Performance Assessments for Fuels and Materials for Advanced Nuclear Reactors
Dr. Daniel LaBrier, Idaho State University (ISU), USA

Berta Oates
Welcome everyone to the next Gen IV International Forum webinar presentation. Today's presentation on the Performance Assessments for Fuels and Materials for Advanced Nuclear Reactors will be presented by Professor Daniel LaBrier. He is with Idaho State University.

Before we get started, there's a couple of housekeeping things that I'd like to take a few minutes to go through quickly. The audio is broadcasted via computer speakers, so please select the mike and speakers radio button on the right-hand audio pane display to make adjustments. And if you have any technical difficulties, please contact the, 'Go To Webinar' helpdesk at the number shown there. To ask a question, select the questions pane in your screen and type in your question. We will take questions at the end following the presentation as time will allow.

Today's presentation is being recorded, so please feel free to watch it again or share it with others. It will be posted with the slide deck at the Gen IV website at www.gen-4.org. The slide deck is also available as a PDF for your download today at your workstation along with a handout of the GIF presentations that have been presented in the past, and a look at the few of the upcoming ones.

Last, and certainly not least, please take a few minutes to answer the survey at SurveyMonkey at the link shown there or at the QR code that's accessible for mobile devices if you are attending in that fashion.

Again, the questions will be at the end of the presentation, but to access the question pane, you should have an orange rectangle with a white arrow, and if you click that, it will expand into a dialogue box where you can type your question, and we will go through those again at the end.

Doing today's introduction is Dr. Patricia Paviet. Patricia is the group leader of the Radiological Materials Group at the Pacific Northwest National Laboratory. She is also the Chair of the GEN IV International Forum Education and Training Work Group. Patricia.

Patricia Paviet
Thank you, Berta. Good morning, everyone. It's a pleasure today to have Dr. Daniel LaBrier with us. I hope everybody is safe during this COVID-19 crisis. Dr. LaBrier is an Assistant Professor of Nuclear Engineering at Idaho State University. He earned his doctorate in nuclear

science and engineering from ISU in 2013, with an emphasis in irradiated materials characterization. His research focuses on characterizing nuclear-grade materials that are exposed to extreme environments and nuclear reactor safety projects, including investigation of corrosion and erosion of structural materials relevant to light water reactors and advanced reactor systems such as sodium fast rector, molten salt reactor, high temperature gas-cooled reactor. His research interests include development and qualification of fuels and materials for advanced reactor concepts, investigating thermal hydraulic effects on material performance, and used-fuel recycling techniques.

After serving as a post-doctorate fellow at the university of New Mexico and as a research professor at Oregon State University, Dr. LaBrier returned to ISU in March 2019 and maintains residence as a researcher at the CAES building, at the Center for Advanced Energy Studies in Idaho Falls, Idaho. I am going to hand it over to Daniel now. Thank you, again, Daniel, for volunteering to give this presentation.

Daniel LaBrier
Of course, Patricia, and thank you very much for the kind introduction. And Berta, thank you very much for the work which you've done to set everything up so that we run smoothly.

The first thing that I want to mention is that, well, I have a slew of partnerships that I am very proud of, both at the university, industrial, and National Lab. The views that I am presenting are solely my own, and so I am not here to put forth a particular reactor technology, nor a particular pathway to deployment. I am not necessarily being supported by any particular entity in giving this presentation, as Patricia mentioned this was a volunteer basis, and I took this as an opportunity to really try and do something to help further our field and our industry as a whole. And I am not being supported financially by any particular entity in order to provide this talk. This is solely my own doing.

I really wanted to spend some time to chat with everyone today is talking about, as the title suggests, performance assessments for different fuels and materials for advanced nuclear reactors. And so, as a part of that, we will take a few minutes to discuss the different pathways that are being investigated, but particularly, we all will look at ending up at the same place, which is qualifications of materials, which then leads us to the point of being able to construct, and then eventually test and deploy advanced reactors. That's our goal in trying to develop these techniques.

