United States
Nuclear Waste Technical Review Board (NWTRB)

Transcript

DOE Research and Development Related to Disposal of Commercial Spent Nuclear Fuel in Dual-Purpose Canisters

VIRTUAL PUBLIC MEETING - DAY TWO

Tuesday

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PROCEEDINGS

BAHR: Okay. Good morning. If we can get the slides, we can get started.

Okay. And welcome back to the U.S. Nuclear Waste Technical Review Board summer meeting. I'm Jean Bahr, chair of the board, and yesterday I described the board's mission and introduced the other board members. So to save time today, I'll direct you to our website, www.nwtrb.gov, where you can find that information, information on our mission and our members as well as board correspondence, our reports, testimony, and meeting materials, including webcasts of the public meetings.

This slide shows yesterday's agenda. Dr. William Boyle of the Department of Energy's Office of Nuclear Energy gave the opening remarks and that was followed by presentations on past studies of the technical feasibility of the disposing of spent nuclear fuel in dual-purpose canisters, including the technical bases for engineering and thermal management of disposing of spent nuclear fuel in these canisters.

And the last presentation yesterday was on the Department of Energy's ongoing research and development activities, which include a reactivity analysis of dual-purpose canisters.

Today we'll continue with the presentations on ongoing Department of Energy research and development activities and we'll focus on analyses of the consequences of potential criticality events during the period after the repository closes, as well as on the development and testing of materials that can be used to fill the void spaces inside dual-purpose canisters prior to disposal as a way to mitigate criticality. These filler materials would be intended to prevent water from filling the void spaces inside the canisters. If the canister is breached and groundwater enters the canister, the filler materials would be intended to prevent nuclear criticality depending on the efficacy of the void filling.

And the last presentation today will be on research and development on cross-cutting issues relevant to the disposal of spent nuclear fuel in the canisters.

We'll take a 30-minute break after the first two presentations and we will also have a public comment period at the end of the day.

As a reminder, because of our virtual format, we can only accommodate written comments at this meeting. When you joined the meeting, you will have seen a link for submitting a comment for the record.

Comments we receive before the end of today's break period will be read online in the order received by board staff member Bret Leslie. And yesterday we were actually able to also accommodate some additional comments that came in towards the end.

Time for each comment may be limited depending on the number of comments we receive, but the entirety of any submitted comments will be included as part of the meeting record. And we expect the meeting to end at approximately 4:30 p.m. Eastern time today.

So with that brief introduction, and without further ado, we're going to start with the first presentation which is from Laura Price of Sandia National Laboratories.

I'll get rid of myself and turn it over to Laura.

PRICE: All right. Thank you, Jean.

As you mentioned, I'm going to be talking about the ongoing research and development into the effects of -- or the consequences of nuclear criticality in DPCs after disposal.

This is one of the many research aspects we've been looking at, as was talked about yesterday.

How do I go to the next slide? There we go.

All right. So the disclaimer -- thank you. So this is the disclaimer that we talked about yesterday. The next one, legal notice. That's all the legal stuff.

I'd like to acknowledge my coworkers who did the heavy lifting on this work. These are the ones who did the work and the various areas that we worked in. So to get started, first the objectives.

We had several objectives. First, we needed to develop some new tools to examine the consequences of postclosure criticality.

There is no code that couples neutronics and performance assessment calculations, so we took PFLOTRAN, which is a code that is used in the geologic disposal community to do performance assessment, and we're working on modifying it to evaluate the performance of the geologic disposal site as with a critical event, postclosure critical event.

Second, we needed to develop a better understanding of what affects criticality and what effects criticality can have on the performance of the repository.

Third, if we're going to model postclosure criticality, we need a basis for knowing when that critical event would cease. Repository time scales are up to 1 million years. For example, the Oklo national reactor went on for hundreds of thousands of years. So we were trying to answer the question, what stops it.

And finally, as preliminary work, we wanted to identify areas where further work is needed, and you can see some of those.

We'll talk about that later.

I think I skipped ahead too far.

All right. So our approach was to look at two hypothetical repositories; one saturated and one unsaturated.

The saturated repository is in a shale layer and in this repository, the waste packages are placed in tunnels horizontally.

Center-to-center spacing is 20 meters. It is surrounded by bentonite, which we call backfill. The bentonite eventually resaturates, but has very low permeability. In our hypothetical repository, the pressure is about 5 MPA, so water boils about 264 Celsius.

The capability of the bentonite to act as a barrier may be affected by heat, which is one of the reasons why there's temperature restrictions on shale repositories, which Ernie talked about yesterday.

The unsaturated repository is in alluvium. It has an atmospheric pressure. It has a crushed alluvium backfill, and the capability of the crushed alluvium to act as a barrier is not affected by the heat.

In our approach, the saturated system, we looked at radionuclide concentrations in the host rock, with and without the occurrence of a critical event, in a single waste package. So we only looked at one waste package.

The inventory of that waste package is known as from the UNF-ST&DARDS database that Kaushik talked about yesterday.

The steady-state critical event is assumed to occur 9,000 years after repository closure and is assumed to last for 10,000 years. It's also a low-power, long-lasting event. Sometimes you'll see it called steady-state.

We're also studying a transient event, which could be a single event that would be high-power and short-lived, but we're working on that right now, so the presentation today is going to focus on the steady-state criticality events.

So we had to make several assumptions to do this work. And many of these will be investigated as the research effort moves forward.

The first is that the waste package is

breached. So the waste package, as Ernie talked about yesterday, consists of a DPC inside a disposal overpack. This disposal overpack would be used to handle the waste package on the surface and in the subsurface.

We did not calculate the probability that the waste package has been breached or we didn't look at the mechanism by which it was breached. We're concerned with consequences, so we're assuming that the waste package is already breached.

It's also important to point out -- as I forget who did yesterday, but criticality can occur only in the presence of water. So criticality can occur only in a waste package that has already failed. So criticality does not make a waste package fail. That means the radionuclides that are released when a critical event occurs represent an incremental increase compared to what would have been released in the absence of criticality.

For the Yucca Mountain performances assessment and for most other performance assessments around the world, it's assumed that cladding fails when the waste package fails.

And for that it's mostly conservative, but this assumption is not conservative with respect to a criticality event.

So for our study we assumed that the fuel assembly lattice remains intact and that the cladding is largely intact but has pinholes and cracks through which water can enter and dissolve radionuclides and exit.

This is a reasonable starting point for our purposes and we're looking into this further, as the asterisk indicates.

And as Kaushik talked about yesterday, we're assuming -- and Ernie, too, we're assuming that the aluminum-based neutron absorbing material which is common in DPCs has corroded and is no longer effective at absorbing neutrons.

And finally, an uncontrolled criticality in a disposed-of DPC is likely to oscillate between being critical and being subcritical as reactivity feedback mechanisms change the environmental conditions.

As an example, evaporation of water in an unsaturated repository. The water would enter the waste package, critical event could start, water evaporates, there's no longer enough moderator so the critical event ceases, water enters the waste package again over a period of time, the critical event starts again.

That's complicated and we did not try to capture that cyclic nature for this go-around, but we're working on it right now.

So to get started, let's talk about the -- this is a hypothetical repository in alluvium.

You can see the waste package circled there in the middle of the repository and you can see a little inset up there, you can see the waste packages and they're laid end to end in that rendering.

And I -- the Mariner, et al., from which this is taken, is one of the references in the back that we can obtain for you.

So here's a model setup for the single DPC. The geometry of the hypothetical unsaturated repository in alluvium is based on previous work done as part of the GDSA project and those references are there as well.

I apologize they're not listed in the back of my presentation, but I can procure those as well.

As you see in the picture on the slide, by symmetry only half the waste package and 20 meters of the drift are modeled.

The model then extends from the land surface to the water table -- I'm sorry, to the land surface and to the water table.

The backfill is assumed to have the same thermal property of the host alluvium but to have a higher permeability.

So as I mentioned before, the model includes just a single waste package.

At 9,000 years after the repository closure, the waste package shell is assumed to fail and we model this by replacing the mesh cells in PFLOTRAN that are associated with the waste package with those associated with the drift backfill.

The waste package shell size and bottom remain intact.

The criticality event is assumed to begin after the waste package is filled with water.

We look at the two different deep percolation rates, 10 millimeters a year, and 2 millimeters per year.

For each percolation rate, different power outputs were assumed and the effect on the water level in the waste package was examined.

In this case, the objective is to identify the power output that could be produced by a criticality event such as the influx of water equals that lost from the evaporation due to the heat of the criticality event.

So we use PFLOTRAN.

PFLOTRAN is an open source code and it's used in the performance assessment community and other communities.

As I said, it's open source, state-of-the-art, massively parallel subsurface flow and reactive transport code.

It solves a system of generally nonlinear, partial differential equations that describe multiphase, multicomponent, and multiscale reactor flow and transport in porous materials.

It's used in -- besides in the performance assessment community, it's used to model surface and subsurface hydrology, supercritical CO2, carbon capture, and a bunch of other things. And this website here, www.pflotran.org, lists publications which shows its many applications, and you can go to the website and see -- learn more about PFLOTRAN if you'd like.

So this curve shows the temperature of the DPCs at the center prior to the critical event and you can see the two curves here.

In the 10 millimeter case the temperature peaks at 233, about 10 to 20 years after closure.

By the time the waste package is breached, the waste package temperature is about 61 degrees.

In the two millimeter case it's a slightly higher temperature because there's less latent heat and vaporization to overcome and the slightly lower thermal conductivity, in the drier two millimeter case.

So this is without critical event.

So these curves -- this is the liquid saturation index field at the time of maximum dryout, and it's shown for both the 10 millimeter case on the left and the 2 millimeter case on the right.

For the 10 millimeter case, the maximum dryout occurs about 500 years postclosure.

For the 2 millimeter case, the maximum dryout occurs about 750 years postclosure.

You can see the little black box in there. That's the waste package and you can see the region of zero liquid saturation, which is indicated by the red, extends several meters into the host formation out from the waste package.

It's vertically asymmetric, so it extends further in the downward direction, which is the yellow, below the red in both cases.

But the dryout does not extend to the pillar center line, which means a perched water table -- perched water would not form.

Water can drain between the drifts without forming a perched zone of higher water content above the repository.

So this is the liquid saturation index for the 10 millimeter case, and in this case we assumed 400-watt critical event.

The first snapshot -- there's snapshots at three different times.

The first snapshot on the left is at 9,000 years.

It's just prior to the waste package breach.

You can see the red box inside the diagram.

That's the waste package, which is dry.

The second snapshot is at 9100 years when the critical event begins.

You can see the middle package, the waste package is blue, which means it's filled with water.

So it has enough water for the steady-state criticality event to begin.

As it generates heat, the water evaporates from the waste package, which causes the criticality event to cease.

At 9,310 years, which is 210 years after criticality event started, the waste package is nearly dry, which you can see in the third diagram.

While it's not shown in this figure and I'll show you later, but the temperature is well below boiling when this criticality event ceases.

So this is the liquid saturation index for the drier case, the 2 millimeter case, in which case a 100-watt criticality event was assumed.

In this case, decay heat alone is sufficient to keep the waste package dry over thousands of years. It was dry at 9,000 years. So we couldn't start a criticality event because there was no water.

The first picture you see is at 15,000 years after repository closure and you can see the waste package is dry.

The rewetting front reaches about 16,000 years and the waste pack is filled with water by 17,000 years, as shown in the middle diagram.

We assumed a 100-watt criticality event initiated at that time and the waste package is dry. The water's driven out of the waste package by about 18,000 years as shown in the picture on the right.

Thus, a 100-watt event is sustainable for several hundred years in the 2 millimeter per year case but can't be sustained indefinitely because of evaporation.

The waste package -- and I'll show you this later -- is only about 57 degrees Celsius, which further underscores the point that evaporation without boiling is sufficient to keep the waste package dry in unsaturated media with low percolation rates.

So this is the post-breach waste package temperatures. The 10 millimeter case is on the left and the 2 millimeter case on the right.

These are plots -- the power -- this is after the assumed steady-state power criticality event has started.

In the 10 millimeter case, 400-watt scenario, the temperature initially increases rapidly following the criticality event and it reaches about 76 degrees at 9200 years.

The temperature continues to slowly increase after that, tipping the balance between infiltrating water and evaporation, more toward evaporation. Water loss becomes rapid and so at this point, the waste package temperature is about 77.

In the 100 millimeter year -- I'm sorry, in the 10 millimeter per year, 300-watt scenario, which I didn't show pictures of, but you can see the second -- that blue line underneath the back line, the temperature increase is not quite as swift and it reaches 77 degrees in about 10,000 years.

What we learned from this is that under these conditions, a steady-state criticality event cannot exceed 400 watts and it's probably closer to 300 watts or lower.

For the 2 millimeter per year case, the criticality event doesn't occur until 17,000 years after closure, like I mentioned earlier.

Because that's how long it takes the waste package to fill with water.

By 18,000 years, the water has evaporated, and -- as is shown on the previous slide, and the temperature is about 57.

So the take-away message from this is

that lower percolation rates lead to lower steady-state power generation rates in the unsaturated zone. And this is significant because lower power generation rates lead to smaller temperature increases and smaller inventory increases because inventory is proportional to the power generated.

So conclusions for the unsaturated case, the center temperature peaks around 20 years after closure, is slightly higher for the 2 millimeter case because there's not as much water, and the -- you don't have vaporization to take away some of the heat, and the thermal conductivity is different.

The dryout zones around individual DPCs don't coalesce, so that allows for vertical drainage.

The criticality is possible after water returns, about 9100 years for the 10 millimeter case and about 17,000 years postclosure for the 2 millimeter case.

And the long-term average power output from criticality event is limited by the thermal hydrology and by the infiltration rate or percolation rate.

So for the 10 millimeter case it's less than 400 watts, probably less than 300 watts, and for the 2 millimeter per year case it's less than 100 watts.

So that's all in the unsaturated repository.

Moving to the saturated repository, this is the argillite reference case, and this is taken from Mariner, et al., which the reference is in the back of this presentation. And you can see up in the upper left-hand corner, instead of what the repository looks like with the waste package, the buffer layer and the concrete liner. I think Ernie talked about that yesterday.

So the point of -- this is a coupling scheme between processes that we considered, and the point of this slide is that there are many processes that are involved in modeling a critical event in a DPC.

