SWEENEY: Can you be more specific? Like you mean actually changing the fracture?

WOODS: Yeah, based on any background over the 10,000 year model.

SWEENEY: Yeah, so that's a really, really hard problem because then you're talking about re-meshing at each time step, running a new flow problem, a new chemistry problem. That would really be the Holy Grail, though, right? You know, a true tightly coupled THM fracture model. This is my personal opinion, and not anyone else's, I think we're a long ways away from that.

WOODS: Sure. Is there anything other than dissolution then where you think then might be something that would be important for long-term behavior changes that you may be able to tackle in the next ten years or so?

SWEENEY: I think in the chemistry realm, I'm not much of a geochemist, I think we're working toward more multicomponent reactions. So, looking at, you know, more realistic chemical systems that might be expected in crystalline rock repositories. That would be something we're working toward. So, dissolution precipitation and multicomponent systems. I think what is in the realm of possibilities in terms of coupled processes is a more tightly coupled version of what I showed. I want to flip through this side thing. At the end, doing, it's not actually changing the fracture geometries, but changing our apertures based on the mechanics. And coupling that in with the chemistry and the flow. I think that's doable in the near term. I know there are several groups around the world doing that. So.

SIU: Okay, thank you very much. And I will take one hour for lunch and reconvene at 1:20. Thank You.

SIU: Okay. Back from lunch, and we're going to start up. First speaker of the afternoon is Dr. Yifeng Wang from Sandia.

WANG: Good Afternoon. So, in this presentation I'm going to be talking about buffer erosion, extrusion, and also in clogging.

This is a short presentation, I hope I can make it up sometime for you. So, okay, so this is the outline of my presentation, starting with relevant process and their potential impact on the total system performance, excuse me, and then followed by bentonite swelling, extrusion, experiment. And then I'm going to be talking about bentonite erosion and fracture clogging. And then one slide I borrowed from Paul Mariner, which will, yeah, I will talk about the implementation of, in a preliminary buffer erosion model in GDSA. And then I will have some concluding remark.

So, in a typical disposal concept in a crystalline rock, so you have in waste package emplaced in a borehole, I mean, in a hole, I mean, underground and then the waste package will be surrounded by a layer of bentonite and buffers. So then, so we talk, as mentioned in the early presentation, so in this, in crystalline rock, we usually have fractures. So, some of these fractures can potentially intersect with the waste package and then, and several process can happen, I mean, after the interphase between bentonite and the fractures.

So after the fracture here, you have bentonite and swelling. Because of this – I mean, so let’s say you got the fracture intersect in the bentonite layer and then the water coming in to contact the waste/bentonite and the bentonite started to hydrate. That would create a swelling and pressure, that the swelling pressure with basically squeeze the bentonite into fractures. So, we call this process an extrusion process.

This extrusion process apparently you can see the bentonite will have a good chance it will plug and the fractures will reduce the hydrological permeabilities for the fractures. And then at the front between, I mean, after the interface between the bentonite and the water and then the bentonite started to dilute and then you form some sort of suspension of particles and then you will have possible erosion happen. And then from buffer erosion we are generate, you are suspend particles with different size. The fine fraction of this suspensions we call the colloid. So if you have colloid, so we needed to consider the colloid facilitated radionuclide transport.

But on the other hand, the suspended and eroded clay particles can eventually settling down due to gravity and then it will start to clog the fractures. I mean, that’s also possible. So, all of this process will impact the total system and performance in one aspect in another. For example, the buffer - let’s say, the bentonite erosion were impacted at the swelling pressure because you basically remove some of the buffer material from the buffer layer. So, you reduce the dry density at this location for buffer material. So, you reduce, basically you reduce and the swelling pressure. And then if more severe, these erosion can potentially create some kind of channel across and the buffer layer that provide some kind of... kind of fast transporter pathway for radionuclides and release.

And then, on the other hand, if you have, if we have the buffer extrusion and then the buffer and clogging, and then that will significantly reduce the permeability of EDZ. So that’s in, that’s beneficial that it will enhance isolation of waste. And then associated are these colloid transport that will also impact the radionuclide release from the repository.

Okay, so the whole objective for crystalline work package buffer erosion, extrusion and clogging is to develop a FEP argument for those kind of processes. So, if we look at those different process, let’s look at the buffer erosion and there’s a lot of international activity has been done in this area. So actually there are also a European group that has also developed some kind of process model which I think is already available for implement, for implementation in GDSA. So this, a lot of work has been done here.

And then also, and then there’s a lot of work that has been done for colloid facilitator and transport for the SFWST, as DOE, and participate and a few years ago and participated, colloid formation, migration, CMF, CFM, and project at the Grimsel Test Site. So, through that kind of collaboration, DOE and teams have developed some kind of like colloid facilitated transport models.

And then for the colloid erosion, like SKB, POSIVA, even at UK, they did quite a bit of work for colloid and erosions. This is one example, provided by UK researchers. Basically, they look at the buffer erosion. They measured the bentonite concentrations as a function of time, I mean, and during erosion.

Basically, they show actually this process can be affected by increasing temperatures here. And this would be 25 degrees C increase to 60 degrees C can enhance the buffer erosion. So that’s a lot of work that’s been done on these two areas. So, this is not a focus area for our work. So, our current work are focused are on three areas. One is the buffer extrusion and fracture and plugging, and then the particle settling and clogging. And then we also look at to the colloid generations to bentonite-water interface.

So, at the Berkeley Lab, the research team develop these triaxial loading systems. Basically, in this system, so you have, so you (unint.) in the rock core and then maybe you can also stack the rock core with bentonite. So, you have this radial confining pressure there. And then you also have load cell at both and provided the stress along axial directions. And also, they have in the channel here to pump through the solutions. So, then they try to push the solution across the samples. And then by measure the rate of outflow, then you can calculate the permeability for the whole column for different parts of the samples.

So, this kind of system is very nice for studying like the EDZ evolution and also it’s very useful to understanding THMC and couplings and we think in a single fracture. Also, this is very important, it’s very useful to study buffer material and its interactions with EDZs.

So, this is just one specific test conducted at Berkeley Lab. So here this is the CT image of the whole column. So, on the bottom you have this fractured granite core as you can see here and then the fractured aperture of the fracture is 1 point micrometer. And then this core is stacked with a column of bentonite. And then this is the condition for the testing.

The confining pressure is 725 psi and then the axial stress is imposed at 540 psi. And then you have these 290 psi pressure gradient to push the flow through the column. And this is the typical result you can obtain. So basically, you measure the flow rate. Yeah, measure the flow rate.

And then from, and this flow rate you can measure the, you can calculate. That’s also model developed. So using the model, you can back calculate the permeability of the columns, I mean of the samples. So, this is very, this is a very interesting result here.

So, based on the flow rate, you can calculate the rock permeabilities, the permeability just across this granite core. And what you can see, with bentonite, and stack it on the top, and then the flow rate is very low. And then you can calculate the permeability of the rock. It’s about maybe point, I think around 0.4 µD. I mean, very different from, and the permeability you measured it just the waste and the fracture core, the granite in a sample there. So definitely you can see a five order reduction in fracture permeability by bentonite extrusion and clogging. I think this result is very important.

And then after experiment, the image of the fractures. What they found. So here is the water and the flow direction and then here, on this side you have bentonite. So, bentonite also tried to swelling to extrude it into fractures. So, some of these particles, clay particles, can reach about 1.2 centimeters. But the most of the clogging was found, yeah, too concentrated just at the entrance, within the range of, let’s see, maybe 1 millimeter from the depths. So this, the clogging effect, is very significant. And then they did a similar experiment for two temperatures, 25 degrees C and 95 degrees C. And then for the whole column probability you can see there’s some kind of difference. Increase in temperatures seems to also to increase the permeability of the core and the whole column.

Okay, so let’s switch the gear to buffer erosion and the buffer particle settling and clogging. And this work was done at Los Alamos. So, the team at Los Alamos developed two devices. This on the left, this is the device and it’s used to study bentonite in colloid generations.

Basically they’re having a column that packed with bentonite. And then on the bottom of the bentonite you have an eroding cell. This will basically to help you to create some kind of swelling pressure in there. So, you can control the swelling in pressure by this load cell. And then on the top of the bentonite column you have this, basically you have this titanium frit basically to filter out, just like in the field, you have to wear let, fine colloid particles, penetrate through in the frit.

And then on the top of the frit, you have in a vessel that you will create some kind of flow regime, something like that. You can even kind of mimic the fractures here and then you can control the flow rate. So basically, use this device you can measure the colloid erosion or colloid generation as the functioning of, and the swelling and pressure and then the velocity of water flow. And also, you can control the chemistry of the solution. So, you can use this kind of measurement too and constrain an erosion model or a colloid generation model as a function of bentonite swelling pressure, water chemistry, and flow and velocity.

And then another device in Los Alamos team developed is the colloid and microfluidic cell. Basically, you have two glasses in slides and they're bonded with PDMS. So, this PDMS will create some kind of pillars, micropillars between the two slides. So you created some kind of like very regular asperities between the glass that to simulate some kind of asperity geometry, geometrical pattern we see in our fracture. And then you can control the water flow and also the water chemistry.

This is a very preliminary result for clog particle settling and fracture clogging. On the left, there are two conditions. So this is, the water pumping from the left and then exiting from the right. So, in this test the solution content in both bentonite colloid particles with sodium chloride. So, in this case you have kind of like a high ionic strength in solution there.

And you can see these white patches actually the accumulation of colloid particles on the surface of these pillars. But if the solution is just pure deionized water with bentonite, you don't see the plugging or the settling or the clogging of these pores by bentonite and colloid. So, this means the chemistry can make a big difference for colloid settling and clogging. I think that’s not too surprising.

And then this is another set of experiments. So, we just look, so look at the bentonite and clogging at the different locations of the cell. Basically, just at the entrance, you see a significant clogging taking place near the entrance and then far from the entrance the clogging becomes less and less important. So, use this kind of data hopefully down the road we can construct some kind of model to predict colloid particle settling and clogging within a single fracture.

Okay, so this is the slides I borrowed from Paul Mariner. He will also talk more on this in his slides. Basically, on the GDSA side they have, they have been implementing a simple conceptual model for buffer erosion. The conceptual model is something like I show here. So, you have buffer material, so you're assuming there's one fracture intersect with bentonite. And then the model, ionic strength threshold. So, basically, at a high ionic strength, the colloid will be destabilized. So that means, that's where kind of inhibit buffer erosion. So, in this model, and in ionic strength threshold which is set at .004 Molality, and then above that there's no erosion and then below that there's erosion. And then the erosion rate is calculated as a function of fracture aperture of angle. But may be also something related to the gravitational enforcement. And then also a function of water and velocity, high water velocity and velocity, high erosion rate. And then also has something to do with diffusion of colloid in particles. So, this is, and they are implementing this conceptual model. And then I think the whole implementation should be, will be finished soon and hopefully.

So, concluding remark. So, for buffer erosion, extrusion and clogging, are indeed we have focused mostly on experimental capability and development. So preliminary testing data show actually the bentonite swelling and extrusion can significantly reduce the permeability in a fracture that intersects buffer materials. And then for the GDSA and preliminary buffer erosion model has been implemented. So, for future work, we need to do more systematical testing of bentonite extrusion and fracture in clogging. And I think we should be able to develop some kind of models to simulate the whole process. Then we also needed to do more systematical investigation of colloid generation from buffer erosion. So, this is an ongoing activity. Then all those tests will provide a comprehensive understanding of clay particle settling and clogging in fractures. I think this is – so okay, I'm happy to take any questions.

ILLANGASEKARE: Thank you very much. Tissa Illangasekare from the Board. So in your conceptualized, it's very early work, it seems like, and your conceptualization, you're assuming that there’s a single fracture somehow hitting the barrier. But in reality, let’s say there’s erosion and erosion eventually, the fracture will enter into another fracture network. Is that correct? So maybe this future work with the fracture network models goes and you are going to a more complex situation because for some reason the colloids go and within a single fracture, you create some zones where they are bypassing. But in a three dimensional single fracture network, it is going to change the pathway. So, have you thought about that, conceptualizing the context of sort of a single fracture colloid generation versus ultimately this in a network? Because a network, it appears you have to deal with this discrete fracture network model or porous media model. But for colloids, you cannot model using equivalent porous media because colloid move in different pathways. So, have you thought about these issues?

WANG: Yes, I think of it. Let’s say if we look at, so for this colloid and erosion experiment, let’s say, so they put all this concept of different fractures. So, you’re pumping from one fracture, and then you pump out from another fracture. So, this kind of experiment may provide some useful information about the transport of colloid within one fracture and then transported into another in fracture to see what’s happening to the colloid settling and the clogging.

ILLANGASEKARE: So, it’s the flow out in this case? So, you are taking a small piece, but it’s a whole.

WANG: Yes.

ILLANGASEKARE: So that basically you are looking at the possibility that’s happening at the fracture junctions and then how we get connected. Okay.

WANG: Yes. But also, there’s another complication in the fracture network. So, colloid usually follow the fast and transport pathways. I mean that’s the way. So that’s making things even more complicated. I think that kind of issue we should look at down the road.

ILLANGASEKARE: Because the flow, the flow will change as you go.

WANG: Yes.

ILLANGASEKARE: Then suddenly one active network will become inactive and suddenly some other network may take over.

WANG: Yeah. Because the permeability or the flow channel is also very heterogenous, not only within the single fracture, it's within the whole network. So that's, yeah, making the things rather complicated.

ILLANGASEKARE: Yeah. So then eventually your concern is that this colloid will end up very far away from the canister. So, do that colloids have to be followed all the way up to the larger system? Is that correct or that's the thinking?

WANG: Well, not exactly. What we hope is likely are these colloid particles that are deposited nearby, I mean from the erosion point. But in nature let's say, in general, all these in natural formations, like for this fractured crystalline rock. They are very effective in filtering out the colloid particles. So, this way I mean you can purify the water or develop really good high quality of water I mean underground. So, what we hope for, I mean, we can demonstrate those, most of the particles were filled out or settling out near, I mean nearby from the erosion. That those particles we are kind of help to reduce the permeability of the fracture. So that’s a way we can demonstrate.

SIU: To help our audiovisual folks, could you make sure you speak into the mic?

WANG: I’m sorry?

MODERATOR: When you answer the questions. Yeah, thank you, Scott?

TYLER: Yeah, Yifeng, thank you. I’ll sort of continue that line of thought. So, the issue is colloid-facilitated transport, is the, I think, is in the long run one of the major issues of, for the contaminant transfer, the radionuclide transport. So, my question kind of is then how are you going to upscale, or how, what efforts are ongoing at the, I think at the PFLOTRAN’s scale for colloid facilitated transport and deposition of transport? Are you, is that that direction you’re going? You’re going to build from these data a model that, a modeling module that is in

PFLOTRANs, that has facilitated transport coupled with some kind of deposition model at the fracture scale, or the larger scale?