Just to mention that there are a host of novel material concepts that are being investigated as part of Gen-IV reactor developments. However, many of these candidates are not necessarily new, even though they are novel. They are rooted in historical programs that go back as far as the

1950s in the United States at least, I think that's pretty naturally the case as well. But the idea is that there have been search and stops for a variety of different reactor types and the campaigns that led them.

And so, much of what we will talk about today as far as the technology goes has been around for quite some time. Of course, there have been advances due to different technological and scientific advances such as the idea of being able to use a printer to print a piece of reactor core as was just demonstrated in the Oak Ridge National Lab for their TCR project.

That's something that couldn't have been even imagined going as far back as 20 years ago. And so, the technologies are almost beyond keeping pace with, but what's most important, in my opinion, is the idea that somehow we all have to end up at the same place, and that's at the ability to qualify these materials. And so, that's what I would like to spend a good portion of my talk today talking about.

Most of what's required to come down to that is the data that's needed for material downselection, studies that determine whether use of a particular material is feasible, and those I just mentioned a bunch of qualifications. That's something that's incredibly costly both in time and money. But that is all discussed a little bit later because this is something that's probably not new to most folks in the industry is that you are usually looking on the order of 20 years' worth of work to be able to qualify, say, a new fuel concept.

And so, the idea that I want to at least dive in a little bit deeper to is the discussion about all the above strategies. And I realize that it's a bit of a buzz phrase, and I'll discuss that in a little bit more detail. But with such a variety of different reactor topics and the variety of materials that go into each one of those different topics, we, as an industry, really have to try and find a way to streamline the process and the strategies that we use, in order to be able to take these concepts from the drawing room, all the way to qualification. And so that moreover is what I'd like to discuss today, is the idea of being able to advance many of these material candidates from the concept all the way to deployment.

As I mentioned, there are a variety of technologies as far as reactor types are concerned, and each one of them have – some can be similar, some can be different. When it comes to their components, all the way from core out through the production of electricity, there are so many different combinations that are possible. But when all is said and done, as I mentioned now probably a couple of times, and will mention a couple of times more, we all need to end up at the same place, which is being able to justify the use of these materials to a regulatory body here in the US that would be going through the regulatory commission, to be able to advance these reactors into the deployment stage.

And so, because of that, we need to come up with a particular pathway that allows us to be able to look at design concept, to be able to carefully select and with purpose select the materials that we use, the variety of heat exchange systems that can be utilized for heat removal, and then eventually delivery of power. And then, of course, the working fluids. You could set up – say, for instance, you could take one particular fuel form, the TRISO particle. It's been investigated for several decades for use in high temperature gas reactors. But now, in the past decade or so, it's also being investigated as part of the campaign for what's called the fluoride high temperature reactor, which actually is a molten salt concept that traditionally used the molten fuel, and now it's using a solid fuel.

Well, based on the working fluid that you have, the fuel could behave in very different ways. The heat transfer could behave in very different ways. And so, being able to say that I have a molten salt reactor or I have a high temperature reactor or I am using TRISO fuel, it really depends on what your combination is. And as we start to delve more into the modular capabilities of our fleet that we want to develop, there are a lot of options for choice, which can be a very good fit.

However, as many of you know, whenever you go to the grocery store and you see that you want to get a type of tomato, canned tomato that's on the shelf and there are 15 different brands, trying to choose the one that is best for you is going to depend on a lot of different things. And the type of choices that you have here are cost, time to market, the ability to be able to test and qualify background information, facilities that you need to utilize to do your testing, these are all components of consideration for driving us towards qualification.

That said, every entity, whether that's a lab or industrial partner, or university or some collaboration thereof, they will go through their own scrutinization of their system process. And so, it's something that we all have to do. We will all have to participate in it in some way, shape, or form regardless of the technology, regardless of design, regardless of ta, ta, ta, ta, ta, whatever you want to insert there.

We will all be in the same place, and so trying to devise a proper strategy that will allow us all to collaborate even if we're working in parallel, and many times in competition, will allow us to kind of get to the goal line in similar fashion.