Some of these feed back on each other, as you can see from the diagram. The preliminary work assumed a critical event.

We looked at the increase in the radionuclide inventory. We looked at the thermal events.

We assumed that the backfill could no longer absorb radionuclides released from the waste package under critical conditions.

We did the qualitative evaluation, in-package chemistry, and radionuclide solubility and then we evaluated radionuclide mass flow out to the shale host rock.

That's what I'll be presenting in the next few slides.

So first of all, we did thermal analysis. The question was how hot -- how much power could a steady-state criticality event generate in a saturated repository.

So to examine that, we -- we did a calculation. The basis for the heat generated by the steady-state critical event comes from calculating the radius of a sphere that has a volume equal to that of the DPC, using a spherical heat conduction equation to calculate the maximum heat output.

It's assumed the maximum temperature in

the sphere was 264 degrees, which is the boiling point.

We're assuming here that the critical event would stop once the water boiled, and we assume the temperature that infinity was ambient.

Doing this calculation yields a power of 4 kilowatts.

The curve you see here, the black curve, represents the assumed power generation history of the DPC that's undergoing the critical event, and you can see the 9,000 years, the temperature -- I'm sorry, the power goes up by 4 kilowatts and then 10,000 years later it goes back down.

Like I said, we assumed 10,000 years of a critical event.

Sorry, it keeps going the wrong way.

So this is temperature versus time graph.

This temperature at various points in the model over time and you can see that -- so the black on the top represents the waste package, and the green curve, second one down, represents the buffer, temperature of the interfacing and the buffer in the waste package.

The third line down, the brownish one, represents interface between the buffer and the disturbed rock zone. And the blue one on the bottom is the host rock.

The initial increase in temperature is from the decay heat, and then this is a log scale, but at 9,000 years you can see the temperature shoot up.

Lasts for about 10,000 years, and then comes back down when the criticality event ceases.

So you can see the temperature goes up more from the criticality event than it had from just decay heat alone.

So next thing we looked at was inventory. What does the inventory -- what kind of inventory changes do we see from the critical event? Because the criticality generates new nuclides.

So we looked at 58 different radionuclides. I didn't show them all here because that would be crazy, so this figure compares inventory of 10 selected nuclides from the model DPC. And the dashed lines in this figure represent the inventory in the case of a 10,000-year-long postclosure critical event.

And the solid lines are without a critical event.

And it's concentration on the Y axis and time on the X axis.

For the long-lived nuclides, inventory increase is very slight. You can barely see it. And numerically it's about 3%

On the short-lived nuclides, such as Americium 241, Pu 238, Caesium 137, Strontium 90, and when I say short-lived we're talking decades, 30 to 80 years, somewhere in that vicinity.

The increase between 9,000 years and 19,000 years is significant.

That is the bumpup you see in the middle of the diagram and you can see it goes up abruptly at 9,000 years and then goes back down just as sharply as those heats to be generated by the critical event.

Sorry, my computer's talking to me.

So we did a qualitative look at chemistry, of in-package of chemistry. A quantitative study is currently underway, but the chemistry inside the waste package would be affected by the criticality event because there are new fission products, there's a higher temperature for 10,000 years, and there's a high radiation environment that has not existed previously in a DPC.

These phenomena affect steel corrosion rates and spent fuel degradation rates. For example, steel corrosion rates are about 25 times higher at the temperatures associated with critical events, 250 degrees or so. The corroding steel leads to reducing conditions in the waste package under anoxic conditions such as a hypothetical saturated repository.

On the other hand, radiolysis produces oxidants such as hydrogen peroxide. So these processes compete with each other. Reaction path modeling that includes radiolysis, steel degradation, and spent fuel degradation is currently being worked on.

We also took a qualitative look at

radionuclide solubilities. It's important in determining the rate at which radionuclide can be transported away from the waste package. Actinides display retrograde solubility, which means their solubilities decrease as temperature increases.

The same for oxides and carbonates as neutron poisons, which can be important for determining whether the waste can go critical. PH also affects solubilities, as actinide solubilities are lowest at a neutral pH.

As I said, this is qualitative and we're working on quantitative analysis now of radionuclide solubility even as we speak.

So the engineered barrier system, for our -- for our system, we assumed four barriers. We assumed the barriers consisted of the waste package overpack, the DPC, the cladding, and the backfill.

And in this study three of these barriers were no longer acting as barriers in their study because we assumed the waste package outer barrier and DPC had failed, thus allowing water into the waste package, and we assumed the cladding had failed enough to allow radionuclides to dissolve and be transported away but not so much that the fuel geometry changed significantly.

Finally, we assumed that because of the high temperatures, radionuclides could not absorb onto the backfill in a critical event.

The effect of the prolonged higher temperature on the behavior of bentonite as a barrier is a point of discussion in the geological repository safety system community, which is why the temperature limits, and this is definitely an area for further study, along with the behavior of the cladding.

And we're currently looking at the behavior of the cladding and other temperature-dependent properties of the backfill such as the permeability and the velocity.

We also looked at the termination of criticality. It's important to know, if we're going to model a critical event, what would make it stop?

Radioactive decay would not be effective in permanent termination of criticality.

Dissolved Pu 239 is being produced in a steady-state critical event and U 233 builds up from decay of Neptunium 37. There's actually a small increase over a few million years of increasing reactivity.

We looked at burnup.

For a saturated repository, you have a criticality event of 4 kilowatts for 10,000 years, that results in an additional about 1 gigawatt day per MTU average burnup. Depending on the excess reactivity in the DPC, that means the burnup could cause a critical event to cease after about 200,000 years, assuming that the geometry is maintained.

So which leads us to irreversible geometry changes.

If the grid spacers corrode or collapse, that would change the geometry and cause a critical event to cease. We found that a reduction of pin pitch of about 3 millimeters could result in permanent termination for most DPCs.

That will eventually happen. The question is when it will happen.

And prior to about 100,000 years, dissolution and transport of plutonium 239 could reduce reactivity, but this is not true for uranium because of the large mass of uranium in a DPC.

That is most of the mass of the fuel in there.

So putting this all together, we come to performance assessment calculations for the hypothetical shale repository.

As I mentioned, we used PFLOTRAN to do this. We modified it to be able to increase the inventory at a specified time because PFLOTRAN did not -- beforehand did not accommodate a change in inventory at 9,000 years. And also to increase the heat generated at a specified time.

This one's before PFLOTRAN had incorporated a simple decay heat.

We're working on some other changes right now such as temperature-dependent thermal conductivities.

Other capabilities we would need to model postclosure criticality.

We looked at the concentrations of 10

selected nuclides in the shale, adjacent to the drift, both without a steady-state critical event and with a steady-state critical event.

Actually, when we tried to do this for the unsaturated alluvial case that I talked about earlier, we were unsuccessful because there wasn't enough water for the chemistry submodel to run. So we're working on that. But the results I've got here are for the saturated shale, steady-state case.

So this is a picture of the model setup. It's quarter symmetry boundaries, the DRZ, you can see there, stands for disturbed rock zone.

Calculate -- the concentrations were calculated right between the -- the gray and the brown, between the DRZ and the buffer. So that's where we calculate concentrations.

And you can see the waste package there in the red. The buffer's in the gray. The disturbed rock zone is the brownish and the host rock is the bigger brown color.

So this is the model results and once again these are concentrations of radionuclide in the shale next to the drift.

Concentrations are on the Y axis and time is on the X axis.

I want to point out that these concentrations are not suitable for calculating doses because it's taken either in the shale next to the drift, so the short-lived nuclides will likely decay or be absorbed before reaching a water well used by the hypothetical dose receptor.

And as before, the dashed lines indicate concentrations with a critical event and the sold lines are without.

For a lot of nuclides there's not much difference.

So the top one is iodine. Iodine is a nonabsorbing radionuclide.

The only difference between the no-criticality concentration and the concentration that includes criticality is increased inventory, which is on the order of 3%, which is why those two lines at the top are practically on top of each other.

For all other nuclides, the difference between the no-criticality concentration and the concentration that includes criticality is from both the increased inventory and because of the assumption we made that there's no absorption in the buffer in the critical event.

In neptunium 237, the increase in concentration long-term is about 50%.

For plutonium 240, thorium 229, and uranium 233, the increase in concentration is about an order of magnitude in the long-term.

And the ones that jump up, americium 241, strontium 90, caesium 137, and plutonium 238, they appear only in the case with criticality because they decayed to nothing in the case without criticality.

So they have dashed lines with no corresponding solid line. And those are the ones that jump up at the beginning and decay in the middle of the time shown there.

This runs from 9,000 years to 90,000 years.

So what do we conclude from this?

First of all, we made some progress in developing a new submodule for PFLOTRAN and begins to include the effects of the postclosure critical event in disposed-of DPC.

We're working on further developments even as we speak.

We quantitatively demonstrated that the availability of water and the higher boiling point in the saturated repository allows more power to be generated than in an unsaturated repository.

I want to point out that even at these powers, the total additional burnup and thus the additional rate of nuclides added to the inventory, would be very small compared to the burnup of the disposed SNF, unless a critical event continues for more than about 100,000 years at a power of about 4 kilowatts.

We gained some insights into the thermal processes and obtained estimates of temperature changes of the critical waste package. We also looked at temperature changes at adjacent waste package, which I don't have slides -- I have backup slides and they're not significant.

About 15 degrees.

Since we had an idea what temperatures might be, we're able to qualitatively look at possible steel degradation rates, radionuclide solubilities, and backfill performance. And these are all areas for further research that we are working on right now.

And note that now that we have a temperature of -- temperatures that might exist in the backfill, this is helping us focus our further study of that barrier and the bentonite and how it might behave at these temperatures.

We also determined that fuel can remain reactive for about a million years, but we identified some termination mechanisms and we're studying those.

Those termination mechanisms we're looking at are loss of geometry from grid spacer degradation or from cladding degradation.

The newly generated short-lived isotopes are probably not significant to the dose receptor because they'll decay before they can reach the dose receptor, assuming the significant travel time, and these insights assume no absorption in the backfill.

In retrospect, that seems like an unnecessarily conservative assumption, but under this assumption we found that the concentration of iodine 129 in the near field increases about 3% and this is totally due to the increased inventory.

The concentration of neptunium 237 in the near field increases about 50 percent in the long-term.

Concentrations of plutonium 240, thorium 229, and U233 in the near field increase about an order of magnitude in the long-term, and as you would expect, americium 241, strontium 90, caesium 137, plutonium 238 appear only in the case with criticality because they decayed to nothing in the case without criticality.

And these are my references.

Any questions?

BAHR: Okay. Laura, thank you very much and for keeping that on time.

I have a question, just a clarification, and then I see there's some other hands up.

You said that there's no significant temperature changes at the adjacent packages, so the conclusion is that criticality and breach in one package would not necessarily accelerate or cause breaches in other packages, is that --

PRICE: Right.

If I have -- if you bring the slides back up, I have some backup slides that show that.

Okay. There we go. Let me find it. Right.

So here's -- we did a calculation.

You can see there's three -- looking at adjacent packages, so the orange line on top is 20 meters center-to-center spacing and an adjacent package and it's about 15 degrees increase.

30 meters center-to-center spacing and adjacent in placement drift, the purple one in the middle and the green one is 40 meter center-to-center spacing, the same in placement drift. So the 20 meter, the one on the top and the one in the green are the same drift, along the same drift, and the purple one is an adjacent placement drift that's 30 meters away.

BAHR: What about the moisture flux that might be driven away from the critical package towards the -- towards the other ones, does that have an effect?

PRICE: Well, in the saturated zone, it's all saturated, so this is for the -- so it wouldn't change the moisture. The unsaturated zone, I think this was -- let me go back to the slide.

So on this slide, these analyses show that you can see the green -- where's the pointer on here?

I can't find the pointer.

But anyway, there's -- you can see it's green to the edge of the drift, so that means there's still water there. So the dryout zone does not go to the next drift.

I mean, we'd have to do more study on this, but that's preliminary, what it looks like.

BAHR: Okay. Thanks. So I see a hand up from Efi Foufoula. I think you need to get her -- there we go. Get her on.

FOUFOULA-GEORGIOU: Yes, Laura, so in your slide 18, you had all this coupled processes. There are too many processes involved in coupling and I know -- so the envelope is huge.

At the same time, Tim Gunter yesterday talked about the probabilistic criticality consequence analysis. So my question is how do you plan to bring in this probabilistic aspect and propagation of uncertainty through all these coupling processes.

You talked about a few case studies, but in this infinite number of possibilities, there will be some extreme case scenarios that you will focus on.

So could you comment on that?

PRICE: Well, we can -- we will -- we can accommodate uncertainty and parameters in the calculations, but in terms of calculating the probability of a waste package failure, that's not in the scope of what we're doing now.

That would be very site specific and design specific.

Without a specific site and a specific design, it's very difficult to address that.

The focus of this is the consequence.

In a performance assessment there's a probability and a consequence and a fair amount of work has been done on probability of occurrence of a critical event.

This focuses on the consequences.

Now, we can include uncertainty.

But not -- it's outside the scope to look at the exact probability of a -- of a waste package failure.

BAHR: And I think you've also made, in some senses, a number of bounding calculations in this analysis because of your assumptions that there's no absorption in the bentonite, for example --

PRICE: Yeah, we've had to change that.

BAHR: -- case in the analysis you've done now. Is that correct?

PRICE: I'm sorry, say it again.

I missed it.

BAHR: I think you're looking at an -- essentially an extreme case in your current analysis because of your conservative assumptions.

PRICE: That was the most conservative assumption, yeah, and as I mentioned, that's probably unnecessarily conservative, looking at the data in some more detail, I think we don't have to make that assumption, but we will be looking at how the heat might degrade the barrier performance of the bentonite.

FOUFOULA-GEORGIOU: Okay. Thank you.

BAHR: Okay. We have a hand up from Tissa.

ILLANGASEKARE: Yeah, this is -- thank you. It was a very nice presentation.

This is more of a detailed question, but maybe -- the question is that when you are looking at the container and the environment in interacting in the case of the unsaturated soil, so the assumption that infiltrating water all enters to the container through the holes; is that correct?

PRICE: Correct.

ILLANGASEKARE: My question I have is that basically you are looking at unsaturated soil and a container, it's also porous medium inside in some way, so in theory you need some more accumulation at the interface for the water to enter because otherwise you're looking at the suction affects the whole, the water.