WANG: So let’s see. Currently, as I mentioned in my earlier presentation this morning, so we almost wrap up in colloid facilitated transport model for the project which model is called a multiple site and colloid transport in model. So that model is already available for implementation in GDSA. But that model only accounted for colloid transport, in some part of filtration of colloid particles and then combined with it the associated radionuclide in transport.

So, I think after we do enough experiment, using these kind of device, hopefully we can incorporate those colloid settling and the clogging model into the existing CFM model. And that for the current CFM model, we tested a model for the column experiment that’s a good size, I mean the experiment. Hopefully that can bridge the gap between the laboratory observation and the (unint.) in transport. So that’s the model.

But, in general, I think we’re still having, we still don’t understand very well, for some observation, I mean that’s long standing issues like at the Nevada test site, people found there's a long distant in transport of a colloids. I don't know if we can capture that, that part. But right now, we have this multiple site model, can reproduce the colloid transport for the column experiment. So, but how to upscale that to the field, that's still in question, I think. But hopefully, so this will help to expand our existing model to account for colloid settling and clogging, yeah, in process.

TYLER: So, as I understand it, that the objective of this, the second half of your presentation here, is to look at, if we start migrating colloidal clay from the buffer, will it affect the engineered disturbed zone permeability in a positive way, i.e., reducing the permeability?

WANG: Yes. Exactly, yeah, hopefully.

TYLER: Okay, all right. Well then, I have one other question which was on the column, the core experiment you did where you had the bentonite swelling extraction and fracture clogging. So, I think a few before this one. Just, yeah, that. So, I'm just curious on this experiment. You have a bentonite plug on top of the granite, and then you are injecting water from above.

WANG: From bottom, and then, yeah. The flow direction from bottom to top, yeah.

TYLER: So how does the, I guess my question is how are you measuring the permeability of the fractured granite post-bentonite injection? Will you still have that plug of bentonite up on the top? And maybe I’m just missing something on the design.

WANG: Yeah, so that’s a good question. So basically, that’s another set of experiment. They measure the permeability just the pure bentonite for a given swelling pressure, I mean dry density. So they have a very good handle for calculating the permeability as a function of dry density. So, and then they are developing a model to conclude the permeability for the rock, I mean, for the granite core.

TYLER: Okay, I’ll follow-up on the paper. That’s a hard problem where you have something really low permeability on top of something very high and you're trying to measure the high permeability, infer the high permeability.

WANG: Yeah.

TYLER: Because you've got this choke on the system. But I'll go back and read the paper. Thanks.

MANEPALLY: Chandrika Manepally, Board Staff. Thanks for the nice presentation. I have a couple of questions. The first one was on the slide itself. The confining stress and the axial stress values were based on what, what was the basis for choosing those values?

WANG: Sorry?

MANEPALLY: So, the confining stress of 725 psi and the actual stress of 540 PSI was based on what? Was some calculation you made and decided that was the confining and axial stress you were going to subject the specimen to? What was that basis?

WANG: This I think it’s, not exactly sure why they chose this specific number. I think that’s maybe in the relevant range in actual like EDZ kind of stress there.

MANEPALLY: Okay, thank you. I had another question for slide four.

WANG: Let’s see, slide four, it’s back. No.

MANEPALLY: No, one more.

WANG: Forward, I think, right?

MANEPALLY: Go back one more. One more. Yes, that’s the one. So in this slide on the bottom right corner, you talk about the international R&D projects. What kind of insights do you gain from the SKB BELBaR project because that particularly looks at bentonite erosion. And how was that, kind of, used or leveraged in your process model for bentonite erosion?

WANG: I think that the erosion model Paul Mariner is implementing is based on this work, POSIVA and SKB, I think, Paul, right?

MANEPALLY: Okay, then I'll ask my question when Paul comes up and during his presentation. Thank you.

LESLIE: Bret Leslie, Board Staff. This figure is good because it's got temperature effects on it. And everyone else uses 100 degrees C as their temperature limit, yet DOE is looking at much higher temperatures. How valid are your models at higher temperatures? Are there effects of material changes with those higher temperatures that affect the erosion rate? Do you have a feel for that?

WANG: That's actually very uncertain. We don't know – I mean, like at Los Alamos they only do, right now, I think they haven't looked at the temperature effect yet. But I think that's something needed to be looked into down the road just based on this kind of published result. I think the effect of temperature on erosion, that's the one I say that we need to look at.

SIU: And speaking of temperature, I guess that’s the subject of your next presentation.

WANG: That’s the next one.

SIU: Okay, please, you’re on.

WANG: So let’s see, so now we are going to talking about possible temperature effect but for material stability and also look at some new materials so that, can be used for harsher environment. By harsher environment, we mean elevated temperature and maybe high pH and environment. So, this is the outline of my presentation. Just I will talk a little bit on relevant disposal environment to set up the boundary conditions for bentonite stability in a test.

And then, we talk about the related activities and then specifically talking about the stability of bentonite. I mean, the chemical thermodynamic stability of bentonite. And then followed by talking about saponite that we are proposing as a new alternative buffer material for harsher environment, high temperature and high pH environment. And then I will have one slide just to update the HotBENT field experiment, HotBENT field experiment is currently conducted at Grimsel test site in Switzerland. DOE, actually, participated from the very beginning. DOE is a major player for HotBENT in test. And then I will have concluding remarks for the presentation.

Okay. So, disposal environment. Why we are interested in this high temperature effect. I mean, very simple, because all of those waste, high level waste, they generate heat by decay and then during the disposal they will create a thermal pulse and the thermal pulse can potentially impact the material in the near field. So, this is just for illustration, this is just calculated thermal evolution for DPCs.

So, this is the thermal loading for a DPC with 37-PWR in assembly with high burnup fuel. And then, we also are assuming this will be disposed in crystalline rock and then with the drift spacing 60 meter and then the canister spacing, 20 meters center-to-center.

So, this is the result we calculated. Basically, you can see, this is the time. So, this is the waste package surface and temperatures. So, depending on the conductivity, thermal conductivity of buffer materials, you will have different kind of like thermal pulse created, with lower thermal conductivity you have high surface temperature you can reach. And then for a typical bentonite material the thermal conductivity ranges from .5 to 1 watts per meter-Kelvin. So, let’s say, look at it in this curve. So, for this DPC, let’s assume it’s cooling, it’s cooled down on the surface 450 years and then you started to dispose it and then it will reach pretty high surface in temperature here.

So, the existing, let’s say, the existing thermal limit for buffer material is usually assumed to be 100 degrees C. The reason for that assumption is that to my knowledge is because we don't know much about the behavior or the performance of the bentonite material above that temperature. So, we just say let’s make it safe, let’s choose 100 degrees C.

There’s another reason probably due to the complexity for multiple phase flow. When you get above 100 degrees C, you need to use multiple phase flow. So, you start to involve boiling kind of like process there. So that’s, I think, that’s two conceptual reasons, this 100 degree C.

But I think it’s, I would say, the thermal limit for this bentonite material can be much higher than 100 degrees C. The bentonite material could be much more stable than we thought. The one evidence actually is we just, just looking at the bentonite materials we are proposing. Let’s say WY bentonite MX80. This bentonite formed 90 million years ago from volcanic ash, but is still, you can see this bentonite, mostly like montmorillonite are still they are in these formations. So those formations have been subjected to various thermal perturbations, for example, by dike intrusion or by kind of like igneous intrusion. Still, there’s a significant portion of bentonite still preserved there. Otherwise, we wouldn’t see that massive bentonite deposit across the U.S. So, I think that thermal limit could be much higher.

So, another point I wanted you to take home is when we talking about the impact of high temperature on bentonite in actual repository, the duration of the pulse is relatively short, I’m relatively to geological time, right? Here let’s say if we look, let’s choose thermal limit to 250 degrees C and then choose a typical thermal conductivity for bentonite, 0.7. So the whole pulse, it’s kind of a last maybe just 200 years. So that’s a very short, I mean compared to the geological time.

So, when we evaluated the stability of the bentonite, we needed also to keep that in mind. So, with all this said, so there’s a good reason to increase the thermal limit. First, I mean for waste disposal. First, your increase the thermal limit, you’re basically maximizing the repository capacity. You can reduce the spacing of the drift or the spacing in between the waste packages.

And then, another benefit is you can reduce the time required to cool down the waste packages. So basically here, okay, so let’s take in the values the thermal conductivity 1, and then increase the thermal limit. So, let’s say to increase it 250. So basically, you can reduce the time needed from here, maybe that’s 300 years to maybe you can get it to close to 75 years. So that’s, you cut it down, the time duration required for cooling down is quite significant. So that’s, in those two are major benefit for raising the thermal limit. And also, to increase the thermal limit, that will also help to demonstrate the barrier capabilities.

And yeah, so, then another perturbation we wanted to deal with is in the alkaline plume generated from cementitious materials. So, cementitious material has been used underground in support, in various liners. And we try to like minimize the use of cementitious material. But there’s no way you can get rid of them completely. So, you always have some cementitious material in a repository. So, depending on the leach state of cementitious material, the pH could be very high, could be above 13 or closer to 14. And then the recent, actually the experiment showed that the bentonite reacted with this kind of high pH in plume, it will change the swelling significantly.

So, the whole objective here, we wanted to find out what kind of controlling factors for these, factors controlling the stability of bentonite at elevated temperatures. And also, we want to develop new materials for harsh environment. So, the whole effort is a joint effort. At Sandia we look at a hydrothermal stability of sodium smectite, sodium montmorillonite. At Lawrence Livermore, they look at radionuclide sorption of hydrothermally altered bentonite. And then also at Sandia, we look at some new materials for elevated temperature and high pH conditions.

And then at Lawrence Berkeley Lab, they're developing a THMC model try to incorporate all these, the related information, to predict the stability of buffer materials. And then there's a few related international programs. As I'm already mentioning, the HotBENT project, they look at the two different temperatures, 175 and 200 degrees C. They look at two materials, one is Wyoming materials. Another is the material from Czech Republic bentonite, which I think is more calcium is leached. And so, DOE directly, I mean, participated in these tests. And then there's another HE-E test. DOE participated in the dismantling phase. So, we got some materials in from our European colleagues and then we, we did some materials in characterization. And then there are also, in Europe, there's EURAD-HITEC project they are looking at the material performance at a temperature from 100 to 150 degree C. So, we are closely following these activities. So basically, all these tests will provide, will support our effort to kind of putting a reference case in together for buffering materials in GDSA and calculations.

Okay. So now then let's go to in some a little bit of detail about how to identify the limiting factors for smectite-to-illite in transformations. Well, the potential controlling factor can be temperature, water/solid ratio, and duration, and cation, different cation, and the solution chemistry. These factors, I mean it's very obvious if we look at these kind of reactions.

So, potassium, you need the potassium to make this transformation happen. And then you need to take out silica. So, you need a lot water to dissolve silica from original and smectite to make this cation go to follow on to the right. But the one challenging thing is this for transformation to happen in nature, I think, it's very slow. I think it's really hard to reproduce this transformation on the laboratory scale. So what we did is, we used so-called accelerator experiment. Basically, we tried to create the best optimal condition to make illite from smectite. After we make that, and then we step, one step back and then by eliminating controlling factors one by one and then we can figure out which factors are the key controlling factors for this transformation. So, we did, we designed a large matrix for testing.

So, this is the key findings. So first off, by creating, that’s the best optimal condition. Actually, we are succeeding in making illite from smectite over in weeks, so in a very, very short time. So then after we making in this, making smectite, and then we reduce, we eliminate the effects one by one and then to find out what are the major contributing factors. So, this is the major findings, two contributing factors.

One is the potassium in concentration. Very surprisingly, if we have the initial bentonite exchanged for potassium, that’s a lot of potassium you’ve got into the mineral structure, but that’s not enough to make the illite. You need additional potassium in the solution, one more potassium in the solution and then you will be able to make the illite.

And then as you can see here the water and rock ratio is very high, 1,000. The only other, this water/rock ratio you can make the illite. Basically, this is two controlling factor. If you look at the actual repository environment, there’s no way you can meet those two requirements. So, the point is, it’s really hard to convert the smectite to illite with a relevant repository environment. If anything happened, that transformation will be very, very limited. So that’s the finding and we have based on our, in testing.

And then another thing, so based on our testing, we construct this phase diagrams. So, this is the activity of silica, dissolved silica, this activity of ratio of potassium, hydrogen and then magnesium. Basically, this is the stability boundary between illite and potassium has changed to smectite.

So, as you can see here in the solution we make the illite the data point close to the boundary and then in the solution with deionized water, so the system is very stable, actually. It’s raising smectite stability in the field. So, the one concept we are proposing to further include the stability of bentonite, we can do, we can add some kind of chemical additives into the bentonite. For example, you can add brucite or add amorphous silica. And then you can push the stability of the system into way into the smectite field. So that provides some kind of engineering option to enhance the stability of the bentonite.

And then we look at the stability of bentonite at high temperature and high pH. So, we cook the bentonite with calcium hydroxide solution at a 100 degrees C, nine days and 150 degrees, 72 days. This is the original x-ray pattern of the material. You can see after the reaction, the whole pattern changes. So basically, the bentonite will be very, will be unstable converted to zeolite.

But we look at another material, which is so-called saponite. Saponite is trioctahedral minerals of smectite in groups. In saponite, the interlayer site is occupied by divalent cation magnesium. This is the XRD pattern for natural materials. By the way, this is a natural occurring material locally available in nature.

So, then we looked the saponite reacted to the waste, the same alkaline elevated temperature. This is the original XRD pattern for saponite and reacted, they are almost identical. So that means the saponite is very stable at elevated temperature and alkaline conditions. If we look at the swelling pressure of saponite, it’s just in the range of MX80 as well as smectite. So saponite could be a good alternative buffer material for, in harsher environment.

Okay, so just quick update for this HotBENT in test. So, this is the configuration of the test, four sections with different materials and they were heated at two different temperatures. So, it will run quite a long time, five to ten years and even up to 20 years. Then I think by June, okay, so heating started on September 9, 2021st and then the heat has been ramped up in steps. By June 2nd, two years ago, 2022, the heater reached their targeted temperature. But there is a problem, I think. They found actually many of these sensors, humidity sensors, there is some problem, there is some problem with those humidity sensors, so they will try to figure out how to handle that. So that’s the update of the HotBENT test.

So, concluding remark. I think, so, it would be very beneficial if we can raise the thermal limit of the buffer materials, both for repository design or to, or facilitate early in disposal. And then the smectite-to-illite transformation is, seems very unfavorable in an actual repository environment. And then the stability of bentonite can be further improved by adding some chemical additives. And then, again, for high temperature and high pH environment, saponite could be an attractive buffer material. Then, I mean just wanted to say by combining the laboratory tests, the long-term field test, we eventually I think it’s possible to raise the thermal limit beyond existing 100 degree C. Thank you.