I mean, it's a conservative assumption that every drop of water goes in, but I think there's some building interaction of the container and the rock -- the porous medium which sort of may let less water into the system than what you assume.

PRICE: Yes, I agree. But this was our first cut at doing this, and so we will refine our assumptions and our model as we go forward.

ILLANGASEKARE: And the second question had to do with, again, the details. When these double models are changing to do simulations over a very long period, so my question is what kind of time steps did you use? And I assume that your model seems to be very stable to go that long periods because normally when models if you're stable a small error can accumulate, then your predictions may become unstable.

Seemed like stable. So what did you do to make sure that the models stay stable?

PRICE: The time steps changed.

Well, shorter time steps when there was more change going on. And I don't have an exact answer for you.

I can get back to you on that because the person who did the modeling is not on the line and it was a year ago so I don't remember.

But we certainly looked at the stability and we had to shorten the time steps actually.

That was one of the things we had to do for PFLOTRAN because the short-lived isotopes -- when I say short-lived, I mean things like 30-year half-life, the strontium 90, the caesium 137, we had to shorten the time steps to accommodate those.

So there was some -- yeah, I'd have to get back to you on the exact time steps that were taken, but I know they varied through the simulation depending on the needs at the time.

ILLANGASEKARE: The last question is did you do any -- because you had some assumptions, did you do any sensitivity analysis on some of the parameters because sometimes, you know, that may be useful to interpret the results.

PRICE: No, we haven't done that yet. We plan to. That's part of our future study.

ILLANGASEKARE: Thank you.

BAHR: Okay. We have Mary Lou.

ZOBACK: Hi, Laura.

PRICE: Hi.

ZOBACK: That was a really nice presentation. Thank you. I appreciate you only putting one image on a slide -- or thought on a slide than rather than resisting the image to put four different figures on it.

I'm not a hydrologist, so I have a couple questions. I know what PFLOTRAN is, but I don't have -- haven't used it.

So one question I have is, and this refers to the unsaturated zone modeling, you used two infiltration rates, 2 millimeters a year, and 10.

It would have been really nice to have seen a plot of measured, assumed infiltration rates for the great basin for Yucca Mountain.

I have no idea if 2 is on the absolute low end and 10 is on the absolute high end or if they sit right in the middle.

So that's one question.

How did you choose these rates, how did they compare with actual measured rates or whatever?

PRICE: Well, that comes from a report by Mariner, and he documented it came from measurements, so I can refer you back to that Mariner -- there's two references listed here.

One has to do with the unsaturated alluvium reference case, so that's where you'd find those rates.

ZOBACK: Okay. Good.

And then since you're talking about events that you hypothesize happen, you know, 10,000 years in the future, seems like climate change could significantly impact the infiltration rates, so just wonder if there -- if you're going to try a larger range?

PRICE: We could.

We could do that, yeah.

ZOBACK: And I don't know how much -- if the great basin turned into a tropical rainforest, it probably would look pretty different.

And then the other question I have, I have done field geology work and looked at a lot of alluvium in the basin range and it's so nonuniform. There's all sorts of gravel channels and things.

Is every cell in your model exactly uniform properties?

PRICE: That's a good question. I don't know the answer to that.

Once again, Mariner, the Mariner report, would probably tell you that.

ZOBACK: Okay. Good.

Thank you.

PRICE: Uh-huh.

BAHR: Okay. Are you done, Mary Lou?

Yes.

And we have Lee Peddicord.

PEDDICORD: Yeah, thank you. Very interesting. Couple questions, maybe a little more bizarre questions.

You made reference to Oklo and so on. If memory serves me correctly that the inventories that -- that have come out of your analysis are quite a bit lower inventories that actually developed in the natural reactor. Do I remember that correctly?

PRICE: I have to go back and look.

PEDDICORD: Okay.

Because, you know, you talked about the one gigawatt day per metric ton.

PRICE: Although I have to say, Oklo was -- it was a lot hotter because it was higher -- higher pressure.

Much deeper, right, so it could generate a lot more power so the inventories probably are significantly different because it could generate way more power.

PEDDICORD: Than the power levels.

PRICE: Right.

PEDDICORD: But the other thing, too, and I don't know how instructive it would be, is there any value or things to be gained, information to be gained from looking at other underground energetic situations?

And the ones that pop to mind are things like the underground coal fields in Western Pennsylvania and Central Illinois that burned over decades. And how this affects the environment, the strata, movement of fluids and so on.

Maybe it's -- maybe it's not instructive, but I wonder if there's some other analogies of underground energetic situations that could be informative or instructive in the things that you're looking at.

PRICE: I haven't thought of that, but that's a good suggestion.

We'll look at that and see if it helps.

PEDDICORD: Thank you.

Thanks, Jean.

BAHR: Thanks, Lee.

Paul Turinsky? I think we need to get your camera and mic on, Paul, to be able to make you live.

There.

TURINSKY: Okay. I had to reboot at one point and forgot to reset.

I'm struggling with what ends this critical event. My understanding is there will be water coming in at some point depending on the reactivity of the fuel itself that's there will go critical.

PRICE: Yes.

TURINSKY: We'll go to an equilibrium power level, based on the Doppler feedback.

PRICE: Yes.

TURINSKY: And on basically on the evaporation rate of the water?

PRICE: For the unsaturated case, yes.

Yeah.

TURINSKY: Okay. What would be different for the saturated case then?

PRICE: So to stop the critical event, boiling would have to occur, not just evaporation.

TURINSKY: Okay. But the Ernie mentioned power level's just going to decrease to a level where criticality can be maintained.

PRICE: Correct. You're assuming -- (inaudible).

TURINSKY: Reactions work, actually.

PRICE: No. We're assuming for this study, we assumed it was steady-state, 4 kilowatts, for 10,000 years.

TURINSKY: Okay. What I'm saying is the real situation is that you would rise to a power level that basically gives you the equilibrium.

PRICE: Yes.

TURINSKY: And you would basically stay there forever except for the effects of the isotopics changing or the water flow changing.

PRICE: Yes.

TURINSKY: For the unsaturated case, maybe you deplete the local water sources that cause the changes in power level, but you would just sit there forever.

At some power level, changing power levels.

PRICE: Yes, so in the unsaturated case, the thought is that the bottom of the waste package would eventually corrode and would no longer act as a bathtub.

So we don't know how long that would take, but eventually would corrode.

In the saturated case, yes, the event could go on and there would be equilibrium, heat loss would equal the heat generated by the critical event.

At some point the fissile material would be used up and that could take 200,000 years, depending on the excess reactivity of the DPC.

TURINSKY: Okay. And I guess my question is are you going to look at these -- at the real scenario where power level will basically change as a function of time but will go on for a long, long period of time, there will be generation, and what the implications of that will be as far as the isotopic generations are concerned?

PRICE: Yes, so we're looking at the temperature changing -- I'm sorry, the power generation changing as a function of the temperature outside the waste package as the -- as the waste package outside heats up and how that changes the power and we're looking at that oscillatory nature and how the inventory would change.

TURINSKY: I'm not sure it would be oscillatory unless the water source was oscillatory. I think it would be just a gradual change.

PRICE: Right, that's what we're assuming, but we're studying this in more detail.

TURINSKY: Okay. That could really change the source term quite a bit, I think, from what you've done now.

PRICE: In terms of nuclide inventory?

TURINSKY: Yeah.

PRICE: Maybe, but you're limited by how deep -- the pressure at the disposal depths and right now with our assumed hypothetical repository, the boiling point is 264, and that limits the power that can be generated along with the thermal characteristics of the backfill and the host rock.

So that limits how hot it can get, which limits, as you know, the isotopes that can be generated and the inventory increases on the order of 3%, which is, in the grand scheme of things, not that significant.

That's within the variability of the inventory, given all the CSNF out there.

TURINSKY: Okay. It's just that it goes on forever.

PRICE: Right. Unless -- unless the grid space would degrade.

And that's one thing we're looking at is grid space degradation from the higher temperatures.

Because the waste package could be at

250 degrees for a long time and the corrosion rates is increased and the theory is, that we're working on now, is if the grid spacers degrade, the fuel will collapse, the configuration will be lost, and the critical event would cease.

TURINSKY: Okay. And at 521 is when this study is going to take place on these points?

PRICE: Yes. Even right now actually.

TURINSKY: Yeah, okay.

Thank you.

PRICE: We can't hear you, Jean.

BAHR: Sorry.

We have a question from Steve Becker.

BECKER: (Inaudible) members of the public and I realize that the research is still very much ongoing, but if you were asked to identify two or three very broad takeaways for the public from what you have learned thus far, what would they be?

PRICE: Thus far, and this is preliminary, so it doesn't look like the inventory increase from a critical event is that significant, and I think in unsaturated conditions, a critical event could be of very, very limited significance because it would be difficult to get a critical event to start and to -- to be maintained, just because the water evaporates so quickly and it's hard to refill the package.

BECKER: Thank you.

BAHR: Okay. Do we have any other questions at this point?

Just one sort of final comment. I assume that you're using unsaturated alluvium as a placeholder for unsaturated material because porous media is easier to simulate than the kind of fractured dual porosity media you might have had at a place like Yucca Mountain.

I don't think anybody's seriously considering building a repository in alluvium?

PRICE: Well, we're using that because Paul Mariner had produced a report that had all the data we needed, such as the 2 millimeter per year and 10 millimeter per year infiltration rates, and the porosities and the permeabilities.

So we already had some research that --

we were leveraging research that had already been done in the unsaturated repository.

BAHR: Do you know why he chose to use that as a -- as a reference case?

I see we have Bret Leslie and Ernie Hardin (inaudible) after that question.

LESLIE: I'll let Ernie answer that question.

BAHR: Okay. We need Ernie's cam and mic on. Okay.

Thanks, Ernie.

HARDIN: I'll go first quickly.

In 2012 we did actually take a serious look at alluvium and the beauty of it is the plant community sucks all the water out and the recharge is almost zero and that's based on work that's been done by USGS and desert research.

As far as finding the right alluvium site, we didn't go there. There's a lot of alluvium in the great basin, but there are limits on the spatial availability.

Yes, it has been considered.

BAHR: Okay. Thank you.

Bret?

LESLIE: Yes.

Laura, could you provide a little more background on whether what you've done is consistent with the disposal topical report on criticality?

And I know this is the first time you guys have looked at -- at -- at looking at the consequences but, you know, I think that was addressed there and it just would help me to understand whether your approach is consistent with that methodology.

In other words, NRC wouldn't be surprised by what you're doing or did you find anything that is different than what NRC suggested?

PRICE: No, we didn't.

I mean, we did look at the -- studied the topical report and I don't think we did anything that's inconsistent with that.

LESLIE: Thank you.

PRICE: Let me put this it way. The saturated repository is a little bit different because the disposal -- that topical report assumes a unsaturated Yucca Mountain repository.

So the saturated case is a little bit different in the sense that in the topical report it assumes if a waste package fails the critical event stops and that's not true for saturated repository.

So there is a few differences there because of the saturated repository, but other than that we've tried to be consistent with that.

LESLIE: Thank you, Laura.

BAHR: We have about three minutes left and I see hands up from Ernie Hardin, Efi Foufoula, and Bobby Pabalan.

If Ernie is clarifying something we can bring him on. Otherwise we should probably go to -- Efi has disappeared.

Go to Bobby's question.

But give Ernie a chance, since he's there.

HARDIN: No, I'm done. I've said my piece. I can say more about alluvium, but I think I made my point.

BAHR: Bobby?

PABALAN: Laura, are you planning to

look at another scenario, that of a fractured crystalline rock, host rock, and the thermohydrological processes will be different than in a saturated play or shale.

I know you've done the reference case for crystalline rocks already, so it's a simple matter to extend it to criticality.

PRICE: Right now we're not planning on doing that, but we can certainly consider it.

PABALAN: Okay. Thank you.

BAHR: Okay. I think that brings us just right about to the end of the time that we had allocated.

Thank you again, Laura, for a very informative presentation and now we're going to go to Kaushik Banerjee, who's going to be talking about fillers that can be used, the approach and testing of those.

So if we can bring him up and his slides. I can get rid of myself.

BANERJEE: Okay. Thank you. So thank you. Good morning or good afternoon.

So today I'm going to talk about the ongoing research and development for filler approach and testing.

So what I'm going to do is I'm going to talk about our overall approach and then Mark is going to talk about some of the work he's doing on cement-based filler materials.

So my name is Kaushik Banerjee and I'm from Oak Ridge National Lab.

So we've seen this a couple of times so I'll just skip this one.

So yesterday we talked about, like, we are taking three approaches to address the DPC criticality issue at this point.

So yesterday we talked about -- yesterday we talked about our reactivity analysis to find out, like, the potential for DPC to go critical.

This morning, today, Laura just talked about the criticality consequence and not only when you talk about filler.

The filler approach is quite simple.

If you remember yesterday I mentioned, like, we need water in the system or we need moderator for the DPC to become critical.

So the filler approach is, like, you

just fill the empty space in a DPC with some aluminum filler material, before putting the DPC in the repository, and that filler material will prevent flooding in a repository time scale of 10,000 years or more. And there's no flooding, there's no criticality, so in a sense that filler will actually reduce the potential for criticality.

So that's -- that's the concern for the filler.

So for our (inaudible) studies we are making some key assumptions here.

One of our assumptions is we're going to use the existing port, so that means existing DPC, they have two holes. One is the pin and the drain ports.

So the idea here is to use one of them or to make some custom-built ports like drilling a hole through the shell of the DPC outer wall.

So currently we are not considering to cutting open the entire thing. So that is a key assumption we are making at this point.

If you see the figure here on the bottom of the slide, this is showing two ports we have.

One is the vent, one is the drain, so there's a pipe attached to the drain port that goes all the way to the bottom of the canister.

So we use this port for upper loading, for draining and drying, so the ports are being used for that, and currently we are actually mainly focusing on that drain port with the drain pipe. That means we are thinking of filling the canister from bottom up.

So some of the properties we would like to have, some of them are necessary, must have, and some of them are nice to have.

So the filler should be compatible with the disposal system. That means it should not accelerate corrosion of the system itself.

That defeat the purpose of the filler.

It should have long -- it should be long-lasting. That means should be -- stay there for long time. If it's not, then it will also defeat the purpose. It should displace moderator, that's the main objective. So that's a must have.

It should have minimal neutron moderations that you can provide a lot of neutron moderation that can make the system critical, so there's no point of doing that so it should provide minimal neutron moderation. So another nice property would be if we can incorporate neutron absorbers.

That's not a must have but would be nice to have. The filler should be easy to inject in the system and should flow properly so we can fill the system properly. It should generate minimum gas or give you any kind of radiolyis or any kind of heat generation in the filler itself.

Radionuclide sequestration would be a nice-to-have property and should be not -- should not be crazy expensive.

If it's crazy expensive, then it can also defeat the purpose of filling the canister.

So filler is not a new concept. It has been considered before. But only solid particulate fillers were tested experimentally, using open canister. That means a canister without a lid.

So previous work actually shown successfully filling a canister without a lid, using a steel shot or glass bead.

But remember one of our key assumptions is we are not cutting open the lid.

So -- and -- and we are trying to use one of the ports for filling the system.

So currently we are considering mostly molten solid as our filler materials, and why we're considering molten solid for one of our filler materials at this point, if you think about, there are probably three types of materials, essentially.

Gas, liquid, and solid.

So gas and liquid, they're not options for DPC direct disposal.

So we need some kind of solid filler.

A solid could be the solid form. That means a solid particulate, the one that has already been used before with the lid open.

Experience we have seen in the previous slide.

Another one could be the solid in a liquid form, so we could pour that into the canister and then it would solidify upon pooling, also chemical reaction.

So as one of our key assumptions, we are not cutting open the lid so we think it would be really difficult to push a solid particulates through one of the port and uniformly fill the canisters.

Because the particulate has to flow properly through the canisters and the canister has a lot of structured weight, structured inside the canister, they have like a basket cell there, neutron absorber there, mouse holes, all different kind of things.

In addition to that, also we think, like, the solid particulate filler could create a large interstitial volume and allow a significant amount of water for solid particulate remaining in the neutron absorber and also we probably need to hydrate or shake the system to achieve some kind of, like, packing fraction or packing density possibly.

On the other hand, for the molten solid filler, we haven't done any experiments, so there's no experimental data.

What just happened?

So there's, like, experimental data for solid -- for the molten solid.

Also do not have any handling experience and also we do not have a simulation tool that can simulate the filling process.

Currently we are focusing on molten solid as one of our filler candidates.

So for the molten solid, currently we are considering cement slurry, and Mark is going to talk about that in details. We are also considering low-temperature metals, alloys, and glass.

So on the previous slide I talked about what kind of -- what type of filler we are going to focus on right now and now I'm going to talk about -- on these two slides, this slide and the next slide, I'm going to talk about our overall approach.

So if you think about it, and Ernie kind of showed that, so there are many different kind of DPCs, DPC designs, and there could be many different choices for your filler materials.

And we cannot do an experiment using all different kind of design and all different kind of filler mix.

So the goal here is to develop a

simulation tool that can simulate various different kinds of DPC design and different kind of filler material, and allow us to develop that simulation tool by step-by-step validation.

So initially what we have done, we started with a flow simulation. It's a single physics, just a flow simulation, and we have done some validation of that simulation in our lab and we're going to talk about that.

After the doing the flow simulation, now we're going to move to our casting and solidification part of the simulation. And that solidification simulation will actually capture what is happening after the solidification.

What kind of defect is forming after the solidification. What kind of void fraction, what kind of holes we are creating after the solidification process.

So this fluid solidification will become the simulation tool eventually, with step-by-step validation, and the goal is to use that tool for simulating the filling process of each various DPC design using different kind of filler material.

So that we can use this simulation tool to down-select our filler materials to some later number of filler material for doing additional testing.

So for this simulation to result in any different kind of input we can think about we need different kind of initial and boundary condition to support this.

So one of these things will be like heating.

So for some of the metal and even for cement study we may need to preheat the DPC. So how are we going to do that? Are we going to use insulation.

So we are also doing the studies in our (inaudible). We're also starting like how -- or what kind of approaches we can take to preheat the DPC.

The other one would be we're thinking of using the pipe, it's a really narrow and long pipe, for filling up the DPC.

So what kind of flow that pipe can sustain?

So we need to figure that out.

So we are planning for a pipe experiment to figure out what kind of flow rate a pipe can sustain.

So that would be another input to our filling simulation.

The other one is to make sure we have properties. Like for example, Mark is working on all this cement-based filler and we can use those cement-based properties for our simulation.

So this cartoon at the bottom of the slide is basically showing that concept.

So here we have a DPC filling simulation. Under that simulation, you will see that the flow and casting are solidification part.

For that simulation we need different input data and we are working on DPC internal heating, how we can preheat a DPC. We are planning for a drain pipe testing to find out what kind of flow rate we can sustain in the drain pipe, and we are also doing some material testing that will provide some input to our filling simulation.

The filling simulation, the flow and gas simulation also is developing step by step and we are doing a step-by-step validation of that simulation in our lab.

So our current goal is to develop a full simulation for a full-size DPC, and if we have that then we can use the simulation tool for down-selecting different kind of filler material. So after down-selecting the filler material, when we have a handful of filler materials, then we can perform additional material testing.

That means we can perform radiation hardening. We can perform corrosion testing using those handful of material.

And those material testing or material calculation will give us even the smaller number of candidates and then we can use the smaller number of candidates that could be one filler or couple of fillers.

We can simulate them using our simulation tool and maybe we can do, like, one or two tests.

So the simulation tool should be able to simulate, like, different kind of DPC design, but for the testing part we need to use one or two designs for the validation process.

So that's the idea.

So in the previous slide I kind of talked about the overall approach. We're trying to come up with a fully calibrated simulation tool that can simulate the DPC filling process and identify the issues, what kind of issues we have during the filling process.

And also we can use that tool for down-selecting or narrowing down the number of filler materials for doing additional tests.

Now I will talk about each component of that and how we are kind of gradually making progress towards that filling simulation tool.

So initially we started with doing a CFD simulation. That's basically a flow simulation, so we made a model.

This is our five-assembly DPC model and so the DPC can hold five-by-five assembly types as shown in this picture on the top.

We used this model and we used surrogate filler, so keep in mind this is not the actual filler we're going to use in the repository. So we used water, we used glycerin, we used silicon oil, we used lead. So they are selected based on their viscosity and density.

And some are easy to handle in the lab.

So we can do lab experiments for benchmarking our simulation.

So at the bottom we are seeing some simulation results for the flow simulation and we're seeing a nice viscosity effect.

So if you see -- this is the bottom two pictures, they are actually taken at 10 seconds during the filling.

So we have -- we have the filler is coming through that drain pipe and the left one is silicon oil, which is highly viscous.

And the right one is water, which is less viscous than silicon oil.

So you see we're using the same flow rate, 6.3 CC per second, for both experiments. And you see at the same time, at 10 seconds, the water can propagate to the other side through the mouse hole, but silicon oil is much more viscous. It is not propagating to the other side. The level of the height will rise and then you can slowly propagate to the other side. So that's the viscosity effect we're seeing from this kind of simulation.

So we have the same system in our lab for doing some validation work on the simulation.

This is the left figure here showing the system we have in our lab.

So in the simulation we use a 180 degree symmetry and we use 6.3 CC per second as the flow rate, so this flow rate was derived based on 17 hours' filling time for a full-sized DPC.

It’s kind of arbitrary at this point. We assumed 17 hours would be a reasonable time and based on that we would derive our flow rate for this scaled-down model.

For the actual experiments as we are not using the symmetry, so the simulation was using 180 symmetry, so we have to double that, the flow rate, to 12.6 CCs, and to maintain the flow rate for viscous liquid, we have to use a pump.

So on this slide you're seeing some of the results, so this is basically the results comparing between the simulation and experimental data. So on the left hand we have the water, on the right hand we have the glycerin.

As I mentioned before, we selected the glycerin because of high viscosity.

We use two-level system and all we are tracking how the level of the liquid is progressing as a function of time.

So as you'll see, they're matching quite well, for the water they're matching quite well. the experimental data is matching very well with the simulation.

The same as for the glycerin but for the glycerin we're seeing there's -- in the simulation there's an initial bump and then we are matching with our experimental data.

We think that initial bump is due to the viscosity effect I just talked about in the previous slide. That means it's the high viscous, the level would rise, and then it will propagate to the other end.

But we -- we did not capture that effect during the experiment.

We were able to capture that in a simulation, but we couldn't capture that in our experiment, as shown in the picture.

So we have done some CFD simulations and using some liquid, and after that we decided to move on and start doing some experiment with actual molten filler.

So the objective was to gain experience with the molten filler and also to collect data so we can use the data for benchmarking our simulation tool.

So we selected paraffin wax for our initial testing.

So we selected paraffin wax because it is easy to handle in the lab. It has a low melting point. So we can easily make that in the lab and pour that in a canister.

So this is our experimental setup or experimental apparatus.

So this is the cooking part where we are kind of making that paraffin wax and pouring that from the top. We also use a heat dip to keep the paraffin wax molten all the way through the pouring process.

And we also use some spacer grids for our assemblies inside the canister. Spacer grid is shown on the left side. The spacer grid has a unique design so you can actually fill them one by one, strip them off, and take a look at the inside to see what kind of solidification is operating inside the spacer grid. If it's creating more void inside the spacer grids or not.

So use multiple thermocouples to measure temperature at a different location during the pouring process and during the solidification process.

Before filling, we're going to heat it up, the canisters, for two hours and also use an insulator to reduce or minimize the heat loss from the system.

So we've got to measure like the average overall temperature around 55 degrees centigrade.

The minimum temperature in the canister was about 43 degrees centigrade, and the molten wax was poured at around 75 degrees centigrade.

We also used three thermocouples around

the length of the pipe just to capture the temperature gradient because the temperature gradient along the length of the pipe would be an important one. And if it is a large temperature gradient that could start a part of that -- part of the canister could start solidifying and that would actually choke that flow. So this table here is showing some of the -- some of the location of the canisters, some of the location of the thermocouple inside the canisters.

We also use a high -- we also used a temperature probe.

This temperature probe is nothing but fiberoptics in a capillary tube.

It has about 511 temperature sensors and the spatial length of this was like 355 millimeter and the spatial resolution was about .65 millimeter.

So we put that -- so what I've done is we have taken one fuel rod out from that assembly and we put this probe inside of that fuel rod inside that assembly.

So on this plot we're seeing some of the temperature profile. If you see this is as a function of time.

So we're starting from the starting time and going all the way to 60 seconds and the X axis is the length, so we can see along the actual length we are maintaining about 50C in pressure, constant in pressure, then you'll see there are some pink circular area where you can see there's an abrupt change in temperature.

That change in temperature is basically indicating that interface between the liquid and the gas.

So that means, as we can see, that pink circle is moving with the time and that's basically showing the way they're filling up this as a function of time.

We also have taken measurement during the actual solidification process and we generated some of the cooling curve for different locations so we have generated cooling curve for canister center, for canister side, and for the spacer grids, and from the cooling curve we can identify when the solidification starts and when solidification completes.

So we're gathering all this information so that we can use this information for doing a validation of our simulation tool.

We have taken a CT scan to find out in nondestructive way the right formation and to quantify what kind of porosity or what kind of void fractions we are getting after the solidification process.

We have done a very simple experiment to find out the externally connected void or externally connected pore. What we have done, we've taken the weight of the canister with the wax and then we fill it up with water.

We have taken the weight again and we measure the difference, and from the difference we can calculate the externally connected or externally connected void and we calculated about 1300 CC of externally connected void in our -- in the system.

So this is some of the images we can generate by high-resolution reconstruction and 3D rendering.

One of the interesting things, for this experiment what we have done, we kept assemblies in one of the cells and in the other cell the canister is already empty and what we're seeing here, we're seeing the empty locations, we are getting more water in this location than actually in the assemblies.

We're not seeing that much of void -- void formation along the actual length of the assemblies, but we're seeing a lot of void formation in those empty locations.

So we have a lot of information from the CT scan and we are currently analyzing those.

We're using a tool called VGSTUDIO.

That can give you an image like this.

It's basically showing like what kind of void we have and it can color the void by the void volume, and if you go and click it -- click the void, it will show you the void profile. That means it will give you the void volume and the diameter of that void.

So currently we started working on the solidification and the casting part of the simulation, so we're using ProCast.

ProCast is a simulation tool for casting.

It can handle both metal and composite.

So ProCast uses a finite element method to model flow, thermal and stress behavior, and also can quantify the defect after the solidification process.

So all the data we collected from our wax experiment, we're going to use that for validating and for benchmarking the ProCast tool.

We're also planning a small, unique set of experiments using molten tin and we're going to collect data from that experiment and we're going to use that data for validating our simulation tool for solidification and casting.

We're going to do the same thing with Mark's cement. We're going to use Mark's cement composition for doing a simulation to find out if we can -- and some testing and to do some validation of that simulation tool.

So here's like a small example of the simulation we can do using ProCast.

This is very hard to read and I apologize for that.

This is basically showing a single assembly filling and is showing the flow rate in temperature profile and solid fracture at 35% of filling, 100% of filling, and during the solidification process.

This is the one we're currently working on and the goal here is to get rid of this ProCast simulation tool for simulating an intact DPC and we can simulate the DPC using any filling materials or filler material.

So we talked about for our simulation, we need some initial boundary conditions.

We need some input.

One of the input would be like what kind of flow rate the pipe can sustain.

We're talking about it's really long, so it's about four meter long and really narrow pipe going all the way through.

So we are planning some pipe experiments just to figure out what would be the maximum flow rate, what put less the strain on the pipe.

If the filling to the pipe would create some kind of hydraulic lock situation.

Those are the things we have in mind and this is something we're planning to do.

So this is basically our pipe simulation or the pipe experiment setup.

So this pipe -- so this is inside the pipe.

So the outer pipe -- there's a pipe inside this, the pipe we're seeing here in the picture.

So what we are going to do -- and this is a storage tank.

The pump will get the filler from the storage tank, we put that to the inner pipe and the filler will go through the inner pipe at the bottom and then will comes up through the annular region, and then go back to the storage tank.

So the inner pipe, we can actually change the inner pipe in this experiment setup, so we can actually do experiments with different kind of pipes, diameter of pipe, wall thickness.

So that's the idea here.