SIU: Okay, thank you, Dr. Wang. Scott?

TYLER: Yeah, thank you. There we go, Scott Tyler, Board member. Thank you very much. So, I guess, there’s been a lot of work done on bentonite stability and temperature in high temperature environments. And I guess, are you planning to continue to work on bentonite at high temperatures in, and again, in an environment that would be typical for a crystalline rock repository, relatively high salinity? Not brine solutions, but relatively high salinity fluids. And combining that with other, the literature from the past and other studies going on? Is it - because there does seem to be some concern in the literature when things get above 150 C with smectite to illite conversions.

And the issues of boiling still come back at you, as well as challenges in the bentonite.

WANG: Yes, yes. So there’s quite a bit of work still remain to be done. And in the end, that’s two, there’s three pieces of information we needed it to put it together. One is, the laboratory’s scale test. The test that we just showed you. And then another piece of information is the field test, like HotBENT. So, we needed to be patient, wait for maybe five or ten years to see what comes out of from the dismantling of those tests. And then another piece of information is actually analog, natural analog. So, there’s a lot of work has been done for diagenesis, for sediment diagenesis. So, we needed to put all those three pieces information together. Eventually we can, I think we can demonstrate we can raise the thermal limit. So still there’s a lot of work needed to be done before we come up with that kind of model.

TYLER: I concur completely. I think using analog sites in the field would be an outstanding way to get to this question. Plus, you have long term, long time scales and measurements that are going on.

WANG: Yes.

TYLER: Yeah. I had another point but I'll come back to it because it just slipped my mind. So, thank you.

ILLANGASEKARE: Thank you. So, these are short questions. So, in your HotBENT experiment, it's a ten, it's a long term, like ten years, fifteen to twenty years. So, you mentioned that the sensors are not working. So, while the experiment is going on, what type of data you are getting to look at the processes you have, you are interested in?

WANG: So, let's say, so this humidity sensor or just one type of these sensor they have, can get some useful information there. But there's something going on with the humidity sensor. But they still, they have the other type of sensors. They are collecting, let's see, the data from other sensors. So, like I think it's temperature, pressure, and then the other, they already collected quite a bit of data already.

ILLANGASEKARE: Yeah, my question is, what type of data you're getting continuous to some of the questions related to the clay going through the process you talked about in your lab systems?

WANG: So, we need kind of like to get the first two type of data. And we needed to know the actual evolution like a thermal, hydrological, chemical evolution during the test. So that data can be obtained from different sensors. And then the most important piece of information you needed to look at the mineral face after dismantling. And then if you look at it, let's say if the, and those tests, let's say at the end of twenty years. And then you find actually there's not a much going on in term of mineral phase transformation. That's a good piece of data to support, I mean, our effort to raise the thermal limit. Yeah?

TYLER: Yeah, I remembered my follow-up question, which was not a question, but a comment and appreciation. I thought your, at the beginning of the presentation, coming up with a scenario for what the heat load and spacing and time would look like in a crystalline rock repository was a very helpful start for the presentation. Really gave us a sense of this is, these are the possible range of conditions that we might see and now we'll study the effects of these temperature ranges. This is what the bounding calculations. So, thank you.

BALLINGER: This is Ron Ballinger, member. To put things in perspective, at what time do we expect the canister to breach? How many years?

WANG: Well, that’s a good question.

BALLINGER: Well, if the temperature in the bentonite gets below 100 degrees C long before the canister breaches, why are we worried?

WANG: That’s a –

BALLINGER: Am I losing my grip here, or what?

TYLER: I think I can help answer it. It’s the, the concern is that the clay minerals will change to a different clay mineral, an illite, which is –

WANG: Yes.

TYLER: a non-swelling or a less swelling clay. So, it’s an irreversible reaction. So, when the temperatures come back down, you’ll have a different buffer material.

BALLINGER: So, then you just treat it as resisters and series?

TYLER: Hmm-mm [affirmative], but now a lower resistor.

BALLINGER: But a 50 micron thick resistor, or 100 micron, 10 Mils, or whatever the number is.

LESLIE: Bret Leslie, Board Staff. Go back to a question that was raised in 2019 at the URL Workshop by Dr. David Bish and it goes to the HotBENT and kind of how hot the waste packages might be. Whether you will ever get a steam environment. Because basically his point was is this ramp up consistent with kind of concept of putting in a hot waste package and putting bentonite around it and would it create a steam environment? Because what you’ve done is in an aqueous environment, and his point is the few laboratory experiments that have shown steam environment is that it’s very rapidly does the illite transformation in a steam environment.

WANG: You mean the smectite-to-illite transformation happen very fast?

LESLIE: Yes, in a steam environment, not in a saturated environment. But do you heat up, could you heat up the buffer material fast enough with these hot waste packages to create a steam environment? If so, then you’re not really modeling the processes that would occur when emplace a hot waste package and put the bentonite around it.

WANG: One thing is I think it’s not – I mean, it’s not an exactly to heat, the heated environment on the surface which you can see clearly the steam generation in all kind of the phase transformation, I mean, the phase separation for water. But in waste disposal environment, considering the depths, usually 500 to 600 meter below the depths, maybe that can reduce the possibility for phase separation of liquid water into steam. But again, maybe there’s some kind of face in separation there. That’s the one thing we also needed to look at if it’s relevant.

MANEPALLY: Chandrika Manepally, Board Staff. When you were talking about the MX 80 and the bentonite deposits, you alluded to a natural analog. So, I was just wondering if there are any plans to kind of get involved with international collaborative programs that focus on natural analogs, like the Natural Analog Working Group?

WANG: Yeah, that's a good idea. I think – so I look at the literature. There's some literatures even about the natural analog. We think this Wyoming bentonite, there's some kind of like, the intrusion of dike or some kind of intrusion of igneous bodies and then they look at what's the effect on this heating, on the heating on the smectite transformation. I think that's, that kind of information we needed to, also to collect more.

MANEPALLY: Yeah, because this working group does not only look at bentonite analogs; it is looking at cementitious materials. And there's a lot of work that is not just done here, but – yeah.

WANG: Yeah, one research they show I think for in some location, Wyoming bentonite subjected to thermal pulse up to 150 degrees C. So that’s a very relevant and natural analog there.

MANEPALLY: Okay. Then the other question I had was the pH range that you are looking at for the, you showed only high pH here. But in your reports – right. So, you just talked about high pH in these slides, that is above 7, correct? But in the, in your, in the reports that you are looking at, I also saw low pH range. So, I was just curious what could cause low pH in a repository environment?

WANG: I may have missed something you’re talking?

MANEPALLY: Okay. So, in the Wang 2023 report that, or 2024, the pH ranges that you were looking at for the test that you did, went down to 4.

WANG: Oh, you mean the, let’s see, the one.

MANEPALLY: I don’t think you have the slide here.

WANG: Here? Let’s see, do I have the, no, I don’t.

MANEPALLY: Yeah.

WANG: I needed to look at a back.

MANEPALLY: Okay.

WANG: I mean, that pH range to see why we put it, yeah.

MANEPALLY: Okay, yeah, we can take it offline then. That’s back.

WANG: Yeah, yeah, we’ll get back to you. Yeah.

MANEPALLY: Yeah, thank you.

SIU: Okay. Seeing no further questions, thank you again, you brought us on schedule. And we’ll take a break until 2:35.

[Break]

SIU: Okay. All right, let's get started. Next talks will be by Paul Mariner and Rosie Leone from Sandia.

MARINER: All right, thank you. My name is Paul Mariner. I am from Sandia National Labs and I'm one of the leads on the GDSA framework development team. I'm going to be talking about the GDSA R&D activities related to crystalline host rock. GDSA, again, is the Geologic Disposal Safety Assessment. Rosie Leone will also be joining me for part of this talk. All right. How do I advance this?

SIU: The big arrow.

MARINER: Oh, the big.

SIU: The big one.

MARINER: Okay, sorry. Yeah, all right. Okay, so the outline of my talk. I'll start out by just talking about the GDSA activities. They're ongoing for crystalline rock. Then I'll talk about the two different crystalline repository reference cases that we've developed. After that I'll talk about a few specific modeling activities we’re involved in, that are specific to the crystalline reference case. One is on modeling excavation effects and the other on buffer erosion. Then Rosie will talk about DECOVALEX crystalline reference case. And I’ll follow that with a talk about performance factor analysis.

The primary GDSA modeling objective, as Dave Sassani was talking about earlier, is to develop modeling capabilities that support simulation of coupled processes controlling disposal system performance. Specifically, the modeling capability will integrate conceptual models of subsystem processes and couplings. It will incorporate reasonable ranges of site characterization data and it will propagate uncertainty.

Another thing we’re doing now more of is developing our reference cases. Up until now mostly we’ve been developing these reference cases to try out, to test out our modeling capabilities, to see if it work. We are now starting to use those reference cases to develop a better understanding of our total system models.

All right. So, these are the two main activities we’re doing in GDSA. Capability development is that first big bullet and reference case development is that second big bullet. Under that first big bullet, discrete fracture network modeling. You’ve heard a lot of us, a lot of talk about discrete fracture network modeling that we’ve done so far and we will continue to do some of that.

The next one there listed is the dual continuum disconnected matrix model. That’s an additional feature that has recently been developed and Rosie will talk about that. You’ve heard a little bit about the buffer erosion, canister corrosion model. There is a slide that I will talk about briefly on that. The next three bullets there are more general activities that we do. That is that they’re not specific to crystalline rock; but they are still very important to developing our capability so that we can model a repository in crystalline rock.

The first one there is performance factor analysis of engineered barriers. That’s a general technique that I’ll talk about at the end of this talk. There’s the tracking tool that Dave Sassani talked about earlier, having to do with FEPs and how our activities map into the FEPs. That tracking tool is pretty close to being ready for the PIs to start filling out the information, so that we can start using that tool.

And then that last bullet there under the big bullet is, we are continuing to work on our automation and reproducibility and transparency, especially as we work on our probabilistic simulations. A lot of that is done by Laura Swiler and her group. What we do there is we run our simulations probabilistically so we can propagate uncertainties of our system and then we are able to do some uncertainty analyses and sensitivity analyses. We also have been developing a workflow that also helps us in automation and reproducibility and transparency.

The last big bullet, the two bullets there, are the two different reference cases that we have primarily developed for crystalline rock. The first one is the international comparison of the performance assessment modeling capabilities through a task on DECOVALEX. And that second one is our original GDSA crystalline reference case that we developed using PFLOTRAN. And

I’m going to talk more about that one, actually both of them, in this next slide.

Here are those two reference cases side by side. On the left is the GDSA crystalline reference case and on the right is the DECOVALEX crystalline reference case. The crystalline, the GDSA case on the left, it is 3 kilometers in length left to right, whereas the DECOVALEX reference case is 5 kilometers from left to right. That’s the main difference in the other, in the dimensions. Otherwise, they are both about 2 kilometers wide and about 1 kilometer deep. The crystalline reference case, the GDSA crystalline reference case, goes 1.3 kilometers deep.

On the left, the GDSA case, it has an overlying glacial aquifer and the groundwater flow is from the left face to the right face, the west to the east. For the DECOVALEX crystalline reference case, we simulate higher ground on the left side of the domain, and lower ground on the right side. It’s kind of flat, high flat on the left and high - low flat on the right and then a hill connecting the two. All the other faces in the DECOVALEX crystalline reference case are no-flow faces.

So, what happens there is that water tends to infiltrate on the left, go downward and then across to the right, and then upward and come out of the domain on the right hand side.

In the DECOVALEX crystalline reference case the repository is at 450 meters and in the GDSA crystalline reference case it’s at 600 meters. What we do in the GDSA crystalline reference case is we put the waste packages within the drifts. Those are 12 PWR waste packages, that is they have 12 fuel assemblies per waste package. And we put them in the middle of the drifts and surround them by bentonite buffer.

For the DECOVALEX crystalline reference case we drill, we have deposition holes in the floors of the tunnels and we put much smaller waste packages down in there, and then surround them by bentonite. Those are 4 PWR waste packages, 4 assemblies per waste package. Because those waste packages are smaller, we also simulate the DECOVALEX crystalline reference case isothermally. We don’t simulate heat. But in the GDSA crystalline reference case on the left, we do simulate heat and the flow of heat and so we can calculate temperatures.

And then that last bullet there is just about the fracture networks. In both cases we have defined fracture zones that are in all of our realizations in the same spot. Those are known fracture zones that we pretend to know. These are fictional sites. They aren’t real sites. But we do fix these fracture zones and then all the other fractures are generated stochastically. And then in both cases we upscale those to equivalent continuous porous medium.

All right. The GDSA crystalline repository looks kind of like this if you were to draw a cartoon of it and cut out some of the host rock. There’s the repository there, the drifts. And then what’s shown in the upper left is sort of a close-up of one of the drifts with three waste packages and they are surrounded by bentonite buffer. And there’s not this two layer system that you’ve seen in some of the other figures. It’s just one, one bentonite surrounding everything, and then there’s the wall of the drifts after that.

So, what I’ve kind of indicated here is that this is the engineered barrier system that we talk about. It’s the waste packages, the buffer around the waste packages, and then the waste forms inside the waste packages. Those are all part of the engineered barrier system.

For this GDSA crystalline reference case, that top layer here, this overburden, are glacial sediments. And that’s an aquifer that we use to sort of represent our interface with the biosphere. So, we’ll keep track of concentrations of radionuclides in that aquifer.

All right. So, this figure is a vertical cross section through three of the drifts. And what it’s showing is really the mesh that we’re using for this reference case, for the GDSA crystalline reference case. Right in the middle of each drift is the waste package. Right around that, that’s the red color, right around that is the buffer cells. And then right around that is what we call the DRZ, the damaged rock zone. That is host rock but it is damaged because of excavation effects.

These drifts are spaced 20 meter center to center. They have those 12 PWR waste packages in them and they are surrounded by this bentonite buffer backfill. The size of this damaged rock zone that we simulate is 1.67 meters and that’s on par with observations from underground research laboratories.

This diagram shows a little bit more why we want to model the damaged rock zone, the DRZ. What can happen with the DRZ is, because it’s a little bit more permeable, the radionuclides that make it through the buffer and into the host rock, the wall of the host rock, it may be able to find pathways much more quickly to another fracture that would move it away from the repository. And if you can imagine, there might even be another fracture to the left of this figure. And so, by constructing the tunnel, this damaged rock zone might connect to fractures that weren’t previously connected.

The permeability of the host rock that’s unfractured is close to 10 to the minus 20 meters squared. What we do in our GDSA reference case is we don’t know exactly what the permeability will be, but we can vary it probabilistically and we vary it between 10 to the minus 19 and 10 to the minus 16 meters squared. And that’s, again, based on observations, underground research laboratories.

We also set the porosity in the DRZ at 1 percent. The host rock porosity is closer to .5 percent. We also increase the effective diffusion coefficient in order of magnitude in the DRZ. And then when we run our models probabilistically, we can look to see how much of an effect that DRZ has on, in this case, the peak iodine 129 concentration in the glacial sediments that overlie the host rock.

This graph is a graph of total index value. And it’s just a way of, it’s an indicator of the relative variance of peak iodine 129 concentration owing to the uncertain parameter and interactions with other uncertain parameters. And what you can see, there’s two different sensitivity analysis methods that were used to try to get a handle of this total index value. And in this particular reference case, it’s the uncertainty in the fuel degradation rate that provides most of the uncertainty that we see in the peak iodine 129 concentration in the glacial sediments.

We also, there’s quite a bit of uncertainty in those concentrations due to the permeability of the glacial sediments. Some of these others have less of an effect. The instant release fraction, the waste package degradation rates. And then there's the DRZ permeability. And it's a little surprising that it's kind of that low. But that doesn't mean it's always going to be that low, either. Remember this is an analysis of uncertainties and how much uncertainty in your parameters is causing uncertainty in your metric. In this case, it's the iodine 129 concentration in the overlying aquifer. As the repository design changes, as uncertainties maybe narrow in some of these, for some of these parameters, it's possible that we could see DRZ permeability become more important.

All right. And you've seen this slide before, so I won't spend too much time on it. Yifeng did a fine job explaining what this model is. It's a borrowed model, and we're just implementing it for PFLOTRAN in more of a 3 dimensional kind of way. And I don't really have anything to add to what Yifeng said, other than what is often, the way the scenario works is, often the groundwater salinity is above this, whoops how do I go back here? Oh, good. The groundwater salinity is above this .004 moles per liter. And so, when it's above that we don't have erosion of the buffer. But after a glacial period, when the glaciers are retreating, there's the possibility that a lot of the meltwater can possibly go down to the depths of the repositories and then possibly cause enough erosion to expose the canisters to flowing groundwater. All right. I think it's Rosie's turn.

LEONE: Thanks, Paul. My name is Rosie Leone, and I'm a member of the technical staff at Sandia National Lab and I'm going to be going in more detail about the DECOVALEX reference case. So, what DECOVALEX is, what the reference case entails, and how we modeled that. And go into and summarize what we learned from this, not only with our own simulations but also comparing with the other teams.

So, DECOVALEX has been mentioned a lot, but it stands for the Development of Coupled Models and their Validation Against Experiments. It's an international research model comparison collaboration. And there's various tasks within DECOVALEX. I'm going to be talking about Task F1 which deals with a generic spent nuclear fuel crystalline repository. And this is actually sort of a new task compared to other DECOVALEX tasks because it doesn't have any actual experiments involved, but instead it's comparing different methods and models. And this task was actually proposed by the DOE team and we’ve led it for the past four years.

And the objectives of it was to build confidence in the models, methods, and software used for performance assessment. So, one of the key things we were trying to get out with this task is looking at the uncertainties in modeling choices, fracture statistics, and parameter uncertainties and how that all plays into your models and your quantities of interest.

And so, we did this through an iterative process. We started out with some simple benchmark cases, looking at simple flow and transport and comparing them to analytical solutions. And then we started getting more complicated, looking at four deterministic fractures, then adding stochastic fractures onto this. And finally, we agreed upon a full reference case to simulate and compare as a team, compare it looking at different, what we wanted to actually look at in respect to like processes.

So, there are seven different international teams, including the DOE team, that modeled this full reference case. So just quickly going through those teams besides us. First there was CNSC from

Canada. And the way they looked at it was they had actually a different near and far field model, and modeled a single deposition hole, and had a source term out to the far field.

Then there was BGR from Germany. And BGR actually did not model the engineered barrier system, but instead just released the tracers where the repository was located. Then there’s NARI from Taiwan. And they did something similar to CNSC with their near field model, and looked at two different types of deposition holes, one that had a fracture flowing through it, and one that didn’t. And they were also the only team that looked at particle tracking.

And there was the KAERI team from South Korea. And one thing they had to do was add in artificial diffusion to help with convergence issues. There’s SSM in Uppsala University from Sweden. And they didn’t actually model the, as Paul mentioned, depth dependent fractures, but instead they had a more homogeneous fracture network. And then lastly there was SURAO from Czech Republic who also, similar to BGR, they included some of the repository features but not all, such as they didn’t include the backfill.

And all these teams were interested in this task because they’re all looking at crystalline rock as a potential host rock. And they were looking at to really either improve their current modeling methods or to kind of validate what they already have.

So just to go in more detail about what the DECOVALEX crystalline reference case entails, I have pictured here what a plane view of the repository. So, it’s about 1040 meters by 652 meters and there’s 50 disposal drifts, 25 on each side of this main tunnel right here. And everything was spaced for the deposition drifts 40 meters center to center. And then the deposition hole spacing along these drifts was 6 meters center to center.

And as Paul mentioned, we’re looking at four PWR waste packages. And we were modeling this based on the KBS-3V concept that the CVN-SKB uses and we’re looking at bentonite buffer backfill. I’m going to go into more detail in the fracture on the next slide, but it’s loosely based on Olkiluoto and each team ran ten different fracture realizations. Some teams used a set of fracture realizations provided by the DOE team, and then other teams decided to create their own fracture realizations based on a common set of fracture statistics that we provided to the teams in our task specification.

We were looking at steady state flow. So, the top of the domain simulates a hillslope. And then we were looking at, for this part, just conservative tracers, one that released instantly and the other that released at a fractural degradation rate. And the reason we did this was just for simplicity, since this is a model comparison project and also to possibly identify these fast fracture pathways.

So, this is similar to what Matt talked about before lunch. But so, applied into the DECOVALEX reference case. But how we actually generate our discrete fracture network and then upscale it. So, we gave the teams various fracture statistics. So, this include pole orientation. So, with that you have the mean trend, which is the angle of the projection, the plane onto the XY plane, sorry, makes with the X axis. Then the mean plunge, which is the angle of the pole makes with the X axis. And also your concentration parameter. And then we're looking at the power-law distribution, the intensity of open flowing fractures, and the transmissivity. So our transmissivity decreased with depth. So basically we had less fractures as you go down. And from within that there was three different depth zones that we looked at and then three fracture families within those depth zones, so sub-horizontal, east-west, and north-south. And these were, the statistics were taken from the central hydraulic unit west depth zones two through four.

So, we plug in these fracture statistics into DFN works and, oops sorry, there I go, and we get stochastic fracture realizations of - based on those statistics. So, in this case, we had ten different stochastic fracture realizations. And then, we had six deterministic fractures that stay the same for all the ten different realizations, ensuring that the repository didn’t intersect with any of those deterministic fractures. And then we take that DFN and we input it into our upscaling software of mapDFN to get an equivalent continuous porous medium.

So, going more into our upscaling options. So, the reason, as mentioned, that we upscale is because it’s a lot more, one of the reasons, is that it’s a lot more computationally efficient.

So, we're lowering the amount of grid cells that we have to run. So, it runs a lot faster compared if we were simulating the DFN. So, the way mapDFN works is it takes that output from dfnWorks and then it calculates equivalent permeability and porosity and we can input that into PFLOTRAN.

So, PFLOTRAN only takes the principal component of the permeability tensor. But here's an example of what the permeability field looks like from the upscaled model. So, we can see that there's a lot higher permeability fractures on the top part of this domain, so that's where that depth dependence comes in.

And then one nice thing about mapDFN is that you can upscale it at different grid cell sizes in different parts of the domain. And so based in the repository, we can actually upscale it at a finer width than at the far fields, which I have shown here. Just a slice of the upscaled permeabilities in the repository. So, we have a fracture here intersecting a deposition hole and we can see that it's about a third of what the far-field upscale is. So that's one nice thing that's been implemented into mapDFN.

And then as Matt talked about, we also have the stair step correction that we can apply to this permeability field. And I'll show an example of that in the next slide. So then once we have our upscaled permeabilities and porosities, we can get our steady state, we get our steady state pressure solution and then from there, there's two different options for transport. One, we can use the ECPM as is and look at a single continuum. But then we can also, a second option is to use a dual continuum model in PFLOTRAN that we've developed and improved in part of this task to work with the full repository.

And so, the dual continuum has advantages because it can model fracture matrix diffusion on centimeter to millimeter scale compared to the ECPM. And it uses a method called the Dual Continuum Discretized Matrix method, so I'll refer to it as the DCDM model.

And the benefit of this is that the secondary continuum is your matrix and then you have your primary continuum, which is your fracture. And it models diffusion into the matrix as a 1D diffusive flux. And this kind of assumption allows us to run the model a lot faster and in parallel, which is valuable for these really large simulations.

So going into kind of the results and what we learned from participating in DECOVALEX... So, this is one of the first benchmark cases we did. It’s four deterministic fractures in a kilometer cubic domain. We had a pressure gradient going from the left side to the right side, and then we inserted a pulse of tracer on that inflow and simulated as it exited the outflow. And we simulated this with both a DFN and an ECPM.

So, I have a breakthrough plot plotted here. You can see the red is the DFM and this dash line is the ECPM with no stair step correction. And then the solid line is the ECPM with the stair step correction. So, we can see how the tools that have been developed in dfnWorks are being used in this reference case and how it improves our comparison. And we’ve actually added this in as the default option within mapDFN and then use this, the full reference case.

The next benchmark case is looking at four deterministic fractures, the same four deterministic fractures and then adding stochastic fractures to that network, but in this case all teams used the same stochastic fracture network. And what we did was we had the same pressure gradient, but this time we injected a continuous point source along that inflow boundary and then simulated the tracer moving through the domain.

And we did this for three different tracers: a conservative tracer, a decaying tracer, and a sorbing tracer. So, I have the, two of the tracers are the conservative and the sorbing plotted up here, comparing the ECPM and the DFN. So once again, the DFN is in red and the ECPM is in blue. And then the dotted lines represent the sorbing tracers.

So once interesting thing we noted here is that the ECPM delays the fastest, 90 percent. So that could be due to the fractures being characterized, the correction. But it speeds up the slowest 10 percent, which could be due to something such as a false connection. So, we see both things kind of at play here.

And then going on to the full reference case. So, this image right here shows a slice along the middle of the Y axis of the tracer concentration at 10,000 years. I just want to note that the bounds of this tracer concentration, the maximum is at 6.8 times 10 to the negative 12 Moles per liter, and most of the tracer reaching the surface is at 1 to the negative 13 and 1 to the negative 14. So, we're looking at really small values here.

But we can see our repository here, how the tracer moves through the bottom of the domain and then flows out of the top surface around the southeast portion mainly, where we had those deterministic fractures.

And one thing that we did was we compared this ECPM method with the DCDM method. So, this plot right here shows the mean of 10... 10 fracture realizations for the ECPM in blue and then the DCDM in yellow. And then those shaded regions are the 95 percent confidence intervals of the mean from the 10 DFN realizations.

And you can see that the DCDM is showing slightly higher concentrations than the ECPM. And one of the reasons we think this might be happening is that there's possibly less numeric dispersion with the DCDM because we're looking at matrix diffusion over a smaller scale. There's also lower volume within the fracture in the DCDM compared to the ECPM, which is looking at the full grid cell. But this is one thing that we're still looking into.

And the important thing here is that we can see that different model choices do make a difference on what we see in the concentration. And I think I forgot to mention, but this concentration has taken an observation point right along here at the top of the domain where deterministic fractures sort of intersect that top surface.

Alright, so to summarize, what we learned by looking at the conservative tracers. So unfortunately, I can't show our results compared to the other teams' results because we're not, the other teams' results aren't publicly available yet, but I can go through the main things that we've learned.

So first, assumptions made in the repositories, repository, can lead to large differences in the far-field observations. And these are more so than choices of upscaling methods or a simulator being used. And this was seen, tying back to the beginning of the presentation, where I went through the different teams. But in the BGR team, who did not include the repository, they had much higher concentrations and mass flows out of the domain. And that outweighed any other decisions that they made. And the same was seen for the team from the Czech Republic who also made simplifying assumptions in the repository.

And the second is that domain-scale heterogeneity plays a role in far-field observations. So, another team is SSM who used, did not use depth dependent fractures. They also showed a lot higher values in concentrations in the far fields because they didn’t include that decreasing of fracture transmissivity with depth which shows us that’s important to get sort of, know the fracture network that you’re looking at.

And thirdly, within our own sort of simulations that we ran, we looked at the choice of grid cell size and how that affects your output and your runtimes. So here I have plotted a result from our simulations, comparing a 25 meter ECPM grid, that’s in red, with a 20 meter ECPM grid in blue. So those bold lines are the means once again, and the light lines are different fracture realizations, except this time we’re looking at cumulative mass flow in moles for the cell with the maximum mass flow out of the entire domain. And we can see that we have overlapping confidence intervals here, which show that they’re giving similar results. But the 25 meter grid was around 26 times faster than the 20 meter grid to run, which is, can be quite significant on the same number of processors.

And lastly, most importantly, but there’s still a lot more information to be learned here because we really want to get into how these modeling choices affect parameter uncertainties, or how they relate with one another and how fracture statistics all play in with that, and that’s something we’re going to continue to look into as the project is going to continue on for the next four years.

So, lastly before I turn it back over to Paul, so I just want to talk about moving on beyond the conservative tracers. We’re also starting to look at a radionuclide decay chain in the reference case. So, to do this we’re using the isotope partitioning and decay model in PFLOTRAN. So, it does isotope partitioning among aqueous, solid, and adsorbed phases. We have decay and ingrowth in all the phases. And this was implemented just in our DECOVALEX reference case for both the ECPM and the DCDM.

And so, you can see the example, radionuclide inventory that we’re looking at here and the decay chain. And also, I don’t have them included, but there’s adsorption and solubility also included in on here. Also, this is kind of looking into the future about what we’re going to look into next. And now I’m going to hand it back over to Paul to talk about performance factor analysis.

MARINER: Alright. We’re finally to performance factor analysis. We’ve mentioned that how many times today already, starting with David? So, what is it? Well, what performance factor analysis does is-it looks at sources of performance and we’re talking about safety performance. When we run our full system simulations our ultimate goal is to be able to calculate the concentrations or doses at the receptor in the biosphere.

And then what we typically do is compare those calculations to the safety thresholds. That’s where we can get an idea of how well this system as a whole performed. But what it doesn’t tell us is where performance comes from in the model and so that’s what performance factor analysis is getting at.