So we are currently considering mercury for doing this experiment. And why we are considering mercury, because mercury has similar properties as metals, for most of the metals, and also mercury is a liquid in the room temperature, so it's very easy to handle, and also we have a mercury loop, existing mercury loop, that we can use for doing this experiment.

The other one where we talked about, we are also working on to find out what other ways we can actually heat up the DPC canisters.

So for -- for most of the metal and glass, we need to preheat our DPC and also to cure concrete we need to preheat our DPC.

One thing I'd like to mention, if you are looking at a PDF version, so I have a simulation on this slide, so your slide number may not match with this one.

If you have seen the PDF version, you may not see this picture -- may not see this figure right here.

They are behind the canister picture.

So we have done some scoping calculations to find out what would be the maximum temperature for 10 kilowatt power and for 6 kilowatt power.

We found the maximum temperature for 10

kilowatt would be slightly above 100 and the minimum would be slightly above 70.

And for 6 kilowatt, the maximum would be around 80 centigrade and the minimum would be slightly above 55 degrees C.

So for those kind of temperature we really cannot, if we start pouring a molten metal or something like that, so that one part of that DPC would start solidifying and that can choke that flow so we need to preheat the system.

So we are considering different options for preheating the system.

One could be simple, just put insulation around the DPC and wait for a day or two for the temperature to rise.

We can also think about (inaudible) gas to the system for preheating.

We are also considering putting an external blanket or external heater for heating up the system.

The other option could be if you're putting that DPC in a filling station and there's an annulus between the DPC wall and the filling station wall, then we can put a vacuum in there and try to increase the temperature.

So we are considering all these options and using COBRA-SFS for modeling some of the options.

So the basic idea here is going to be to design a filling station that should be able to preheat the DPC in a desired temperature, so the temperature will depend on what kind of filler we're talking about and based on that, we need to find out what kind of preheating we need.

So that's something also we are working on and we're using COBRA-SFS for doing that kind of model.

So this is the simulation I was talking about. This is just to show what would be your canister surface temperature, a DPC surface temperature with 10 kilowatt power, and as you can see some of the locations the surface temperature can go below 50 C.

So I think this is my last slide.

So I talked about -- so our focus is molten solid as our filler materials, but we are planning to do some testing using the solid particulates in the future as well.

So current approach is to develop a fully validated or benchmark tool that we can use for simulating actual DPC and we can use that for simulating different DPC design and with different filler materials.

And that we can -- should be able to use the down-select or narrowing down our filler materials.

So we started with doing some CFD calculations, CFD calculation was just flow, and we've done some benchmarking for CFD calculations and seen some results.

Then we have done some experiments with wax just to have gather some experience to handle the molten filler in lab space and also collect data that we can use for benchmarking or for validating our casting and solidification simulation.

At the same time we're also working on some -- some input that we need for our casting simulation and one of the input would be the pipe experiment I talked about, what kind of flow rate we can sustain in the pipe and the other one would be the DPC heating simulation we're working on that basically provide us what kind of boundary conditions we need to maintain the DPC to certain temperature.

And next Mark will talk about all the filler material testing Mark is doing.

With that, I can take any questions. Thank you.

BAHR: Okay. Thank you very much, Kaushik.

Question from me, the heating in order to fill, are there implications for the condition of the fuel and the cladding and the components of the DPC from that heating process? How are those being considered?

BANERJEE: One of the assumptions is we're taking on not to exceed 400 C cladding temperature.

BAHR: But it could go up to 390 or something like that, which actually could be higher temperature than the fuel experiences during the drying process based on some of the current records of the drawing for --

BANERJEE: Right. But I think the way I

think about it, if we fill the system with some filler materials, I don't think that we need to really think about keeping that 400 C temperature for the cladding.

But the idea here is to have something so that we should not exceed that temperature at this point.

BAHR: Okay. Thank you.

I see a hand up from Tissa. So --

ILLANGASEKARE: Kaushik, thank you for your presentation. It's very nice to see some experiments and your approach doing it multiscale (inaudible).

So I have a question related to the experiment itself. Maybe I misunderstood.

So in the experiment you used silicone oil. Is that correct when you look at the cement material, then viscosity is going to be non-Newtonian fluid so in your CFD, you allow for the viscosity, different type of -- like a non-Newtonian viscous simulation.

BANERJEE: We run that with different kind of viscosity for sure, but I am not -- not a CFD guy so I cannot answer that question but I can get the information to you.

But we definitely have done that calculation or done the simulation in different kind of viscosity.

ILLANGASEKARE: Yeah, the question is did the experiment you used silicone oil, which is good, but the question is can you go to a non-Newtonian fluid or experiment can be quite complicated and the model may be validated for that situation but when you go with like a cement material, both the way it behaves in the injection and the distribution, it may behave quite differently.

BANERJEE: Yes, I understand that. We are slowly getting there. We haven't done that yet.

ILLANGASEKARE: Okay. Thank you.

BAHR: Thanks.

We have a question from Paul.

TURINSKY: Yeah, two questions.

What is -- I didn't hear anything about research going on for the chemistry between the filler material, the basket material, the fuel, and even basically the -- the water, the geological formation itself.

BANERJEE: That's definitely one of the things, if you see my slides, one of the -- one of the criteria for selecting a filler, the filler should be compatible with your canister or your fuel. So it should not like accelerate the corrosion inside the process.

We should take that into account when we down-select our filler materials. We haven't done that yet. We're not there yet.

TURINSKY: And also never forget about the water basically coming in, what its composition is, based on the geological formation.

The second thing is I don't know if there's any validity to this, but you have some full-scale experiments going on right now but it's called drain.

That is, people are filling canisters constantly at nuclear power plants and they're draining.

Would there be any merit in using that data, collecting that data for validation purposes?

BANERJEE: I think so. I think we can collect some data and do some valuation. Yeah, I agree with you.

TURINSKY: Okay.

BAHR: Okay. We have Mary Lou next.

ZOBACK: Yeah, hi, thanks.

That was a very nice talk and I agree it's nice to see some actual experiments rather than just models.

I have a general question and it may not be just for you. And maybe someone else could better answer it, but it seems that the assumption in the models is that the fuel assemblies are intact inside the canisters, and I just wonder is that a valid assumption for some of these casts that have had fuel -- have had some of the oldest fuel assemblies in them, they've been there a long time, the ones at North Anna got shaken quite a lot during the earthquake.

So will that have any impact on the models if the -- if the fuel assemblies are not intact?

BANERJEE: Are you talking about the

filling model?

ZOBACK: Pardon?

BANERJEE: Are you talking about the filler model or the criticality model?

ZOBACK: Well, either. The geometry seemed important.

BANERJEE: Yeah, it is, for sure. If you put some damaged assemblies in the system, the way they're doing that, they put the damaged fuel in a damaged fuel can and that can go inside the DPC and that can has like a mesh at the bottom and the top, so if you have to fill the system, it would be hard to fill those locations. They have to pump through that. So, yes, you would have some issue with that, so we would need to look into that for sure.

ZOBACK: Okay. And then just a general question, for all this modeling, you are -- you talk a lot about chemistry but what about microbiology, what some of the water coming in that has a microorganism that likes warm water?

BANERJEE: I don't feel I have enough knowledge to answer that question, but that's something we need to take a look at in the future.

The way I'm thinking about it, we are doing the simulations and we are doing the validation to down-selecting our filler materials.

If we know these three or four are going to be our filler materials then we can do all the testing to find out if there is biological leaching of that thing or what corrosion, what could be the radiation damage from the fuel.

But initially the way I think about it, there are so many materials options and if we do those types of testing it's very expensive to do anything like that so we need to down-select, we need to come up with a couple of handful of materials and we can do the simulation and after we do the simulation, we can do the actual testing about the leaching, corrosion, radiation hardening and all those things.

ZOBACK: Thank you.

Thanks, Jean.

BAHR: Okay. We have a question from Nigel.

Nigel needs his camera and mic on in

order to ask your question.

There we go.

MOTE: I was getting blocked from letting my camera join.

Thanks, Kaushik, nice presentation. I appreciate that.

You talked about the thermal properties -- or talked about the properties of the materials you might use as a filler.

What you didn't talk about was the fill of properties over time.

In the sort of time frames we're talking about in a repository, have you looked at how there may be separation from the filler and the fuel so that in fact you target any water that enters the canister adjacent to the fuel and what the implications of that would be for dissolution, migration of active species, those sort of things?

BANERJEE: No, we haven't done that yet and I think we need to come up with a handful of filler materials first, which we do not have at this point.

If we know these are our filler

materials we can do all that kind of testing and simulation.

We're not there yet.

MOTE: Okay.

Jean, can I have a second one?

BAHR: Sure.

MOTE: On Page 3, you have the bottom comment says, "Cutting open the canister lid is currently out of consideration."

Does that mean you're not looking at it yet, or you've dismissed that in the long term as an option for filling canisters?

BANERJEE: So to me I'm thinking of -- back in the day, it's basically similar to repackaging, so we have mostly the repackaging space.

We can look at that in the future, but currently that is not the focus.

MOTE: Okay. And the reason for that is because refitting the lid is going to be a complex undertaking, is that the reason for not looking at taking the lid off completely?

BANERJEE: No, not really that. I think that we need to design some kind of big hot cell facility for doing any such operation and we're talking about like high dose. If you take off the lid, the dose is really, really high.

And also we're talking about like -- and if you take the dose -- if you take the lid off, why not just repackage that?

MOTE: Well, because yesterday we heard the cost of disposing of the canisters and the dose that would be (inaudible) and so on.

Okay. Thanks for the answer.

But the comment above that says purpose-built ports that you could put in the canister and use those for filling.

Have you looked at the potential difficulties of resealing the canisters if you put as many ports in because that may be getting on for as difficult as taking the lid off.

BANERJEE: No, not yet. Right now they're just considering that vent and drain port. They're not (inaudible) when you think about the port, but we're not there yet.

MOTE: Okay. All right. Thank you.

Thanks, Jean.

BAHR: All right. Thanks, Nigel.

We have a question from Lee Peddicord.

PEDDICORD: Yes, thank you. Interesting nice stuff and very nice detailed work there.

Mine is a very general question, I think, that would kind of represent the crossover point, if you will, between the Sandia work and the Oak Ridge work, and what I mean by that is the following: The background, as Ernie Hardin pointed out, is keep the water out and you're subcritical and so Laura Price gave us a really good look at achieving criticality, water coming in, the consequences and so on. So the filler work is really to keep the water out, as I understand it.

You had a really interesting list of the criteria you ought to consider for your filler and so on. But it seems to me you only need one element, one line on that criteria. It's got to be not as good as water in moderating neutrons or something like that.

Pretty simple. Just can't be water. Something less than water. And then you'll add a lot of other things that made it more robust.

But the crossover point that comes to

mind between the Oak Ridge work and -- and your work is how much of any kind of filler you need to put in even if the canister fails and water comes in, do you not need to go through to the extent that you're doing which is in no way saying it's bad work of getting the degree of penetration and filling and so on, just got to keep some of the water out to make sure it stays subcritical.

So as I say, it seems to me there's kind of a crossover point of how much filler of any kind, not as good as water, you need to put in so when Laura Price runs her calculations it doesn't go critical.

Something of a -- a pretty straightforward maybe simple criteria, but it would seem to me that you all can talk back and forth and find out what's needed, kind of what is the minimum amount of some kind of filler so no matter what happens with water coming in, it won't go critical.

BANERJEE: I completely agree with you and actually we are working on that right now, as we are talking, we're working on that.

I have a filler composition from Mark from Sandia and we are actually putting that in the canister and trying to figure out what is the minimum we need.

So we are working on it right now.

PEDDICORD: Because we talked about costs and things like that and, you know, and some of your solutions are very elegant, perhaps costly, and so on.

So, again, this might be a point around which one could optimize or maybe find a maximum or a minimum or whatever is the right characterization without going to a very elegant, more involved, expensive solution.

BANERJEE: Yeah, completely agree and we are working on that right now. They are working on that.

PEDDICORD: Okay. Thank you, Jean. Appreciate it.

BAHR: Okay. Thanks.

I don't see any more questions.

Bobby Pabalan?

PABALAN: Yeah, just to follow up on Lee's question about what is the minimum amount of void space that needs to be filled but the question also is what if the filler does not solidify uniformly so you have gaps or additional void spaces and what if it starts solidifying while still on top of the DPC, it doesn't really get to the bottom, so really just another question on top of Lee's, something to look into.

BANERJEE: Yeah, exactly. So those are the things we're trying to investigate using our simulation tool.

The simulation tool will tell us like if there's some kind of a differential solidification, and if there's a differential solidification, it starts solidifying from the bottom, it can (inaudible) as well, and also trying to quantify like what would be the void or what would is the defect after the solidification process, so those are the answers we're trying to get out of the simulation tool.

PABALAN: Okay. Thank you.

BAHR: So I see one question from Bret Leslie and then after this, we're going to take a break.

So Bret?

LESLIE: So Kaushik, have you thought about the implications basically of filling vertically and disposing horizontally?

So, for instance, you fill -- you're only 50% effective. Well, now you have a half a bathtub when you go to the side, so is the -- is it a simple geometric analysis of the geometry of disposal that you need to be considering rather than the filling efficiency because you're filling it vertically?

BANERJEE: I don't think so. Right now the idea we are filling bottom up, so I think that would solidify and then put that in the repository. So there should not be any implications from the criticality perspective.

LESLIE: Okay.

BAHR: Thanks, everyone. We're scheduled for a break right now that should go to 2:45 Eastern time, and 11:45 Pacific Coast time.

So we'll look forward to seeing you all back in about half an hour.

Thanks.

(Recess taken.)

BAHR: Okay. We're back. We're going -- our break is going to end in just a couple of minutes, so I'm back online and in about two minutes we will key up the next speaker.

So if Mark Rigali from Sandia National Labs and Rob Howard from -- oh, sorry, that's the next one.

Mark Rigali from Sandia National Labs -- (audio overlap.)

RIGALI: Can everybody hear me?

BAHR: Yes.

RIGALI: Excellent. I hope everybody had a nice lunch break.

Unfortunately, I was answering the cell phone and dealing with texts so I didn't get to eat. If my stomach growls and you hear it, I apologize in advance.

So we're going to go ahead and continue the discussion on fillers and talk about Sandia's efforts and research around cement filler development.