So, when we ask the question, where does performance come from? The very simple answer, the unquantitative simple answer, is that it comes from natural barriers and engineered barriers. There's a lot of performance from the natural barriers. Just the simple act of taking your waste and putting it 500 meters below ground, far away from the biosphere, that provides a lot of performance.

So, what we're going to be doing now is looking at, okay, of the engineered barriers, how much performance is coming from them? The engineered barriers, again, here's kind of a quick summary of the major components of the engineered barriers. We have backfill, buffer, the waste form, and the waste package.

The waste form barrier is the solid form. In other words, it doesn't release the radionuclides right away when the waste package breaches. It takes time for that waste form to degrade and release the radionuclides. And so, for that reason it has performance, just the waste form itself. It's part of the engineered barrier system. The natural barrier system is basically the host rock and other lithologies that are between the biosphere and the repository.

Now, when we're trying to calculate how much performance comes from the engineered barriers, we have to use a model. And so of course those calculations, they're going to depend on the repository design, geosphere and biosphere characteristics, and model assumptions and simplifications. The actual measurement, the actual calculation of performance for the overall repository system is done by calculating probabilistically the peak of the performance metric, like dose, during the regulatory period in a full system model and comparing it to the regulatory limit or the safety threshold.

When we want to look at performance of individual components in the model, then we calculate performance factors. And this is the equation for a performance factor. It's very simple. It's the value of the performance metric when the component *i*, okay, component *i* is the, is the component we are evaluating the performance factor for. So that could be a buffer for example.

Let’s just pretend it’s a buffer right now, the buffer material. So, to calculate the performance factor you take the ratio of the performance metric when the buffer, the component *i*, is excluded, divided by the value of the performance factor that’s calculated when the component i is included.

So, for example, if the dose is 9 times higher when the component, in this case the buffer, is excluded, then the performance factor is 9. It’s a very simple concept. It’s very intuitive and it makes explanations and relative comparisons very easy.

This is our first demonstration of the performance factor analysis and we did this on the DECOVALEX crystalline reference case. We took the DECOVALEX crystalline reference case and we added performance to the waste packages, and we added performance to the waste form. So otherwise, it was the DECOVALEX reference case. And then we simulated the model for actually 100 million years because we wanted the full breakthrough curves.

So, this graph on the left side is the concentration at the receptor versus time in years and both are on log scales. The time here goes from one year to 100 million years. This black line is the Iodine 129, as if all components are performing as designed and as expected. And this reference case, in the reference case for Iodine 129, this is the breakthrough at the concentration at the receptor for Iodine 129. And we're looking at Iodine 129 because that's typically the radionuclide that drives the dose.

This red line here is a little bit different from the black line. And what we did there is we just took away the decaying part of the Iodine 129. So, this is the effect of decay, if you take away decay from Iodine 129. It just changes that breakthrough curve just a little bit. But then if you take away the waste form performance, you get this yellow curve. You can see the concentration goes much higher. The peak is much higher when you take away the performance of the waste form.

Now if we further take away the performance of the waste package, we get this green line here and then we see Iodine 129 showing up much earlier at the receptor, but it really has almost no effect on the peak. And that's because in this reference case what we are assuming is that the waste packages are lasting approximately 30,000 years on average so by a million years they're pretty much all failed.

And then this last line, this last blue line, is what if we further take away the buffer and we replace that with crushed rock, then what do we get? And we get this blue line. So, this is with all the EBS components taken away. So that's what you get just from the natural barrier system. You get a breakthrough curve that looks like this blue line. Now we can take these breakthrough curves and calculate the performance factor straight from this graph and that's what I've done here. So, if we start off with the 10,000 year period, the 10,000 year period goes to right here. That's the light blue performance factors in the graph on the right.

Right at 10,000 years that's when we have the peak concentrations for every situation here, for every breakthrough curve. So, we're just going to be comparing concentrations at 10,000 years because that's the highest concentrations. When the whole system is performing as expected, the EBS is performing as expected, the concentration is right where my pointer here is, for - at the 10,000 years. When we take away the performance of the waste form, the concentration increases tenfold, exactly tenfold. If you compare those two concentrations you get a performance factor of 10.

Now we further take away the waste package performance, and we get a 23-fold increase in the concentration at 10,000 years at the receptor. And then when we further take away the buffer and replace it with backfill, it’s another 12.8, a factor of 12.8 higher, the concentration is. So overall when you take away all the EBS components the concentration increases almost by a factor of 3,000 and that’s that value at the top, for engineered barrier system performance. You get a performance factor of 3,000 for the EBS components in this particular model.

And what’s kind of interesting there is that if you multiply the performance factors of the waste form, the waste package, and the buffer, you get 3,000. And that’s because it just comes straight from this, these breakthrough curves.

When we look at a million years it gets a little more complicated because again, we're looking at the highest concentrations in those million years. When we take away the waste-form performance, the concentration increases by a factor of 6. The peak concentration increases by a factor of 6.

When we further take away the waste package performance, it doesn't increase hardly at all, so the waste package performance factor over a million years is 1.02 in this case. But when we replace the buffer with the crushed rock, we see that there's still some performance provided by the buffer, a factor of 2.32 we get as we go from the peak here to the very peak at, what, 300,000 years.

Okay, I thought I had one more point I wanted to make here. Just lost it, I guess. Okay, so performance factor analysis I think can be very useful, and we're going to be building this into all our reference cases because it helps to explain and evaluate our reference cases and better understand the systems that our models are simulating.

We think that these performance factors not only help quantify how much performance is coming from different components, but they are useful because they can easily communicate the model barrier performance.

One thing that we’re starting to do now is, we’re starting to look at not just whether the component is there or it’s not, on/off. We are now also doing performance factor analysis when we start looking at different ranges of lifetimes. So, for example, for the waste package performance, we’re going to, we will do simulations for lifetimes of, say, 100,000 years versus 10,000 years versus 2,000 years versus 3 million years. Because each of those cases might represent a different material for the overpack. But they are also going to have their own performance factors associated with them. And then we’re doing combinations, so we might have a certain lifetime for a waste package versus a certain lifetime for a waste form. Those analyses are ongoing now.

Another kind of useful benefit of this performance factor analysis is that we can use them to help us quantify how much we rely on engineered barriers in one host rock versus another host rock. You know, we do have a lot of reliance on engineered barriers and crystalline rock and we do have less reliance on them in salt. It's just not as necessary in salt.

This second major bullet here kind of gets to some of the ideas that Dave Sassani was talking about earlier in the day. There are a whole lot of radionuclides that are solubility limited. As the waste package breaches and then the waste form starts degrading, the actinides, I would say most of the radionuclides, most of the elements that are released have solubility limits in that system.

And there's a lot of performance from that. Just by putting this into an environment where their solubilities are low, that's going to prevent a lot of transport of these actinides. And so, we might be able to use performance factors to help kind of quantify and help explain how much performance we're getting from those, I wouldn't call them natural barriers, but those are more natural processes that help us, that help the system work.

And then finally on that last bullet, we are certainly, we certainly need to be careful with how we use performance factors. Performance factors are going to be very conditional. We just can’t blanket say the performance factors for a salt case is this. For those components, you have to know the entire repository system that you’re modeling and all the assumptions that go into it.

More work to be done is to run our simulations probabilistically so that we can calculate performance factors probabilistically so we know the uncertainties surrounding those performance factors that we’re calculating. That’s in the works. And then, of course once we do that, looking at the sensitivities of the performance factors based on those uncertainties. Alright, and then I think that’s it. Questions?

TYLER: Thanks Paul, thanks Rosie. Scott Tyler with the Board. Just kind of a question on both the GDSA reference case and the DECOVALEX reference case. What’s the, what’s controlling the peak concentrations in this cases of, I think it was iodine 129? What’s the, if I distill back down to what are the factors that limit the concentration for those models?

MARINER: Well, it’s not being limited by solubility or sorption. It is enhanced in a way because we simulate approximately 10 percent of the iodine 129 as being instantly released.

TYLER: Okay, I saw that earlier.

MARINER: Okay, and there’s uncertainty around that as well. But it certainly is visible. There is, there was a slide early on in my talk where I showed the relative variance, the total value index comparisons. And instant release fraction is, does have the uncertainty there. It does have a pretty big effect on the uncertainty in the peak iodine 129 concentration. But it’s that figure, and maybe I should go back to it, because I think that probably answers many of the questions that you – of what causes the highest peak iodine 129 concentrations. There it is.

Certainly, the fuel degradation rate is very important. That’s your source term, how fast it’s going to degrade. That’s going to have a big effect. Yeah, maybe that is your answer right there. Would you like to add to that?

LEONE: I guess I'll just add that also I think the fracture network plays a role in it, too. So, I know for this case we also looked at the fracture statistics, so like the intensity of the fractures. I know in the DECOVALEX case, having that depth-dependent fracture relationship helped control that peak concentration you see.

TYLER: Rosie, I think it was in your case, but it looked like the concentrations were fairly uniform from the source, from what I think where the source was, up all the way to the surface. I saw a lot of red, anyway. I didn't see a lot of –

LEONE: Yeah, it was in log scale, but it's definitely, the most towards where there was deterministic fractures and kind of just where the flow path is going, if that makes sense.

TYLER: Okay, but there was a log scale on there.

LEONE: Yeah.

TYLER: Okay, that helps.

LEONE: That was magnitudes, I think, of about 1 to the negative 14, 13. It’s very small.

TYLER: Okay. And the 10 percent release rate is 10 percent of the entire inventory, it’s there in the canisters, all canisters. Okay.

MARINER: Yeah, that’s correct. So, of course, these canisters don't all breach at the same time and we have them breaching over time. But when a canister breaches, yeah, 10 percent of the iodine 129 is instantly released and the rest of the 90 percent in that canister degrades slowly with the fuel matrix and is released slowly as the fuel matrix degrades.

TYLER: So, it’s a combination, then, of the failure rate times the release, plus the 10 percent release rate when it fails. Now I understand.

MARINER: Right.

TYLER: Thank you, okay.

ILLANGASEKARE: Thank you. So in the reference case, when you generate stochastically the disturbed zone and there are different statistics for the disturbed zone and the far other zone, is that correct, the fracture network? Because there are different studies statistics to generate the network, is that correct? Am I understanding? How do you generate the fracture network stochastically?

MARINER: Right, so this actually shows the results of those kind of simulations. So, in this particular case, we are, we have an uncertainty range for the DRZ, the Damaged Rock Zone, of permeability between 10 to the minus 19 and 10 to the minus 16 meter squared. It’s three orders of magnitude of uncertainty that we sample from. And even that kind of large range of uncertainty doesn’t really, it’s kind of masked by these other factors when we look at the peak iodine 129 concentration in the aquifer.

ILLANGASEKARE: Okay, that explains it. The second question is a more general question. So, you are using steady – steady state. So, you think, I don't know, the steady state the most conservative case? When you say the steady state assumption, is it going to give you the most conservative case, or the worst case, worst cases? I don't know the answer, but I’m asking you.

MARINER: I guess I don't think of it as the most conservative case. Right now, we are not considering changes to hydrology over time. We’re not, we have not developed that far to take on those types of scenarios, changes in climate and things like that. That is something that we will definitely consider at some point. But as far as conservative, no, I would say that just the steady state here is really just giving us, helping us just to understand our system better.

ILLANGASEKARE: But some of the source term, it depends on the groundwater flow?

MARINER: Well, so when we have our DFN realizations – for example, for this crystalline reference case, I believe we had 40 different DFN realizations. When you have different DFN realizations, you have a different number, usually a different number of fractures that actually intersect the repository. And another figure I could have shown from the same report actually looks at the number of fractures that intersect the repository and it does have an effect on that peak iodine 129 concentration. In fact, it has a very, very significant effect. So, in a way, you know, that’s why we kind of run these simulations probabilistically so that we can kind of see what’s possible. And in some cases, yeah, there’s a bunch of fractures that intersect repository and that causes a higher peak iodine 129 concentration.

ILLANGASEKARE: Okay, thank you.

TYLER: So Paul, on that point, that’s a good point. That... in that case then while the uncertainty in the DRZ permeability is a small factor in this case, if you multiplied it by the probability of intersection of a fracture, if you will, it could have a much higher impact in the concentrations than this issues individually. So it’s... it’s kind of a joint probability, the probability of intersection of a fracture with some of the other factors in the disturbed zone.

MARINER: That’s right. And it starts getting a little complicated that way. Now I would say, though, that if – when we’re actually constructing a repository and we build our drift and we see a flowing fracture, we’re probably not going to put any waste packages right there. And we haven't built that little conditional statement into our modeling yet.

SIU: I have a few questions. First, Rosie, I guess first of all, a comment. I guess I’m not surprised in this international benchmark that people follow different modeling assumptions and that those can drive the results. But I still think there’s value in doing this, and you’ll learn a lot from that. So, when will the report come out that compares the different results? Is that the end of the four year project or is there something sooner?

LEONE: Yeah, so we’ve actually written the final report already and I’m also in the process of writing a paper on it. I believe they said it would be available at the end of this year maybe. Do you remember, Paul? I know they’re holding out to publish them publicly I think because of their having a special journal paper, so people can publish their individual results. So, I think hopefully by the end of this year, but yeah, I agree, there’s been a lot of value from it and we have a lot still, more to learn from it. So, we’re excited to continue on with it.

SIU: Paul, a couple of questions. I know that there was, Dave emphasized that we're in the development stage, building capacity, building capabilities. Still, are you thinking of using GDSA in its current form to support prioritization of activities, or is this purely a demonstration?

MARINER: I would say only qualitatively at most at this point. Because these are, these reference cases are very specific and we know that our...eventual site may be very different. But we will be prioritizing R&D going forward. And I think we're going to be learning a lot about what parts of our system tend to be important when we calculate dose.

SIU: Yeah.

MARINER: And so I do see it feeding in.

SIU: The second question, you've settled on a particular performance factor definition. It makes a lot of sense. As you know, in the reactor community, they've settled on actually two different equivalent performance factors. They're different ideas, different ways to measure importance of a particular topic or barrier. Are you guys thinking of looking at alternative or additional performance factors, or is this –

MARINER: I’d be happy to, yeah. We hadn’t so far. We’ve just started exploring this. But I’d be happy to take a look at that. I’m sure we can learn a lot from it.

WOODS: Brian Woods, Board. On the topic of performance factors, at the very end you talked about, you know, things you wanted to do going forward and I guess it was investigate sensitivities. I’m just curious, could you explain a little bit more about that? Because right now, it’s kind of off and on, right? You either have it or you don't. Are you going to start looking at maybe marginal or fractional degradations and see how that affects, or – so yeah, could you just explain a little bit about your plans for sensitivity studies regarding them?

MARINER: Yeah. So, we are actually right in the middle of a project that we are going to report on. We’re going to have a report on it in September. Where we are, we have this table set up of waste package performance versus wasteform performance.

And from like zero, like slow degradation rates to high degradation rates for the waste package and the same for the waste form. And so different combinations. We are looking at every single one of those combinations and we're going to plot up all those breakthrough curves for that and calculate performance factors for that and then step back even farther to see if there's trends that we can learn from, from that. Yes?

BALLINGER: This is Ron Ballinger, Board member. The way I read your presentation is, the canister buys you 10,000 years and after that, it's the fuel degradation rate. And those are the two dominant factors.

MARINER: Well, remember, we have to start somewhere.

BALLINGER: Okay.

MARINER: And in the current conceptual model, our waste package lasts on the average about 30,000 years. We're not even saying what the material is; we're just saying okay, we're going to assume this.

BALLINGER: Yes.

MARINER: Now, if you actually put a copper canister in there, it can last well over your million year regulatory period. In fact, that’s what they’re banking on and that’s what they show very strongly in the Scandinavian models.

BALLINGER: So, which canister material are you using here?

MARINER: Well, again, we don’t actually specify the material; we’re just, we’re assuming a lifetime, basically.

BALLINGER: Okay.

MARINER: And we’re seeing, and we are now, you know, like my answer to Brian, we are now looking at, well, what if it’s only a 1,000-year lifetime? Or what if it’s 100,000-year lifetime? Or what if it’s a million year? How much performance does that buy you? Do we have materials that can satisfy, or a combination of materials and buffer and everything that can satisfy that we can do? And it’s all part of just looking at alternatives right now and what buys you what?

BALLINGER: Thank you.

SIU: Chandrika?

MANEPALLY: Chandrika Manepally, Board Staff. Thank you, Paul and Rosie, very nice presentation. I’ll first ask Paul. This refers to the erosion model, buffer erosion model on slide 10. Yeah. So, I was curious that, I think in Yifeng’s presentation they refer to the BELBaR project. I don’t know if you have looked at that results, that focused on buffer erosion and, you know, what are the important properties that you need to take care of. And one of the conclusions of the BELBaR project was the physical factors like the groundwater velocity is not as important as the chemical aspects. But then I see here that the buffer erosion rate is a function of fracture aperture angle, which I think influences the water velocity in some cases, is one of the functions. So, I was just wondering if you had any opinion about what the BELBaR project concluded was, is what you are thinking?

MARINER: Well, this is a model that we started with and it’s been in the works for a little while. It’s been slowly making progress. Rosie is actually working on that too.

MANEPALLY: Okay.

MARINER: There are, I have noticed that there are more models coming out on this. So, what we’re actually doing is we’re building this framework. A lot of it has to do with, you know, how do we build in these intersecting fractures into our repository? That’s what Rosie’s really been working on. So, we can actually do this in three dimensions. We can get those water velocities and stuff like that. It’s pretty kind of ingenious how, I think how we’re doing that. But really, it’s all about building this framework first and then we can start working on improving those models. And maybe it’s already time to update our plan for buffer erosion. But I would bet that a lot of the work that we’re doing to put this model together is going to just put us in a very easy place to adapt to bigger and better models.

MANEPALLY: Okay. The next question I had was, you’ve been using SKB and POSIVA data, right? And you’ve been doing a lot of modeling and getting results, whether it is breakthrough times or concentrations. I was wondering, have you kind of gone back and looked at their reports to see how you sort of compare in terms of are you getting consistent answers, or I mean consistent results, or is it different because you’ve been using DFN and they probably use, you know, like equivalent continuum porous media models. So, have you kind of gone and checked?

MARINER: We haven’t done a lot of that. We’re really focused on building capabilities right now. We know that they rely on copper canisters and those copper canisters last a million, million-plus years. There’s only one or two that fail in their entire repository. So, in a way, it’s not really relevant to the kinds of models that we’re, the reference cases that we’re building right now because right now we’re just, we’re working on the capabilities. But yeah, it’s definitely something that we need to be very aware of, what those folks are doing, the data they have, the ideas they have. It’s very important to keep on top of that.

MANEPALLY: Okay.

BALLINGER: Can I ask another? Just to be clear, I'm looking at this curve. You're making assumption here about when the canister fails. And I don't know, you just made the assumption. But the shape of the iodine release curve won't change. Once you fail the canister, the shape is the same. Is that right?

MARINER: The iodine, 10 percent of the iodine in that waste package immediately gets released and so you actually kind of will see a little spike if you looked really closely.

BALLINGER: Yeah, I see.

MARINER: But then, and then from then on as that little spike kind of diffuses out from that waste package, it kind of goes away and it's just slowly, iodine is released congruently.

BALLINGER: Right. But the shape of this curve will be independent. It just depends on when the canisters start to fail. Because the fuel degradation model is what it is. So, if you fail the canisters, you have the same shape of the curve.

So, I’m looking at this in the buffer and everything buys, is good for 500 to 1,000 years. And then you breach the canisters. And now you release this, you have the shape of this curve. So it keeps telling me that for this case the barrier material which defines when the canisters start to fail and the fuel degradation model dominate. I’m just, is that too many assumptions on my part?

MARINER: I don’t know if I followed everything there. Are you, you’re going from the performance factor analysis breakthrough curves?

BALLINGER: Yeah because, I don’t know what slide number it is, 24 maybe. That’s not it. What did I do? There it is. Okay. So the way I look at this, the shape of the, if you fail the - once you start failing the canisters, assume they fail over a reasonably short period of time. It looks like they fail, you make an assumption on when they fail. Is there a distribution on when they fail? Okay. So there’s some distribution. But once they start to fail, it’s the fuel degradation model that governs.

MARINER: Right.

BALLINGER: So, I’m just trying to get a handle on it for this set of calculations, the importance of that canister.

MARINER: Right, okay. So the mean lifetime of the canister is, let’s see, that’s 10,000 years. Okay, it’s right in here. This is the mean. It’s right between these two gridlines.

BALLINGER: Okay.

MARINER: That’s the mean canister lifetime right here.

BALLINGER: Yeah.

MARINER: Or median, yeah.

BALLINGER: Okay. I’m just trying to make sure I understand in my head what the dominant variables actually are for this case.

MARINER: Right. Because it’s important when you start to talk about performance factors for it.

SIU: Okay, we may actually have time at the, after the end of the upcoming presentation, but for the sake of the schedule let’s move on. Thank you again. Sorry, Bret. Next presentation is by Professor Laura Pyrak-Nolte.

PYRAK-NOLTE: Okay, thank you. As we’ve heard a lot today, the geometry of your fracture, your fracture network, is really important and I was asked to talk on some of these topics which this is from the email. And what I’ve done is highlighted in red what I’m going to talk about. Probably the main focus of my talk is sharing insights on representing fractures within a flow model. And this is going to be based on experience that I had working on crystalline rock, as well as other rock types and synthetic materials.

There’ll be one slide on fracture characterization to show that in a certain representation of fractures you have a link to seismic wave attenuation and velocity. And then sprinkled throughout my talk, I come to the last part, maybe I don’t know if it’s so much vision for the research, but certain questions that maybe should be addressed.

And so, we’ve seen today that you can model your fracture network by discrete fracture networks, DFN, or multi-continuum models. No matter what type of model you’re using, at some point you have to make certain assumptions. Now, I’m going to pretty much talk about simulating fracture flow and deformation because I think they sort of go hand in hand.

And the first thing you have to assume, what is your fracture geometry? So, how many fractures you have, their orientation, what are their apertures, do they have contact area, what are their lengths. The other thing you need to know is how this geometry evolves under stress or possibly from other physical and chemical processes.

One thing that hasn’t really been talked about today are intersections, which give you the connectivity between your fractures. They have their own aperture and contact area and pinch points. And, of course, you care about your fluid and material properties.

So today what I’m going to talk out, talk about, and this is all insights from the laboratory, is first the single fracture representation, since that’s your basic element of the network. And then that’s going to be followed by the impact of your intersecting, the orientation of your intersecting fractures relative to some stress field, on not only the apertures in your fracture network, but the geometry of the intersections.

And then the final thing I’m going to touch on are mixing rules. And so, if you have an intersection which is undergoing stress, will the mixing rules used in discrete fracture networks still apply?

So, I’m going to begin with single flow in a fracture, and we heard about this a lot today. That you can take your single fracture and represent it by a set of parallel plates which follows the cubic law where your aperture b is raised to the power of 3. But we know that if you look at real fractures that they have contact area which is shown here in white and then they have voids of variable shape and geometry. In this case red being large aperture, blue being small.

So, as we’ve heard in many talks, what do you use for b’s? At the hydraulic aperture, the mechanical aperture, are either of them sufficient? And what if you have anisotropic flow? So, a preferred direction, how can you represent that?

Well just to give you a sense of what laboratory data looks like when you measure fluid flow through a single fracture, here I’m showing you data of flow per unit head as a function of stress, for 13 different samples, different types of granite, different sizes, but they all had a single fracture that was loaded perpendicular to the fracture plane. And so, if you look at that you see as a function of stress your flow magnitudes are all over the place, and how they fall off with stress.

So let’s just focus on two of these samples. And so I selected these because at very low stress they have the same flow rate. So you would assign them the same aperture in your model. However, if you had to stress the system, these two fractures behave very differently. The red curve with the squares, if you see, falls off very slowly with stress; while the blank circles drops very rapidly as you start to load it.

So how does this occur and how do you capture these effects? This is where we go to how our view of fluid flow and fractures evolved based on experimental data. So you go back to the ‘50s, yes, and they said, well we can model flow as parallel plates. But as everyone knows, usually the cubic law fails when you try to match it to laboratory data.

So then we looked at having rough surfaces, adding contact area, until today we pretty much know that you need the, you can image the entire fracture plane, get out the aperture, the roughness, and the contact area. And so, what matters is not only that you have some aperture, but it’s going to depend on how your aperture is spatially distributed.

So, we’re looking at two cases here on the left. We have a random distribution of aperture, and on the right it’s spatially correlated. It’s being loaded perpendicular to the plane. Red is large aperture, blue is small, and white is contact area. And in the right side of each of these movies, you’re looking at the flux through the fracture plane.

And what you notice on the random distribution, that even as you stress it and you’re increasing the contact area, you have multiple flow paths which are still supporting flow. So here’s a case where the stress would be increasing but your flowrate wouldn’t be changing very rapidly.

If you have spatially correlated or what we heard about channelized flow, then you have one or two connected paths which can shut down rapidly, and quickly shut off the flow through the fracture network. So in terms of fluid flow, it’s not only your probability distribution of apertures that’s important, but also the spatial distribution.

Now what about deformation? Because we have to make assumptions about how things are going to change as the stresses in the network change. Well, if you’re just choosing a parallel plate model and you close it, well, it’s either going to be opened or it’s going to be closed; just have some reduced aperture. As we saw, I think in Matt’s talk, he talked about the banded Spartan model and this sort to takes into account, they recognize that surfaces or roughness and closure just isn’t changing your b. But the problem here is that you don't really know how closure relates to the aperture, because you have a distribution of aperture and is there, maybe, some disconnect between the cubic law and the closure law?

So how do they look at fracture closure in the laboratory? Well, if you go back to the ‘70s, it started with Hertzian contact, but there only the tips of the asperity is deformed. You go to the bed of nails model in the upper right, well, that just had the asperities getting shorter with stress. Other people for convenience took two rough surfaces and just inter-penetrated them. But it wasn’t until Hopkins in 1991, where she had a model that captured three important effects when you bring two rough surfaces together in contact. Yes, you get a shortening of the asperities, and they also widen. You can get, as shown in the lower right, asperity interaction, so that is when one asperity is deforming and deforming the matrix, an adjacent one will also deform. But the third aspect, which is most important, is the matrix deformation. Most of the deformation that you’re measuring in the laboratory comes from how the matrix deforms as a function of stress.

And to show that, I took this very simple model. I did this in 3D, but I’ve just taken out a slice. And what we’re looking at here is here we have two asperities in contact. This is at zero stress. I put in some asperities that are not in contact. The different frames show how the geometry increases with increasing stress as we go zero to 3 MPa. And then on the graph on the right, we’re looking at the displacement, which is the blue curve as a function of stress and the contact area, which is the red curve and it’s given on the vertical right axis.

Now I recognize the stress here is on log, but that’s mainly so you can see the different stages of the deformation of the fracture. So, when you first start loading the fracture in these little squares go with the individual boxes, you don't have much change in contact area or displacement; you just have asperity widening.

And then you go into this phase before you even start increasing your contact area where all your closures due to matrix deformation. And it’s not just a simple coming together. The b is getting smaller. You’re getting variable shapes in geometry. And then once your contacts come into contact, after that the deformation is very little, but you’re having a tremendous change in contact area. So you’re going to be changing the tortuosity of your flow path.

And so again, what we see is that how this fracture is going to close depends on both your spatial and probabilistic distribution of your apertures and your contact area. So how do we capture this with some effective parameter, right? People talk about they don't want to have to put in the entire aperture distribution into a discrete fracture network, or maybe into your continuum models.

Well, that’s where we go to this effective parameter, fracture specific stiffness. It’s a force per volume. It comes from Dick Goodman in the ‘60s. And back then we had no way of measuring the entire surface roughness easily for fractures. And so, what you could do in the laboratory, let me go back, in the laboratory is take a sample with a single fracture. You’re going to stress the uniaxial load. You measure the displacement across the region of solid material, or no-through going macroscopic fracture and then cross an equivalent length across the fracture where you have both fracture and solid deformation.

And then if you take the difference of these two, you end up with the excess displacement, which is due to the fracture. And so, you could plot that as a function of stress and then one over this slope gives you the stiffness of the fracture. And so this stiffness obviously is changing as a function of stress because the slope of this curve is, but it’s changing as you deform your fracture geometry.

Now why do I like this parameter? It’s because it’s linked to theories that we have for how a wave interacts, an elastic wave, interacts with a fracture. So, on the left here we’re looking at a model of the P wave hitting a fracture. These gray areas are a void. And what you see is the movie runs that as the wave comes in, it’s reflected off the voids and transmitted through the contact regions. If we go to the theory, and I’m only showing transmission at normal incidence to the fracture plane, we see that how much energy is transmitted across the fracture is a function of a specific fracture stiffness.

And so, if we look at data we propagated compressional waves across a single fracture in quartz monzonite in the lab as a function of stress. You're looking at the Fourier magnitude as a function of frequency. The dashed curve is the theory, the red is the experiment. What we see is that as we increase the stress on the fracture, the theory captures the increase in transmission because the fracture's getting stiffer because you're closing the apertures. You're increasing the contact area. And it also captures the shift in the dominant frequency. So frequency dependence is a very strong tool that's available to help capture where you are in the stiffness space in a fracture under stress.