And let's see, next slide. There we go.

Okay. This is the obligatory disclaimer. People may have gotten on late and not heard Tim Gunter or Bill Boyle describe this. If there are questions, you could potentially ask them later.

All right. So this is a slide very similar to the one Kaushik showed with a description of key attributes that we're looking for for DPC fillers.

A lot of this came from work by Hardin & Brady in a document that was published in 2017 and, of course, material compatibility and ease of injectability are going to be very important to us.

Most important of all, I need to emphasize that, is that we want to keep the water out. Want to keep the water moderator out of the DPC.

And, again, we want these materials that we choose to have minimal intrinsic neutron moderation.

Another important consideration, and this is particularly with the cements, is we want minimal gas generation in the end, particularly after we close the canisters, we don't want any residual water that we use in the system to make the cements potentially go through radiolysis and generate gas that would potentially pressurize the DPC.

Long-term chemical stability, very similar to mechanical -- material compatibility, but here we're talking about the materials themselves having a long-term chemical stability in the filler system.

The other very desirable attribute is the ability for the filler materials to have some capacity to take up radionuclides.

It's not a requirement, but it is a desired feature for these materials.

So Hardin & Brady focused on us a couple of priorities for filler research, and that includes the phosphate-based cements that I'm going to be talking about and the low melting point metals that you heard Kaushik talk about earlier today.

So why phosphate cements?

There are a number of advantages for the phosphate cements.

They start with simple inorganic reactants, they form to -- the reactive form, nontoxic solids, they're -- these are typically acid-based reactions, so the end product is at near neutral pH, and at these pH's they have very low solubilities.

They can be self-bonding, in other words, they'll stick to each other layer by layer, and some of them, in particular, the calcium phosphates, have an intrinsic ability for radionuclide sequestration.

Now, you had asked in your questions to us before the presentations about disadvantages and challenges.

One of the challenges that we're going to have, because we use water as a carrier and additive to control viscosity and these acid-based reactions tend to generate water, we have to be able to get the water out.

So it's important that these cements have an intrinsic porosity and permeability that allows the water to escape readily.

So some of the materials under evaluation and the focus of this presentation is going to be primarily on our work in developing these filler materials, developing formulations, developing consolidation conditions, in order to get well-consolidated cement bodies.

The system that's our primary focus right now is aluminum oxide, aluminum phosphate.

We're also looking at calcium phosphate cements, possibly with a calcium phosphate or apatite filler that's bound by a calcium phosphate cement.

Wollastonite, which is a calcium silicate, is also being look at with an aluminum phosphate binder.

We did some work on flyash aluminum phosphate cements.

This was actually something that came about because we had initially started looking at flyash as a co-additive to aluminum oxide and the aluminum oxide-aluminum phosphate cement, but as it turned out in our control experiments, the pure flyash reacted with an aluminum and a phosphate which made a very nice cement.

I'm not going to present on -- on the flyash or any of the other commercially available cements we've been looking today due to time constraints. But you can find information on those in the 2019 report.

Okay. Aluminum phosphate cements. Aluminum phosphate cements were originally developed by Kingery, a ceramicist, back in the '60s. More recently Arun Wagh at Argonne National Labs has developed these materials for radioactive waste disposal applications.

The reaction involves taking an aluminum oxide powder, mixing it with phosphoric acid, additional water is added to enable the creation of a smooth, pourable slurry, and then an acid-base reaction takes place to form aluminum phosphate and chemical water.

So the aluminum oxide is typically added in excess.

We've been doing this at about 5 to 1 so that we have excess aluminum oxide in the cement that acts as a filler and the aluminum phosphate forms the binder.

The reaction, once it's complete, we end up with near neutral pH at the post set.

The temperatures -- the set

temperatures -- this material doesn't actually set near room temperature. It requires heating. And what -- there's some advantages to this.

We expect, of course, heat in the DPC, heat that we may be able to take advantage of in order to set the cement, but also because these mixtures don't react at room temperature, we can make smooth, pourable slurries in water that are stable for many days.

And that gives us a lot of working time from the time we would mix till the time we would complete the filling of the DPC canister.

So early attempts -- this material system turns out to have some challenges.

Following the baseline Wagh recipe, we were able to form a very hard, well-consolidated cement; however, there's significant porosity, which you can actually see in the photograph on -- on the top.

And that's something we're wanting to avoid.

We want to be able to more carefully control the porosity and permeability of the materials. Again, we want the water to be able to escape but we do not want enough water to be able to return into the DPC postclosure and have an effect on criticality, so there's going to be a balancing act there with porosity and permeability.

We also looked at simple hydrothermal synthesis of these materials.

This is -- the picture on the bottom is cement that was formed.

We were able to reduce the large porosity considerably, but under the reaction conditions, the cement didn't consolidate very well.

So this left us with a couple of pathways in terms of improving the properties of the material.

And I'm going to talk about those next.

So we decided to -- in consultation with Arun Wagh, who is the developer of the material, decided to start with looking at more of a hydrothermal approach where we vary pressure, temperature, and time in order to get a well-consolidated and minimally porous -- or excuse me -- body with a porosity that's well distributed.

Then as far as the continuing to work on the -- the ambient pressure approach, we looked at a number of additives.

Again, the goal there was to accelerate the reaction and formation of the cement and then minimize the generation of these -- these large pores we see.

Gadolinium oxide and boric acid were looked at.

Unfortunately, they accelerate the reaction too fast and we actually see reaction initiating at or near room temperature with these additives.

They would be particularly useful because they would serve as neutron poisons.

Now, while these additives didn't work, we are moving forward and looking at simple solid additives, in particular, boron carbide.

So our other path then is also keeping in mind that we have a basic acid-base reaction, looking at additives that are stronger bases than aluminum oxide, looking at additives -- phosphate additives that are weaker acids than phosphoric acid.

We expected to be able to control the time of reaction and the setting and minimize the formation of the porosity.

Particularly the large pores.

Okay. So -- so down the first pathways with aluminum phosphate and elevated pressures.

We looked at pressures between .2 MPa and 1 MPa.

1 MPa is approximately 10 times atmospheric pressure at sea level.

Again, the reaction temperatures were varied between 150 and 200 degrees C and we looked at a variety of different reaction times.

We're able to get well-consolidated monoliths.

Depending on pressure and temperature conditions, the reactants will set to form one or more binder phases.

We will see berlinite and sometimes an aluminum phosphate hydrate and aluminum phosphate cristobalite.

If some of this terminology sounds familiar to you, you should be aware that the aluminum phosphate system is very similar to quartz in it has a number of polymorphs, so these are phases that are the same chemically but they differ in their crystalline structure.

We found we were able to eliminate the -- the aluminum phosphate hydrate with a cure step and then we end up with either a berlinite or cristobalite binder phase depending on pressure and temperature conditions.

At this point it's not clear which of these phases would be more effective as a binder. My suspicion is that it won't make a big difference.

And with this process, with the elevated pressure process, we're able to obtain cements with unconfined compressive strengths of around 5.5 MPa. This is a -- a bit on the low side for a cement.

The -- but the target strengths that harden and set were around 3.5 MPa, so we are achieving our minimum strengths and as I go forward, you'll see we are able to improve that.

Okay. APCs at ambient pressure.

This is actually the preferred pathway

to synthesize these cements, because it avoids pressurizing the DPC during cement consolidation.

Working with different aluminum sources as additives and different phosphate sources as additives, we're able to eliminate expansion in these large voids that form, like you'd see at the top right.

With these additives, the consolidation temperature starts lower, somewhat below 100 degrees C, and we're able to get well-consolidated ceramic bodies like you see at the bottom with well-distributed porosity, and the strengths on these modified Wagh recipes effectively doubled.

Now, I should note -- and this is something that's still under investigation -- it appears that the binder phase is not the expected berlinite or aluminum phosphate cristobalite. We're seeing some kind of amorphous or poorly crystalline phase as the binder. This is an area of active investigation, but the cements themselves have many of the properties that we're looking for as a potential filler material.

So a bit about the wollastonite aluminum phosphates.

This -- this cement system is actually something that was developed by Colorado, et al., and you'll see a reference to that at the end of the presentation.

Again, their goal was to develop a material for radioactive waste disposal applications.

So using wollastonite, calcium silicate as a filler, and aluminum hydroxide and sodium hydrogen diphosphate, we're able to make very well-consolidated monoliths.

Be set at lower temperatures, and then we do a cure step up to 250 degrees C. so this is-- I should mention that the cure step is commonly done for all the ceramic materials we're developing.

What we've observed with the cure step at the elevated temperature is improvements in the strength of the -- of the cements.

Unconfined compressive strengths of this material with the highest we tested at 11.5 MPa.

Again, though, we have a difficult-to-identify binder phase, x-ray diffraction has not enabled us to identify what that phase is.

Again, a poorly crystalline amorphous phase with the presence of the phosphate and the sodium and the silica, I can't rule out the possibility that we may have a glass phase.

Okay. Calcium phosphate cements.

So these are very commonly used materials. There's a plethora of literature on these materials. They are used for dental appliances, they are used for bone scaffolds and bone replacements. The resulting calcium phosphate, known as hydroxyapatite, is very similar to the material in human bone.

So following some of the recipes that are in the literature to form this material, you can take tetracalcium phosphate, basic calcium phosphate, mix them with water and they react readily to form the calcium phosphate cement.

So the challenge with this particular formulation is that the set times are fairly rapid. About 25 minutes. And we want much longer set times, on the order of hours.

Again, the reason for that is we would be mixing large batches of cement, pumping it into the DPC, so we want to give ourselves hours of working time. And our first idea was to try calcium chelators, which effectively tie up the calcium and slow the reaction down, and so we are able to increase set times to two to three hours.

Dodecanedioic acid is what worked best and one of the challenges with the process we developed here is we do see hydroxyapatite in the product but we have residual starting product as well, so the reaction hasn't actually gone to completion.

There may be some interference with the presence of the calcium chelator. We're still investigating that.

But, again, we can get nice, well-consolidated monoliths, although they have relatively low strengths.

And something I want to point out here that I neglected to point out earlier is if you look at that figure, you can see volume marks from the beaker in which this sample was cast.

This is typical of all the cements that we're working with.

What we see is the -- the cement doesn't shrink away from the canister in which it's cast. In fact, there's very little shrinkage at all.

This is probably as a result of the -- the shrinkage that you might expect is basically being offset by the formation of porosity.

Again, we want to have porosity in there so that we're able to easily drive off the water after the cement is consolidated.

Okay. Summary and next steps.

The aluminum phosphate ceramics and the wollastonite aluminum phosphate ceramics are showing the greatest promise for continued development.

We're continuing to optimize both processing and formulation for these cements. We're trying some different pathways with the calcium phosphate cements. My goal is to try to get a cement mixture that we can set at elevated temperatures.

This is a challenge because calcium and calcium oxide, calcium hydroxide, many of the calcium salts are very reactive and tend to react at lower temperatures.

We have had some success developing some calcium phosphate gels that don't appear to set at room temperature and so there is some hope that we can get to an elevated temperature set with these materials.

A lot of research activities under way in terms of characterization, we're measuring the cement porosities and permeabilities, particularly permeability to water and gas, looking at the distribution of phases and porosity by SEM as well as the CT scanning that Kaushik discussed earlier.

And, again, in those early experiments, we're seeing well-distributed porosity, very little large, isolated pores, which is the direction we want to head with this material.

So future work, looking at radiation stability, looking at long-term solubility on the optimized products.

We've started to think about and do a

little bit of geochemical modeling to look at the stability of these materials in potential repository environments. That work will continue.

And we're working towards small-scale testing of DPC -- of these cements in DPC filler mockups with the goal of hopefully getting to a full-scale test.

A lot of this future work I'm describing is going to be -- appear in a joint work plan between Oak Ridge and Sandia National Labs that we're preparing currently, and we expect to complete that document in mid-November, so that will be a set of multiyear recommendations to the Department of Energy for how we move these filler experiments and research forward, ultimately getting to hopefully a full-scale test.

So I'll end just by showing you the selected references and the -- we'll move on to the end and I'll turn it back over to the moderators for questions.

BAHR: Okay. Thanks, Mark.

I'm sure we're going to have a lot of

questions on this. I have a couple myself to start out with.

You're talking about removing the water I guess after the cement sets, and would that be by draining, would that be by heating to vaporize the water?

And the remaining porosity, my conceptual model of how pores form in these kind of materials is you're probably likely to get a lot of unconnected pores and it's really connected porosity that you're going to need for that permeability, not a lot of dead-end pores.

Without shrinkage you may not have a lot of good connection between those residual pores.

That's several things all at once.

RIGALI: Yes. Let's see now, hopefully I can -- let's address the last one first.

The -- the interconnected porosity, of course, is something that we're looking at very carefully.

I can tell you an observation by SEM, the porosity seems very well distributed throughout the -- throughout the sample.

The pores are small, on the order of 10

microns, but well distributed.

BAHR: (inaudible) doesn't mean connected. You can have well distributed --

RIGALI: True. Agreed.

And this is the point of doing the porosity and permeability measurements, we'll see where we're at.

BAHR: So the -- in removing that water, would it be by gravity drainage? Would it be by trying to vaporize it?

And I guess where I'm going is what do you then do with the water or the vapor that you drive out of the DPCs?

RIGALI: So I actually hadn't considered the drainage.

The plan would be vaporization of the water and then trapping it as it -- as it comes out of the DPC.

BAHR: Okay. And then one other one, you talked about using chelators in the case of the calcium phosphate and those are organics.

Is there a concern about the radiolysis and gas generation due to breakdown of those organics in the long run?

RIGALI: Yeah, the chelators are used in small amounts, but the good news is I've actually moved on from chelators. We've moved away from that path.

We're not able to get enough working time with the utilization of chelators, so that's not a path I'm going to continue to follow.

BAHR: Okay. Okay.

So the first person up I see on the list is Tissa, and we need his mic and cam.

ILLANGASEKARE: Yeah, sorry.

I have a follow-up question with Jean.

I think about the same way, the porous media has primary porosity because some pores aren't connected and some pores are connected. My question is that seems like you don't have microfractures, so in a way having fractures may be helpful in getting the vapor out.

Have you looked at getting some fractures and then maybe sealing it later?

RIGALI: Yes, good question.

And I've had -- it is possible to create microporosity. Or, excuse me, we've seen fracturing. We can create fracturing.