Now if we notice here, we have these estimates of stiffness based on the theory. We go from about 10 to the 12th, 10 to the 13th. Now this looks infinitely stiff. What does that mean? It means it's transmitting as well as the intact sample we have. Does that mean it's not supporting flow? Well, I know because we're measuring flow at the same time that it was. But if we wanted to detect that stiffness, we'd have to go to a higher frequency. So, what's nice about the theory is that in addition to stiffness, it has a scale on it which is the wavelength that you're using, the frequency. And so, the fractures that you can detect are a function of the frequency that you're using. So what I can sense in the laboratory is much different than what you would sense in the field. But in both cases, you can look at your change in transmission and velocity and link it back to normal, as well as shear stiffness.

So now that I’ve told you all this, what was sort of our goal in this whole study – well, I was showing you that using seismic waves, we can interpret fracture stiffness. We also show that fracture stiffness depends on the aperture and the contact area of your fracture, but we also know that fluid flow depends on these same two geometrical aspects.

So, this means that implicitly fracture stiffness and fluid flow should be related through the geometry of a fracture. Why is this important? Because it means we have the opportunity for the Holy Grail, which would be going from a geophysical measurement to detecting relative flow among different fractures, so stiffer fractures would support less flow.

So, the first question that we address was does this relationship exist? And so of course, I’m going to show you yes, that it does. Again, this is for a single fracture. And let me just describe a little bit what we’re looking at. We’re looking at this graph, I know it’s a very complicated axis, but think of this as scaled flow and this is scaled stiffness. We looked at fractures with different distributions of apertures and we also had some where we purposefully eroded some channels so they’d have channelized flow.

Now, in this study what would did is we took percolation and finite size, a renormalization approach. And what that means is that the flow through any pattern, you could look at with percolation theory, right? Now percolation theory though, when you do it, you’re usually looking at flow as a function of area fraction, area of voids. Well, what we found out in this numerical study was that fracture specific stiffness is a surrogate for your void area. And so this enabled this relationship between scaled stiffness and scaled flow. What’s nice about this theory, it has a length scale in here, which could be a physical length or it could be a wavelength.

But if we look at the curve, we see that they often would call this that the scaling is breaking, because there’s a knee in the curve. So what do we have here? Well, there’s actually two regimes. If you’re in what would be a low stiffness regime, all that matters essentially is the porosity of the fracture. So maybe getting away with a cubic law would be okay. And so, we call this the effective medium regime, because you have multiple flow paths that you can access.

On the other side you’re in a percolation regime. And what does this mean? Well, your flow is going to depend on the connectivity of these few flow paths. And so what happens, when you have a connectivity dominated regime, just tiny changes in aperture rapidly decrease the flow.

Now when you’re on the knee of the fracture, and at this point you have a combination of both effective medium and connectivity, but with this theory now you have a way of linking flow and fracture stiffness and fracture stiffness is a property that you can monitor remotely.

One thing that needs to be done, right, since we did this numerically, we do know that someone, some theorist has to work on getting the analytic solution for this relationship, but we do know that the parameters that we’re showing here, which is length, correlation coefficient, the stiffness of the fracture, are in the function.

So what we did is just numerically fit a function form, which maybe this would be the first thing someone could try in a numerical model where either for discrete fracture network or maybe you want to use this in a continuum model, you can look at how flow should scale as a function of stiffness.

How could you use this? Well, we sort of already heard that, in the previous talk, that as they're modeling, they're using apertures that decrease with depth. Well, you could also then start to look at how would you expect to change as a function of stress. So, the shallower fractures might not change tremendously when you're initially changing the stress on them, but the deeper fractures may or may not experience some sort of channeling which would have it drop off more rapidly.

And so in terms of future directions, is this something that can be implemented to more accurately capture stress dependent changes in fracture geometry or permeability? This is all for normal stress on a fracture. How does the flow stiffness relationship change if you have shear stress? And then a question is, is there equivalent flow stiffness relationship for fracture networks? Because you could imagine a compliance for the network and the more fractures you have, and their apertures would probably affect this stiffness of that system.

So since I told you that geometry is the key link between all these behaviors of the fractures from flows to stiffness as well as seismic, you can ask what controls fracture geometry? Well, we probably all can guess that it depends on the minerology, the structure, the stress, maybe even geochemistry. Well, we did a small study on looking at how minerology and structure affects surface roughness, and fracture geometry. We're specifically interested in what we call corrugated fractures. And what do I mean by this?

Well, here we're looking at a sample of shale from the laboratory, from this reference I'm showing down here. And I'm showing you the trace of the fracture perpendicular to the layers, which is fairly rough and almost corrugated, but parallel it's relatively smooth. So why are corrugated fractures important? Well, we did a simple example here to show you on idealized correlated fracture. And we can look at flow perpendicular to the ridges, and flow parallel to the ridges. What we’re plotting here is the normalized flow. So we’re normalizing it with respect to flow perpendicular to the ridges. And you can see, this has anisotropic flow. Why? Well, you have a much longer flow path if you’re going perpendicular to the ridges than across the sample.

If we now take and offset the fracture, what happens? Well, what we’re showing here is just with the 5 percent and 10 percent offset you quickly pinch off the flow in the direction perpendicular to the ridges because you’re going to start narrowing down or necking down the apertures. But in the direction parallel to the ridges, you still have a significant flowrate with a very small drop.

And so here’s a case where if you’re having shear in a system with a particular roughness, it can strongly impact which direction is going to have your strongest or largest magnitude of flow. And so we were interested in what causes that. And so we could assume that, yes, layering would probably give you corrugated surfaces. We were using in this case 3D printed gypsum rock. It happened to have a preferred direction. And what does that mean? If we, red lines here represented the direction of the print head, that gave us a preferred mineral fabric which had an orientation within the layer.

So what we did was print two different samples, one where the mineral orientation is in the long axis; here it’s in the short. And then we did three point bending experiments. So essentially we put a line load on the top and a crack forms from the notch. So what did we find? Well, we did expect that above the notch where the crack’s going perpendicular to the layers, that it would deviate because the layers, you know, in between layers have different strength. What was surprising was this mineral banding because of the way the sample is printed, also cause a deviation in the fracture path and it turns out that the correlations were roughly the width of these mineral bands.

What effect did that have on the roughness of these fractures? So here I’m showing a 3D surface that we measured with laser profilometry. Below it is just a contour map. Y and X are shown here, where Y is in the vertical direction, X is in the horizontal. And we see just by changing the orientation of this mineral fabric, we go from an isotropic surface in terms of roughness, to one which is strongly corrugated, and it's going to end up with anisotropic flow. And that's what we're showing here, is the permeability and it's roughly isotropic when our mineral fabric is providing resistance in the direction orthogonal to the layers. It's strongly anisotropic when the mineral fabric and the resistance from the layers are in the same direction. And so you can see you have a large difference in flow.

And so the implication here is that your geology matters, which we all know. Whether this is going to occur in granitic rock, maybe not so much. Maybe more in more metamorphic rock. Or if you're thinking of shales. The thing I wanted to show is that a colleague, Xin Gu from Oakridge, sent this picture after seeing my talk because he saw this on this 20 micron scale. Going across layers of biotype, ended up in the rough fracture, and parallel to it you have layers. I showed you this earlier in the shale. And this is up at the underground mine which Pat Dobson referred to. They see corrugations due to the foliation in the schist. And so, a very important, you know, to consider your site geology, look at rock type layering, orientation. To me it wouldn’t hurt from any site to measure the surface roughness of your fractures.

So, we did single fracture representation and now I want to go on to intersections, because intersections are fairly important. What we are interested in looking at was that if we had the simplest network, which is just two perpendicular fractures, how would the void geometry and the intersection geometry differ if we just changed their orientation relative to stress?

So what was the direction of stress that we’re going to be using here? Well, it’s going to be vertical loading on each of these samples. We did this with 3D printing. This was not gypsum, this was, I guess you’d call it a plastic a polymer, so that we could control the void space geometry. We looked at correlated aperture distributions and random aperture distributions.

So what did we find? Now I’m just going to show you a series of slides as we increase stress on these two samples. But first let me describe what you’re looking at here. The items labeled thickness map are essentially the size of the aperture with yellow being large, blue being small, and gray areas being contact area.

On the left we’re looking at the plus. At the bottom we have 2D cross-sections. So, you can see that they start out with the same topology, they’re both essentially plusses or Xs. And in between, what you’re looking at, is I extracted the intersection geometry. And so in the center, this one is 25 Newtons for the plus. And if we look at the X, we see that the geometry of the intersection is different. And you can see it in the cross-sections. So here it’s just essentially a pipe. It’s a little bit cut off, because we have a little contact area on the back there. And on the X fracture, orientation relative to stress, we see we sort of have like a dog bone. So, it’s two linear pipes that are connected by this thin area in the beginning.

So, let’s now increase the stress, there, okay, so now we’re at 100 Ns. What do we see? We see for the plus, the horizontal fracture is increasing and with contact area, but very little is happening to the vertical fracture. And we see the intersection geometry is relatively the same. And why is that? It’s because this vertical intersection is maintaining the connection between the horizontal and the vertical fracture. But now if we come over to the X, what we see is that we have regions along the intersection that have contact and some that are still connected.

And so, the topology of the intersection at some points is still X, but in the other spots along it, you’ve gone to a V topology and completely disconnected your two fracture plains. But now if we come back to the geometry of the intersection, we see that again, we have now two linear pipes that are partially connected.

So, if we increase the stress once more, what do we see? Well, we mostly have most of the plus intersection. Now the contact area from the horizontal fracture is starting to have an impact. But in terms of contact area, for the way that we loaded the sample, so we have to qualify all our observations here. This was just uniaxial loading. The vertical fracture is essentially unaffected.

If we come to the X fracture, we’ve now completely disconnected our original fractures, which were intersecting and your intersection is two linear pipes. And so, you can see that if you have changing stresses in your fracture network, your intersection geometry will be changing.

What impact does this have on flow? In these two graphs we're looking at normalized flows of function of the load. It's normalized just to the 25 newton measurement of geometry. So, this is a simulation, these flow results. And the letters here, FB is front to back, so that's flow flowing from the front of the sample to the back.

Top to bottom is vertically and LR is left to right. And as you expect, the horizontal flow left to right falls off much more rapidly because this is the one that's sensitive to the uniaxial loading. The front to back only drops off a little, because there is a little interaction between the horizontal and vertical. But top to bottom is essentially unaffected because the stress was such that it just remains open.

If we come now to the X condition, so we still have our front to back, to bottom, left to right, in this case they all sort of decrease together. And why does this occur? Well, all the fractures are experiencing both normal and shear stress and they all sort of close down together. So, in all directions you sort of have the same relative drop-off in the flow rate.

And so in terms of future directions or things to think about, do current network models adequately capture the difference in fracture deformation with different orientation? We heard Matt Sweeney say that they’re starting to incorporate that using the (()) . Can the effects of fracture orientation on network connectivity be incorporated into the network models? And then develop methods to incorporate deformation and closure of intersections into flow network simulations. So those are areas I think that are ripe for research.

And so now we’re going to come to the last part of my talk, which is the mixing rules for fracture intersections. So, we just showed you that, we’re only going to look at the X here, that when we have two intersecting fractures and we’re loading them vertically, we’re closing down the apertures within the planes and we’re also affecting the intersections.

You can get topological changes, so you might have started out with an X. You can get a little bit of shearing, which will give you a Z, or you might go completely to a V. And now if you come and look at the intersections for the three cases shown here, you might start off with a pipe and then go to these two linear features which become weakly connected.

So the question would be, do you expect that if I was introducing two fluids into this network, and one was a concentration of something, would you expect them to mix the same given that this intersection geometry differs? And I don't expect you go to into the details here. This is just to say well, Peter Kang at University of Minnesota is doing the full Navier-Stokes advection-diffusion equation to look at what is the mass fraction coming out of this upper fracture. If we have, let’s say, water coming in with no concentration other than being water and then some other liquid coming here with a concentration of 1, what will be the mass fraction at this outlet? And what we wanted to look at is how does this compare to the mixing rules used in discrete fracture networks? Here one is diffusion dominated, known as complete mixing where the other one is streamlined routing which is dominated by advection.

So, what did we find? Well, first if we look at the full pore scale modeling with the Navier-Stokes and the advection equation, we see that as the intersection becomes less connected, the amount of solute coming out at this fracture, fracture up at the upper left just decreases with increasing stress. Here you can see the streamlines and how as the channel becomes pinched off, your amount of streamlines crossing decreases. What happens if we use the mixing rules? Well, we see that both of them fail. And what do I mean? Well, in the pore scale modeling, we just see a monochromic decrease. But the complete mixing in the streamlined routing are not monotonic. And why is that? It’s because these are based on the mean aperture, or even doing it with hydraulic aperture of the fracture. So, it doesn’t even take into account the geometry of the intersection. And so even though this would indicate that you should have more flow coming out of this fracture at the top here, in reality because of the pinching off of part of the intersection, you actually get a decrease in the mixing at that location.

And so, to summarize this part, deformations of a fracture network as we see affect connectivity and geometry of the flow paths. If you’re using mixing ratios that only depend on mean aperture, this can lead to under-prediction or over-prediction of mixing. And mixing ratios need to be developed, which can take into account how they evolve with stress and as your fracture geometry or topology changes. So the future development, development of the stress-dependent mixing ratio formulation or a mixing ratio that depends on intersection geometry and it forms under stress, is altered by chemical processes.

So to summarize, I hope I got across the point that geometry does matter and geometry is the link along your flow, your deformation and your size and weight propagation. And so it is important to know how fracture deforms, how it’s affected by your material properties and any chemical or any other physical properties, processes.

This I hear is already going on, but I think is really important, experimentalists and modelers working together. So we’re working at a group with, with a group at Los Alamos. We’re doing some sliding of blocks and doing imaging on it to look at what the aperture distribution is when you have shear stresses. What’s been nice is I just give them the four blocks and then they see if they can reproduce it in the model with the goal being that if they can, then they can start doing stresses and stress distributions that may be more relevant to field applications, and as I have written here, because in the laboratory we can’t do all permutations. So I think experimentalists and modelers working together is good because they, I can help inform the model, but they also help me inform aspects of the experiment and what’s important and what they need to know.

And then the final thing is, you know, I think we can maybe improve our representation of fracture behavior in models. Maybe possibly just pre-modeling of the individual fractures for different stress conditions to correctly update as your stress conditions from your repository change. Or is there some way to incorporate this flow stiffness scaling relationship? So, thank you.

SIU: Thank you, that was very nice. Tissa, we can start.

ILLANGASEKARE: Thank you, Laura. So, this question more has to do with the work you have earlier covered. So you have studied this at the scale you are starting at the smaller scale and try to understand the processes. The number one question is that in your first model you are looking at two surfaces coming together and crushing the asperities.

PYRAK-NOLTE: Well not crushing. So, we’re purely an elastic regime.