It's something I've tended to avoid pursuing to this point mainly because I'm -- I'm thinking again about -- between the balance of porosity and the amount of water that's able to get into the system and -- and, you know, not wanting too much water in the system if it were to -- if water were able to enter later, postclosure, I want to -- I want to make sure I don't have a level or an amount of volume of water that would do anything to facilitate criticality.

So there's a balance there.

The answer is it is possible to create the microfractures. I hadn't thought about that as an advantage, but that's -- that's worth considering.

ILLANGASEKARE: But can you follow up with once you are sure it's gone, then you can put a sealer.

That may be expensive -- it has to be a special fluid but it's going to be on (inaudible) condition -- the capillary forces have to drive water or fluid into the fractures.

RIGALI: So you're suggesting the addition of a sealer post-cure of the cement and after the water has left the system?

ILLANGASEKARE: Yeah.

RIGALI: Interesting idea. I will give that consideration. Thank you.

BAHR: Okay.

Lee Peddicord?

PEDDICORD: Yes, thank you. Interesting stuff.

You mentioned about you've looked at some neutron absorbers and you mentioned gadolinium as not being suitable, maybe look at boron, how about something like hafnium, a lot of that comes along when you refine zirconium and so on.

Might that be a suitable neutron absorber that would work with your materials?

RIGALI: You know, I hadn't thought about hafnium.

Yes, it's possible and it happens to be one of my favorite minerals because I used to make hafnium carbide composites in my old life.

But I hadn't thought about it the

hafnium.

It can be quite expensive, but then as an additive for -- as a neutron poison we may not need a lot of it.

PEDDICORD: That's right.

RIGALI: I'm going to ask if -- Ernie Hardin had done some work in thinking about the various potential neutron poisons and he may have looked at hafnium, just to see if he has any comments about that particular option.

BAHR: Can we get Ernie to raise his hand?

He may not be there.

PEDDICORD: No comment?

HARDIN: Yeah, I think it's available as an oxide, but that's about all I can tell you.

RIGALI: That's true. Yeah. Okay.

I just -- I wasn't sure if you'd looked at it or not. I wanted to just check.

PEDDICORD: The only other question I had then was, you know, with the cement -- again, already concerns about the weight of these DPCs and placement, how much more weight do you anticipate adding using these cement fillers?

RIGALI: Yeah, at the densities we have right now, it would be 12 metric tons.

PEDDICORD: Okay. Thank you.

Thank you, Jean.

BAHR: Okay.

Paul Turinsky is next.

TURINSKY: Yeah, is there a target minimum thermal conductivity you guys are shooting for and what -- what's the impact on the cladding temperatures?

Which I know it's canister dependent, as they use different mechanisms to remove the energy -- the heat energy.

RIGALI: Right. Yes. And we -- we have measured thermal conductivities and off the top of my head, I'm not remembering them, but they are in the report, I believe. And, yeah, they're what you'd expect for these kind of materials. Thermal conductivities are relatively low.

Again, something we -- there is some thinking going on in terms of how that's going to affect the internal temperature of the canister.

TURINSKY: Yeah, have you done scoping calculations on impact on the fuel temperature -- the cladding temperature?

RIGALI: Yeah, again, you know, I'll ask Ernie to comment on that because he's actually done some work in that area.

BAHR: If we can get Ernie.

There we go.

HARDIN: Well --

RIGALI: I keep putting you on the spot, Ernie, sorry.

HARDIN: You do.

Yeah, you know, I think as long as we're up in the -- if our cements have a thermal conductivity that resembles other cements in common use, I don't think we can go wrong.

One of the variables in this is how much thermal aging do you need?

And there's no downside to waiting 100 years before you apply a filler.

Since we have to age them that far anyway, where most of these (inaudible) just concept.

But with that said, we might -- another downside could be that we have to actually apply heat to get the canister heated up to drive the water off.

So there's kind of a balance there.

We -- I have looked at, you know, what the safety considerations and what the apparatus might look like to drive the water off, and that -- that to me is the most ambitious part of this concept.

BAHR: And we -- the effects of heating on the fuel, the cladding, if you do have to heat again?

I asked this earlier but I --

HARDIN: Yeah, I'll just -- I'll just restate that ISG3 gives you a number of different kinds of limits.

It covers dewatering. It allows some much higher peak temperatures for cladding but temporarily. And it addresses also cyclic thermal loading of a cladding.

So I think there's some room in there, although -- I mean if somebody told us we absolutely couldn't exceed 400 degrees C on the cladding, we might have to carefully design the process and figure out a way of monitoring what we're doing.

TURINSKY: Yeah, plus you're applying it to perhaps 200-year-old fuel.

HARDIN: I'm sorry, was that a question?

TURINSKY: It was a comment.

HARDIN: Okay.

TURINSKY: This is not fuel that, you know, has been sitting there for five years. It may have been sitting there for 200 years.

HARDIN: Yeah.

BAHR: I guess the question is, has anyone been looking into what might be the physical changes to the fuel -- old fuel like that from this kind of heating?

This is a naive question because I don't know a lot about this, but I know in the questions about hydride reorientation, the peak temperatures and the amount of time the fuel spends seems to be some of the critical issues.

HARDIN: Yeah, I consider that a handoff from our DPC studies, as I mentioned yesterday, the stability of the canister and the fuel needs to be maintained for the duration of the aging until you're ready to dispose, so, yeah, we're operating right now with fillers under the assumption that we have fuel that's in its present condition and not degraded by time.

BAHR: Okay. Anything else, Paul?

TURINSKY: No. That's fine.

BAHR: Okay. Looks like Tissa has his hand up again.

ILLANGASEKARE: No, no, sorry, I thought I put it down.

BAHR: Oh, okay.

Do we have any other questions at this point?

Ernie is coming back live. Was that intentional or were you trying --

HARDIN: Oh, I don't think it was.

BAHR: Nice to see you again. Good-bye.

I have a hand from Geoff Freeze. Did you want to say something, Geoff?

If you do, your mic and your camera are not on. And if that was a mistake, you can put your hand down. There.

FREEZE: Yeah, just to follow up on your

question about the condition of the cladding and what kind of studies are being done.

Of course in our storage and transportation work, we are looking at extended storage, you know, decades, but certainly not a couple hundred years.

And I think people are familiar with the NRC new reg on continued storage, used to be the waste confidence rule that says that cladding and fuel integrity can be assumed for a storage period -- dry storage period of up to 100 years, so, you know, there's a -- we're missing a little bit of overlap, but there is certainly research on cladding conditions at high temperatures and high -- you know, now high burnup fuel for some extended periods of time.

BAHR: But that is assuming that the fuel is not subjected to another heating episode after the original drawing, correct?

FREEZE: That's correct. Yes.

Yeah, you're right, in those cases the highest temperatures are during the initial drying period typically.

BAHR: Again, these are naive questions.

I'm not a materials person. I'm just going on the things that I've heard people worrying about.

But thanks for that clarification, Geoff.

Any other questions for Mark at this point?

If not, we're right on schedule to move on to Geoff Freeze, so we can bring Geoff back if he's ready.

Okay. And I'm going to go away.

FREEZE: All right, thanks, Jean. I guess this is our last presentation. We'll let Mark go get some lunch now.

It's hard to follow up -- he's a true scientist when he said he has a favorite metal. I thought that was pretty good.

Anyway, this presentation -- this is going to be a tag-team between myself and Rob Howard at Oak Ridge. I'll do the first several slides and then Rob will jump in.

And like everybody else, trying to figure out how to advance the -- ah, there we go.

So the purpose of this talk is -- Rob and I are going to provide a high-level summary of how DPC considerations are integrated into the ongoing work in other areas of the SFWST program, so we're going to talk a little bit about various processes and process models, but we're not the experts on that, so we may not be prepared to answer the detailed questions, but we -- we do want to identify specific DPC considerations and make sure that we've captured them.

So I'm going to talk about the source terms and interactions with the engineered barriers.

Both of which are going to be discussed in the context of how they're implemented in the GDSA performance assessment modeling, and then Rob's going to talk about the DPC considerations for thermal and shielding implications.

But before we go on to that, there was a couple of questions yesterday that we thought would be useful to just address quickly here as part of this catchall presentation.

First of which, there were several

questions about the various costs and how they're calculated, and they were referenced back to the Sandia report that was in Tim's presentation, Sand 2019-6999.

And it has a lot of detail, lots of tables and graphs and breaks down the costs by different area, by who -- where the cost -- the payments might come from, the nuclear waste fund, the judgment fund, or other, and also out into time, you know, various times when the repository might actually be constructed.

So, again, that's a very useful reference for people that were looking for costs.

The second thing has to do with the bare fuel casks or the bolted lid casks.

There was a question about have we done research or are they included in what we're doing.

And so to put into context, the end of 2019, there were 3,203 dry storage systems. Of that, 229, or only about 7%, were bare fuel casks. The remainder were welded canisters.

And so the bare fuel casks we have not

done explicit reactivity or thermal analyses of, but we do know the inventory, the design, and the neutron absorber materials, so because there's such a small percentage, we're not focusing on them right now, but we do believe as the time comes, we would be able to design either an overpack or, because they're bolted, it's not quite as challenging to, quote, cut the lid off.

We might be able to, you know, put some fillers in, or that small percentage might need to be repackaged.

The third area was the justification for the low-level waste disposal of the DPC shells and baskets, and Rob's going to talk about that once -- once I turn it over to him.

So moving on to the source term processes and the DPC considerations, this is a simplified representation of how this works in our performance assessment model.

So first you have the waste package degradation, which determines when the waste package breaches. And once the waste package breaches, water gets in which then initiates the waste form dissolution.

So I'm going to talk about one waste package degradation model, the general corrosion rate, and then I'm going to talk about two waste form dissolution models, the fractional dissolution model, then what we call the FMD or the fuel matrix degradation model which I think you heard mentioned yesterday.

And specifically how the -- the DPCs might affect those models or what would need to be considered.

So the waste package degradation model is referred to as the canister vitality model and that sounds elegant.

What it is, is simply a temperature-dependent general corrosion rate.

You can see the equation up in the upper right, above the first graphic.

It can be defined -- deterministically or as a probabilistic rate with some sort of distribution as is shown in that upper right graphic.

The PFLOTRAN code also gives you an option to define a breach time specifically, which you might do if you're looking at early failures.

And so with that, what you're gonna get, which is shown in the lower right graphic, is some distribution of waste package failures over time.

This model just assumes once -- once it's breached, the entire waste package is gone, so that's obviously an oversimplification.

The future developments which are documented in that Mariner, et al., 2018 report that's listed is to have a much more mechanistic representation not just of general corrosion but also of localized corrosion and there's actually an activity in the European DECOVALEX project where they're going to look at that and compare it with implementations from other countries.

Also, getting the effects of groundwater chemistry and redox and then later on would be waste package damage and failures due to seismic and igneous, which is not really being focused on right now as it's more of a site-specific process.

So then the last bullet in blue or so

what do we need to worry about for DPCs?

Everything I've said so far is sort of agnostic to the canister, but so the DPCs, as we've talked about, will lead to elevated temperatures so we need to understand that effect on various corrosion rates and chemistry and also what sort of disposal overpack we might use for a DPC, might be copper, might be alloy 22, might be something else. And so that's going to be an important consideration.

And you also heard Ernie talk about the -- the super overpack, I think he called it, that might be involved.

So moving on to the first of the waste form dissolution models, this is the simplest one.

This is just a -- a fractional dissolution rate where you might have an instant release fraction, again, once the waste package breaches, you'd have the instant release fraction.

Then you would have just an ongoing fractional dissolution rate.

And this is what's implemented in

PFLOTRAN.

In the graphic -- the plot on the right, if you look at the top, it may not be that easy to read, but at early time you see the canister vitality from time 10 to the zero to 10 to the three years and you can see at that point the canister -- the waste package fails.

And then you have the waste package breach and then you begin to have the waste form dissolution, the fractional dissolution with the potential instantaneous release, so that's a fairly simple representation, again, and at this point, that has nothing to do with whether it's a DPC or any other kind of waste -- waste package.

But I'll talk about that in a couple of slides.

So the second waste form degradation model is this FMD model and it's a 1-D reactive transport model.

The reference there, Jerden, et al., 2017, describes a detailed description of the processes.

Over on the right is an excerpt from his report and I -- I don't really intend to talk about those details at all again.

Those are a function of the model more so than of the DPC itself.

But I guess the simple description is in the second bullet.

The dissolution rate's a function of radiolysis, an alteration layer that grows on the UO2 surface and then diffusion of reactants through the alteration layer.

The table down below shows various considerations and the main thing that would be important for a DPC, of course, is the temperature.

That might be larger than what the initial model development had assumed or at least the parameters that it might be validated for.

So this model has been coupled to PFLOTRAN.

When it's coupled to PFLOTRAN, it takes a very long time to run and so for a multi-realization performance assessment, it takes too long.

So they've also developed what they call emulators or reduced order models to try to represent it in PFLOTRAN.

So what does all this -- what does all this mean for DPCs or what are the DPC considerations that need to go into the waste form degradation?

First is the in-package chemistry and the field degradation processes. Again, there's an elevated temperature. It might come to boiling.

Laura mentioned for the typical repository depths, the boiling is at about 260 degrees C.

High burnup fuels might have a reduced instant release fraction, so that might need to be factored into the models.

The effects of different geologies which would lead to different groundwater chemistries which then, of course, affect both the waste package corrosion and the in-package chemistry.

Chemical effects from the potential filler materials, if those are used.

What happens in a criticality event?

Laura talked about the changes in the radionuclide inventory, so that would need to be considered. And then the resulting effects on the in-package chemistry.

The second key consideration has to do with the cladding and the cladding assumptions.

Again, there's an elevated temperature, we were just talking about that at the -- during the last presentation and actually several before.

What condition is the cladding in?

The second thing that -- Laura mentioned this -- is currently the critical configuration that's assumed for these criticality consequence models is that the cladding stays intact which keeps the fuel intact, but it has, I guess, the Cinderella condition, it's intact but has some pinholes in it that allows the water in and the radionuclide to diffuse out.

But those of you that recall the Yucca Mountain SAR, it had the opposite condition, cladding -- there was no cladding credit.

It was assumed that the cladding had degraded before anything else happened.

So we need to do some studies on what is, in fact, the cladding condition and the evolution of the cladding postclosure, not just for the criticality conditions but also for, you know, I guess what I'll call nominal conditions.

And then, of course, also the neutron absorbers, what effect do they have on the chemistry and the physical configuration once they degrade?

So this -- this slide is sort of the summary of what's important, I think, and the things that are all going to be integrated into the waste form and waste package degradation studies that go on in the other areas of SFWST.

So a couple slides on the interactions with the engineered barriers.

For direct disposal -- Ernie talked about this yesterday, but there's likely to be fairly high temperatures, as high as 200 degrees C, unless the spent fuel is aged for hundreds of years.

For -- for bentonite backfill, peak temperature of 100 degrees is often adopted as the limit.

Some of that's based on the FEBEX experiments in Switzerland, but now the program, specifically Jonny Rutqvist at Lawrence Berkeley Lab -- I guess I forgot to point out, that's the reference up top, Rutqvist 2019, describes a lot of this, but he's looking at peak backfill temperatures going above 100 degrees C, specifically bentonite.

So he's involved -- we, the SFWST program, is involved in experiments at the Mont Terri, where they're looking at temperatures up to 140 degrees C and then the planned hotBENT experiment where it might go up to as much as 200 degrees C.

They're also reporting on backfill mixtures that can increase the thermal conductivity.

So, again, this is important to the work -- the DPC disposal work where we might have these elevated temperatures.

And so this -- this work, THMC modeling and effects of the high temperatures on bentonite and the near-field host rock are actually being examined in a number of different work packages.

Argillite disposal, EBS, R & D, and in the international collaborations, as I've mentioned.

And so, again, these effects will be captured in the GDSA reference cases.

Laura mentioned them, but these are right now a DPC disposal in unsaturated alluvium and DPC disposal in saturated argillite and there are other GDSA reference cases that have been completed, and they may be revisited, in salt and in crystalline that did use as its basis a multi-assembly canister.

So with that, I'm going to turn it over to Rob.

Maybe.

HOWARD: Let me unmute my microphone.

Good afternoon. My name's Rob Howard. I'm from Oak Ridge National Lab. I'm also the deputy national technical director for what's called the integrated waste management program, which is kind of like the sister organization that's doing all this R&D for the direct disposal of DPCs. And so we look at a lot of the front end aspects of the back end of the fuel cycle, like transportation, storage configurations, that sort of thing.

So you've seen this or a version of this slide before, as recently as yesterday. Dr. Banerjee showed a similar slide that discussed the UNF-ST&DARDS and unified database tool which is the tool we've been doing to do the analysis for criticality for these DPCs.

Well, we used the same tools, the same databases, the same information sets and model templates, if you will, to take a look at any implications for storage and transportation.

In fact, that was the first use of these tools was to do analysis related to storage and transportation.

So all of the -- the data that we use is actual reactor discharge data and assembly data that we get, so the -- the analysis of the 800 canisters that Kaushik discussed yesterday, we can run these same tools to look at the formal and radiological dose conditions of the canisters to determine when they might be eligible to transport away from their current residing place, the reactors or shutdown sites.

I've got the controls here. It doesn't seem like I get to advance these slides.

Okay. Thanks. So Geoff's going to be my slide man.

So the -- this is just an example of how the unified database can be used to -- to check an actual cask configuration to determine when it will meet the certificate of compliance limits for when it could be shipped.

And this is for a decay heat example and we'll look at dose on the next slide.

But basically what you see here is you see the assembly decay heat information plotted as a function of time, and you see where we have the date when all the assemblies would actually meet the CoC limit, so we can use that as a check to say, well, in this particular case, this canister could have been shipped, if there was a place to ship it, back in 2014.

So about six years after it was actually loaded and put on the storage pad.

Next slide, Geoff. All right.

Similar example except for we're looking at dose. Now, remember that in order to transport fuel, the CoCs have both thermal limits and radiological dose limits on them. You have to meet both before you can put that canister on the road.

Same idea here, we've got the information from the GCA59 data collection exercise on when the material was discharged. We know what its burnup is. We take that burnup and we do our analysis to calculate the dose and we say minimum cooling time, think of it as the minimum decay time once these canisters are loaded for when it can be shipped.

In this case, you can see where we -- this actual canister was loaded in around 2008, again, but if you look at the dose requirements, we wouldn't be able to ship the canister until sometime after 2018.

So that's just an example of how we use the same tools, the same data, same information sets to make sure that we are consistent and integrated across all of the analysis that we're doing with respect to spent fuel research.

Geoff mentioned that I would address the issue on the low-level waste of these DPCs if we have to actually unpack them.

If you look at the FSARS that the vendors produce and submit to the Nuclear Regulatory Commission, they do analysis of these canisters and activation analysis of the materials and the internals and the baskets such that they've made a determination that the basket materials and the inside of the canisters could become activated and therefore would be classified as low-level waste if you chose not to decontaminate them.

So you could decontaminate them.

There's issues and costs associated with that.

There has been some discussions of repurposing these canisters.

In other words, taking the -- the lids off and putting other materials, low-level waste, in them.

And then cover them up and disposing of them.

Or actually reusing them. If you cut the lids off in a way that you don't damage the rest of the canister, it might be possible to send these back to another utility, have them fill up the canister, and put a new lid on it.

But I've had some informal discussions with the vendors on that and there's some mixed views on how viable that is, but it is something that could be studied.

And so with that, we've got our references, and I think Geoff and I are ready to take questions.

BAHR: Okay. Thanks to Geoff and Rob. Let me scroll up here. I don't see anyone with their hand up. Do we have questions?

Tissa?

We need your mic and --

ILLANGASEKARE: Yeah, I'd like to get a little more detail -- not detail, may not be -- I don't need an answer, but my observation is that you are using PFLOTRAN and then you are trying to couple that with the container and then expense the computational demands come from the coupling or why is it -- which part of the model is residing in this very high complication needs?

FREEZE: Yeah, it's the FMD, the fuel matrix degradation model.

It's not the coupling per se, it's the detail that's in that fuel matrix degradation model itself that has the computational burden.

ILLANGASEKARE: And this model is for what, the whole system or --

FREEZE: Well, they try to apply it -- when they get to a -- if it's for one waste package it may not be so bad, but if they start to try to apply it to a full repository where they might model maybe not all 10,000 or so waste packages but some large number, then it starts to become a burden and I have to admit, that's kind of the extent of what I know about that.

The GDSA folks and Paul Mariner would be able to provide a more detailed answer of exactly what's computational burden, what's driving that.

ILLANGASEKARE: Thank you.

BAHR: Okay. Paul Turinsky?

TURINSKY: Yeah, how in the world are you ever going to validate this model?

Multiphysics can be really tricky.

HOWARD: Do you want to take that, Geoff, or do you want me to take it?

FREEZE: You started. Feel free.

HOWARD: When you say this model, we'll just talk about the source in general, the source term model.

Model validation, we did model validation for a similar source term model that we used for repository in volcanic tuft, so there's a number of things you can do, you can do analog studies, you can do dissolution tests, that sort of thing.

In fact, another integration topic is that we are considering taking the remnants of the fuel that is being tested as part of the high burnup demo, those sister pins, and using that material to develop experiments that we can validate these codes from.

So we're going to use -- the idea is to actually use the spent fuel that we have that's really well characterized and develop experiments to validate different pieces of these coupled models.

So that's how we'll get started on it. It is going to be tough.

TURINSKY: Yeah, yeah. I'm always concerned when there's strong multi-physics aspects. You can validate sometimes the separate pieces, but you put the system together and it gets very, very difficult to validate.

HOWARD: Agreed.

Geoff, do you want to add to that?

FREEZE: No, that was good.

But, again, I would point you back to the 2008 SAR, you know, there's 100 pages on model validation there, the same -- yeah, the same type of problem.

And, of course, not just the coupling but the time scale, too.

TURINSKY: Right. And I assume very large uncertainties are applied --

FREEZE: Right.

HOWARD: Yeah, and we'll do that.

That is part of it is appropriately characterizing the uncertainties in the output.

BAHR: Anything else?

HOWARD: Thank you.

BAHR: Okay. Thanks.

Any other questions? I'm not seeing any, which is good, because that means we're right on time --

HOWARD: People are getting hungry.

BAHR: -- for the public comment period.

Yes, people are getting hungry.

So we're going to bring Bret Leslie on because he's been compiling the comments that have come in over the web and we'll go through those.

LESLIE: Okay. Let me -- I think there are six so far and I'll check again once I'm done going through them.

Hold on a second.

And what I'll try to do is if there is a comment that is specific to a particular speaker, I'll identify that and then I'll say this is the comment so people can understand that I'm doing a little bit of editorializing before the comment.

So we have the first comment by -- that does not address any particular topic or speaker, I should say.

The commenter is Darrell Gale and his message is, very concerned about lack of management for commercial nuclear waste.

The next comment, it contains a question and it was generated during Laura Price's talk, and so the commenter is Donna Gilmore. Her affiliation is sanonofresafety.org and her message was, what is the technical reference for assumption of condition of fuel rod cladding after long-term storage?

Given Argonne data for high burnup fuel rod cladding degradations as referenced in the 2010 NWTRB report graph, this appears very optimistic.

PRICE: Well, I guess it's optimistic from one perspective to assume that cladding is intact, but it's pessimistic for the criticality study.

So it's an example of a -- an assumption that is conservative for one aspect of a model but not for another.

We made that assumption, otherwise if the fuel is not intact and the fuel pellets have lost their configuration there can be no criticality.

So from that perspective it's conservative to assume the cladding is still intact.

That's why we made it.

BAHR: Thank you, Laura.

LESLIE: Thank you, Laura.

Let me move on to the next one. This had to do with Kaushik's talk.

The commenter was Brett Carlsen from Idaho National Lab, and the question is, when using fillers, has the effect of increased potential for pressurization, i.e., overpressurization of the canister, due to the substantially decreased void volume within the canister been evaluated, i.e., in the event of gas generation.

BANERJEE: Yeah, we have not looked into that yet.

LESLIE: Thank you, Kaushik.

Around the same time, another comment came in during Kaushik's talk, but the commenter is Donna Gilmore of sanonofresafety.org. And the message is, how are you addressing hydrogen gas that may be in the canister due to the irradiation of water remaining after canister drying or from hydrides created from higher burnup fuel?

BANERJEE: So we -- again, we have not specifically looked into that yet, but so for putting any kind of filler you need to cut open those vent, so I guess you can purge it out, the hydrogen gas starts filling in.

LESLIE: Thank you, Kaushik.

The next couple came in in Laura's -- well, they came in after that, but -- but are most relevant to Laura's talk.

So the next commenter, again, is Brett Carlsen from Idaho National Lab. And it may be a comment that can be addressed by Laura or Kaushik.

His message is, have TSPA calcs looked at degraded cases, i.e., near-field and far-field criticality, and how the filler material comes into play in these scenarios?

PRICE: I haven't looked at filler. As Kaushik mentioned earlier, he's looking at the porosity needed to complete to make sure criticality doesn't occur by eliminating water.

I guess I'm not quite sure where else to go with that question.

Kaushik, if you have any ideas, I'm welcome to hear them. Or Ernie.

HARDIN: I'd just like to add that the work you've heard about in this meeting concerns internal package criticality, not external.

We've done a lot of work on external criticality in the past, and that stands, and it would be -- we draw upon that for licensing some other site.

So in other words, we think we know how to do external criticality and it's been analyzed before and we're not doing it now.

PRICE: Correct.

BANERJEE: Yeah.

LESLIE: Okay. The next one, again, was later in the -- in the presentation, but I believe it pulled out one whole section of Laura's slide, so the commenter is Patricia Borshman, with no affiliation.

And the comment or message is, many of

the technical assumptions applied in DOE research reflect certain conditions but fail to adequately foresee actual conditions or unanticipated gaps that might occur. What if cladding configuration is not attained?

What if an engineered barrier does not maintain geometry? What about extreme high burnup fuel that is still not sufficiently understood to accurately calculate limits?

The comment goes on to -- to say the following: Engineered barrier system degradation, in the hypothetical repositories assumed in this work, engineered barriers consist of waste package outer barrier, DPC, fuel cladding, backfilled, in parentheses, bentonite.

Waste package is assumed to have failed for critical event to occur, no longer serving as an engineered barrier but is still a circular cylinder.

Cladding is assumed to maintain configuration but have small holes. Bentonite backfill is assumed to not to act as a barrier to radionuclide transfer during critical event.

That's the end of that comment/question.

PRICE: I'll see if I can remember all of this.

The first -- the first -- with respect to the first specific example, if a (inaudible) doesn't maintain its configuration then the critical event will cease because the rods are engineered are to be critical with a certain pitch between them, and if that pitch is not maintained, the critical event will cease. So assuming they've maintained their configuration is what allows the critical event to continue.

You'll have to remind me -- Ernie, do you want to say anything?

You may have to remind me of the second question, too, Bret.

LESLIE: Yeah, what if an engineered barrier does not maintain geometry?

PRICE: Well, we would have to model that. I mean this is all preliminary. We started this work a year and a half ago.

We are starting with very simple models. This is also a hypothetical site because we don't have a real site.

I would also add that in as well.

LESLIE: Thank you, Laura.

BAHR: Does Ernie have something he wanted to say?

HARDIN: Yeah, I'd say that when the engineered barrier system components start losing their geometry, we lose the critical configuration.

We're looking at this, but one of the hardest things to model about postclosure performance of an engineered barrier is its partial performance.

You know, it's easier to characterize its intact full functional performance than it is partial, such as a waste package that has a small hole in it.

So anyway, these are -- that's an area that's kind of on the frontier of what we're doing in performance assessment.

BAHR: Okay. Thanks, Ernie.

LESLIE: Jean, I just checked again and there are no other comments at this point.

BAHR: Okay. Well, thanks again to everyone for your attention, for all of the people who did the technical work to make this meeting feasible when we can't travel.

And the recordings of these last two days will be posted on our website eventually. I'm not sure exactly what the time frame for that will be, but as usual, we'll have a transcript of the meeting, and the comments that are submitted will be part of that.

Thanks to all the speakers. Thanks to the staff.

And I know I speak for the board that we look forward at some point in the future to having another meeting where we can see everyone in person, but I think this worked out quite well, so thanks for all of your time.

(End of meeting.)