ILLANGASEKARE: Yeah, but then later you look about it and there’s a slip... There’s a slip. Those little hills and valleys are going to get sheared.

PYRAK-NOLTE: Oh, yeah, that’s another one.

ILLANGASEKARE: Yes. So that you didn’t look at in those earlier models.

PYRAK-NOLTE: No, that’s what I said. That’s an open research area, how does the flow stiffness relationship change under other stress conditions, which would be shearing, especially in the corrugated fracture. That would be really important because you have anisotropic flow. Now, our scaling relationship, which I didn't talk about, is built for anisotropic flow. And what's the parameter that will let you know that you have anisotropic flow? It's the correlation exponent. And so, at normal stress I only have one stiffness. But your correlation exponent differs in different directions in the fracture and that's taken into account in the flow stiffness relationship.

ILLANGASEKARE: Okay. Then the next question is upscaling the geometry, in a way. So, you're looking at this fracture intersection, but when you go to large network, there will be intersections and continuous pathways, and you know, there are no intersections. There are intersections but they're longer. The intersection area is small compared to the length of fracture. So, in the upscaling sense, how sensitive are these things you are looking... at single fracture intersection compared to the large system area?

PYRAK-NOLTE: Well, the intersection will always come down to the small scale. Right?

ILLANGASEKARE: Yeah.

PYRAK-NOLTE: Because it’s essentially what the fracture is. And obviously you have your fracture-length. And the question is, is it always true that the longer the fracture, the bigger the apertures? I mean, you know, it may be, but it may not be.

ILLANGASEKARE: And how sensitive - the final. Let’s say you’re looking at the effect your behavioral block with has intersections and different lengths of fractures. So if water is flowing this way and coming out that way, how sensitive is the total behavior to what’s happening in intersection compared to the head losses in the length of the fracture?

PYRAK-NOLTE: Well, I’ll be dramatic and say I closed all the intersections under stress and then yeah that would dominate everything, right? So I can’t tell you, so unless may, are you pumping with the pressure that would prop open the intersections? Yeah. And so, to me the weak links are the intersections. Right? And those can be shut down in different ways. I didn’t show it here. In the laboratory we were doing shearing. What was interesting, a little bit of shearing almost cut off the flow but then it sheared a little more. And then it was connected by an array of very small apertures. And so, this whole thing that shearing should enhance flow, people think of that for single fractures, but what is it doing at the intersection? And so that’s another area, well, how does shearing at an intersection affect your connectivity?

ILLANGASEKARE: Okay, thank you.

TYLER: Thank you, Laura. Scott Tyler with the Board. An excellent presentation. I appreciated it. Maybe continuing on, on the scaling question that Tissa just brought up. I mean at some point a fracture becomes a fault. And where is that transition, and do we define the fault as much more, you know, as some X amount of shear, greater, and where do we stand on that?

PYRAK-NOLTE: No, that’s another question. I was talking to someone last week. You know, given that what I’m showing is a scaling relationship. And anyone who was involved ever with fractals, saying only maybe a fractal over 1 to 3 orders of magnitude, and then it breaks down. Right? And so, an unknown here is, it’s sort of what you’re getting to, when does the scaling relationship break down? One point could be a change in geology or it could be going into what I’m thinking of a fracture is two rough surfaces in contact. But a fault is a zone, right, with whatever’s in the center, then a damaged area, and everything. So what happens at that point? And that’s another area ripe for research, is what I’d say.

TYLER: Okay, thank you, yeah. And I was intrigued by the relation, the opportunities perhaps, that seismic tools may open up for us in mapping and understanding state of fractures. Can you speak any more to that? What other tools are out there or have been used, I assume in the oil and gas patch? People are doing all kinds of interesting things with whole geophysics and post-fracking.

PYRAK-NOLTE: And with the modeling. And so, the theory I showed is called the displacement discontinuity theory. That’s been demonstrated to work to predict fracture stiffness, from the laboratory to the field. You know, single fractures, very controlled. And it also shows that if you’re working at a 100 hertz, which is more like the field than in the laboratory, you’re going to get much lower stiffness fractures.

Modelers have taken, so how does this theory work? It represents the fracture as a boundary condition between two elastic half spaces, the condition is continuous stress, discontinuous displacement. They’ve implemented that into models. So, they get the correct energy partitioning if they want to put in a series of fractures or faults or whatever.

The other thing that’s going on out there, which is pretty cool, are Krauklis waves. And so, these are waves which are generated by resonating the fluid in the fracture plane. And so, oh, I can’t remember his name, someone at AGU showed in the talk that doing a seismic survey you could resonate the fluid in these very open fractures and then they would be highlighted in their geophysical interpretations.

And so, there’s a lot of modes to use. I think underappreciated is the frequency dependence. And so, in the theory I showed you, there was omega over K. Well, so omega-z over K. You can, if you have a fixed stiffness, but then look at your spectral content as your wave form, you can sort of bracket where you are in stiffness. Or if you change the stiffness, you should see the equivalent change in frequency. So, there’s these things that are in the data that are useful.

And then with machine learning now, and I think we’ve heard I think in Pat Dobson, about using ambient noise. Someone talked about using coda waves. The coda waves now, you can actually start to disentangle them where often they’re just like in the noise. We showed experimentally that we could tell if there was, if you had a set of parallel fractures, if the saturation changed in one, just down the difference in the coda wave arrival time and signature. And so, there’s I think a lot of potential for using the underappreciated portions of the signal because they were too complicated to interpret, that machine learning can help you with.

TYLER: Fascinating. Down hole, seismic sweep sources, things like that?

PYRAK-NOLTE: That, I’m less knowledgeable about, but I do remember something which motivated something we did in the lab.

A person said, he was in the field, they did a down hole measurement and he said, the right rock was isotropic. So, I took the core back to the lab and I measured the velocities and it was anisotropic. And then I asked him, I said, were there fractures in the borehole? And he said yes. And so, we showed this experimentally that fractures are going to give you anisotropy. Your matrix is anisotropy. Depending on your stress, you can go from fracture-dominated anisotropy to matrix, but there’s a sweet spot in the center where it’ll look isotropic because they’re balancing the two out. And that’s all I know about borehole, which isn’t really bore. Yeah.

TYLER: Thank you very much.

MANEPALLY: Chandrika Manepally, Board Staff. Thank you so much for the wonderful presentation. I was wondering if you could comment a little bit about the couple processes and representation in flow models. Because that is one of the things of interest for a geologic repository because of the emplaced waste causing a thermal perturbation which could perturb up the system, especially near the waste. So, the temperatures that are expected you saw in the previous presentations, you know, in the rock it would probably be less but definitely above boiling. So, do you have any experience in looking at these aspects?

PYRAK-NOLTE: Well, my thesis work was actually on Stripa Granite, which was related to repository in Sweden and we were looking at fracture displacement. And we would heat the rock up to 100 degrees C, but we'd heat it uniformly and we basically saw the same displacements. Now, again, we don't have a fully confined sample. The interesting thing, one day was, as I was heating it up, suddenly the displacements were going crazy and I didn't know what was wrong until we found out that the upper heater was off. So my walkaway information from that was that temperature gradients maybe are more of an issue in how that affects your fracture because you don't have uniform heating, you don't have uniform expansion. And so, your displacements may not be predicted like based on the current model I showed. And so, someone would have to study, was that really true what I saw, that gradients would have a bigger effect and cause things to close in a non-uniform way? And so, but with the framework that we've set up here, if you understand how each of your processes changes your geometry, then in principle you still have the link to couple them together.

MANEPALLY: Thank you.

SIU: Okay. I guess the Board doesn’t have any more questions. Thank you very much.

PYRAK-NOLTE: Okay, thank you.

SIU: And we have, it’s time now for a couple of comments if we have any. The answer is no. So, at the risk of prolonging things just a bit longer, if there were any questions to the presenters that we missed because of time considerations, his would be a reasonable time to bring up. I think I know I skipped over Bret.

LESLIE: Thank you, Nathan. And this is a kind of a bigger picture question for Paul and Dave Sassani. I mean, with the performance factors you’re really focusing on dose in terms of developing capability. And if you look at what’s required for post-closure assessment, it’s not just dose, it’s multiple barriers. And the capabilities to describe and have the technical basis for why those things are, aren’t from performance factors, they’re from being able to explain that all of the chemistry is such that there’s no mobility. So, in terms of explaining a repository system, do you think you’ve developed the capability to explain your multiple barriers? Because doing the iodine and performance factor isn’t really describing how capable overall system is to the total inventory in the radionuclide.

SASSANI: I think I’ve got a light. There we go. Dave Sassani, Sandia National Laboratories. Bret, you’re right. I won’t argue that. It’s the performance factors are to help elucidate aspects of the barriers and how they relate to each other to bring together the model performance, at this point. Right? It’s not really about the system yet. And Professor Ballinger talked to some of those aspects catching on with the big pieces which we explained from other performance assessments. And I’ll speak to one a little bit tomorrow that looks at how much waste form degradation rate matters. And it depends on what type of concept you’re looking at, what the other barriers are, what their lifetimes are, and how they all come together.

So, it’s not to get after the regulatory aspects as much. Because doing that – doing the actual system analysis for the regulations, that answers that mail, that brings it all together. It’s more to somewhat deconstruct it but in a systematic fashion to help communicate outwardly.

Also we get some questions from upper management about aspects like, how much more effort and/or resources should we put into making better waste forms or better waste packages, et cetera, or different barrier type materials for buffers. And so it’s to put more context to some of those questions as well, but also to try to explain some of the simple aspects that - Peter Swift and I wrote a paper back in 2020, it was for the 2019 spent fuel workshop for the IAEA that talked about what matters for repository systems post-closure.

If you’re going to do something on the front-end of the fuel cycle, to your materials, process them, treat them, what matters? A lot of people off of just a general topic will say, well it’s the absolute volume of the material. Well, that’s what drives your footprint of your repository. And that’s matters somewhat, but it’s really not what drives the footprint. It’s really the thermal aspects, particularly with the U.S. inventory. So, it’s to look at those kinds of aspects and start to try to get some simpler representations for communications purposes. And to provide some justification as to why do you want to look at a copper coated canister for performance in a crystalline fracture repository system?

SIU: Thank you.

OGG: Dan Ogg with the Board Staff. I have a follow up question on the crystalline rock reference case and this ties to Ron Ballinger's question. You explained that there's 10 percent of the waste material is released in an instant release type scenario, but I don't recall you saying then what are your assumptions about the long-term release of material from the waste form? Is that a constant release, a constant degradation? What is the assumption there?

MARINER: Yeah. So, for Iodine 129 it's very element-specific. For iodine we model 10 percent instant release as soon as a waste package breaches. There are a few other elements that also, a small fraction of them can be instantly released upon waste package breach. And so the way we model that is, we let that, those fractions go. Let's say we have five of them in our entire inventory in our waste package and we let 5 percent of Iodine 129 go, and maybe a small fraction of the chlorine or whatever it is.

And then we have this waste form that's remaining there with the rest of the inventory. And then that all, the radionuclides in that waste form then get released congruently as the matrix degrades over time. And we have a couple different models that we simulate right now that I'll talk about tomorrow, for how we simulate the degradation over time of the waste form matrix.

OGG: But for the reference case that you showed us there, what was the assumption?

MARINER: That was a fractional degradation rate for the matrix.

OGG: Okay. Right, I think that maybe helps get at Ron's question because it was just an assumption about how the waste form degrades over time. And make a different assumption, you'll get a different answer or a different shape of curve.

MARINER: Okay, great, thanks.

JUNG: This is Hundal Jung. Relate to the waste form degradation model you will present, for performance factors, especially for a waste form, exclusion of this waste form performance does mean 100 percent instant release once waste package breached. I'm maybe just for a sensitivity analysis, it's okay, but it's kind of very extreme case. It's not realistic actually assumption by comparing exclusion and inclusion of these components, for each component for your performance inspector.

MARINER: I see what you mean, but what it does do is it permits you to calculate that performance factor. You don't know how much performance you're getting from that matrix unless you actually fail it 100 percent and then see what concentration you get in your, at your receptor when there's no performance from it. Certainly, it's not realistic; but that's how you get to that number.

JUNG: Yeah, understand. I mean, because there is an EBS, the other buffer, and the others can maybe have some barriers. But still as long as your first basic assumption is not realistic, and then whatever you have the accomplishment afterward, I mean how can you make a credit?

MARINER: Yeah. It’s a different, it’s very different from our probabilistic simulations. In our probabilistic simulations we propagate the uncertainties, realistic uncertainties. That’s a separate analysis than the performance factor analysis. For performance factor analysis, because we’re specifically measuring the performance of something, the only way you know what that performance is, is by taking it away. The only way to measure it.

JUNG: Yeah. Just that you can just identify what is the key process and the, you know, component would be affect to the total components assessment. But just other countries, like Swedish KBS3, also have some, this similar approach, performance factors they have used, or this is the unique?

MARINER: I’m not aware. I’m not aware of any other program that does this.

JUNG: Okay, thanks.

SIU: Yeah, just a reference, the reactor community has used similar measures for similar reasons. It’s not to say this is the risk that’s going to arise, but this is one way of looking at importance.

SASSANI: Yeah, that’s exactly what it’s for, right, is just to look at the performance of the actual values that are used in the analysis and the demonstration of that particular reference case. It’s not to say, oh, we think we’re going to have a case where there’s zero performance for all the waste form. It’s only to look and highlight, shine a light on, the actual model results of the reference case. And other countries do other types of analyses. We’ve had experience in the U.S. on the Yucca Mountain project with these one-off analyses where you have to be very careful, particularly with a model like the total system performance assessment. Which, even though these models have a lot more grid cells in them, that model had a different type of complexity to it.

So that if you didn’t look at the whole model and the different aspects you could step in some various places that you didn’t want to step into by doing these one-offs and draw conclusions which aren’t actually accurate. Which, in some of those reports, there was a lot of debate technically within the project about, well, you can’t really say that this doesn’t matter, because you haven’t done a through-going assessment.

These, these are simple enough with the barriers being turned on and off, that you know that it’s all off. It’s the only aspect of the barrier that’s functioning that’s being turned on. It’s really just to shine that light. The plot I’ll show tomorrow in reference to how much does the degradation rate matter, it’s actually in the paper from 2020 and other presentations that myself and Peter have done. [Break in audio]

SIU: Apologies for that.

SASSANI: Oh, no worries. So, the plot I’ll show tomorrow, it, I think that instance just fails all the waste canisters at like 500,000 years. That is not something they think is a justified functioning of their repository; it’s simply to do the analysis to look at how much the waste form degradation rate matters in their performance of their system.

SIU: Okay, do we have any other questions, comments? That being said, I guess we can call it a day and we will start again tomorrow morning. Thank you.

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