The qualification process, I really do like this graphic that was developed by a couple of colleagues, Steve Hayes and Mitch Meyer, that I know in one of the papers they published, so probably 10-12 years ago, really kind of gives you the idea that there are so many different aspects to the qualification process. Now, in this particular gimmick, if you look at it moving clockwise from the top, you take a particular design, you prepare the feedstock and start giving the characterization, you start doing the fabrication, fuel characterization. As you continue around the cycle, these are all aspects, at least for fuel development of the process, that will need to be done in order to sort of vet or qualify any of the materials that we are planning on using. We will have to go through radiation testing or some sort of – whether that's neutron irradiation or whether we can justify the use of ion irradiation, and similar techniques – we will have to go through some set of accident scenario analysis, whether that's through thermal, neutronic, and generally some combination thereof.

And then the examination of materials both prior to and after your testing, whether that's through irradiation testing of the reactor, or whether that's through transient testing.

Eventually, you end up at what looks to be about the 10 o'clock hour on your dial there, a performance assessment. And that's kind of a nebulous term, and I realize that is also part of the title of this talk, what exactly is meant by performance assessment?

You can have assessment relative to a particular metric, how it performs in a particular temperature range, let's say, or whether it's suitable up to particular pressures and what is considered suitable? Is it something where you have materials that have changes in the bulk properties that are very noticeable, or something that maybe changes on the microstructural level that's isn't as easy to assess in a bulk property. And so, we not only have to look at particular materials, we have to look at different scales, and how the effects of something that might happen at the nano or micro state can and will affect materials in the bulk property scale.

And this needs to be considered, and of course, one thing I have left out and I shouldn't at all, is that modeling and simulation plays a significant role in helping to supplement the testing that needs to be done. And supplement maybe isn't the right word you use, but it is a complementary piece in that you could use modeling and simulation to help develop your materials through like DFT for being able to go from first principle always and sort of dope them with different materials, in different places within the structure of the material and then see how that changes the properties.

That could be much more efficiently done on the modeling and simulation scale, but eventually have to go through the physical testing. And then there is sort of a back and forth synergistic relationship between the two as you actually go through this process, which is also why it's very fitting that this is in the form of a cycle, because you will typically go through multiple cycles just looking at a single material for a single purpose.

Now, you can start to see that through all these processes, this is where the time and expense starts to really add up. And considering that we need to consider this for not just core components within the reactor itself, but structural materials, as I mentioned, the heat removal and heat exchange systems, the safety systems that go into advanced reactor design, these are all things that have to be considered as part of this process to be able to go from the concept to the deployment.

As I mentioned, modeling and simulation, while very useful, can only go so far. While the techniques and the computational power is growing vastly by the day, many times the models that are input into a particular system are only as good as the data from which those models were derived. And so, well-vetted experimental data is crucial to the qualification process and to being successful at it. And again, it comes down to what you would consider as success, does that mean reducing the amount of time, does this mean reduced capital cost, does this mean being able to vet a particular material and have it be used for multiple platforms. There are different ways to define what success may be, but the idea being is that there has to be some relationship between actually acquiring the experimental data at each point along the process.

One of the limiting factors for the qualification process most often comes down to the testing capabilities. I mentioned computational resources are actually starting to wrap up significantly. And while they, of course, have their limitations, they are actually starting to become more plentiful, and that's a good thing. However, the experimental testing capabilities are currently stretched pretty thin for the data that was needed for the qualification process. If you want to think of it as kind of a bottleneck in the system, when you get materials that are going to be part of the core or the structure within your reactor system, you are going to have to go through a set of safety tests, think of thermal cycle or high pressure inlets or something along those lines, you need to consider irradiation testing, and you need to consider transient testing, looking at essentially steady state day-to-day ops and the effects that could be related to both thermal mechanical properties and irradiation materials, and then start to consider what happens during an accident scenario.

Again, these are not new concepts as far as qualification of materials goes, but it is something that can hold us back as far as the timeframe goes and as far as the cost goes because the facilities that we have to work those particular sets of data that we need for qualification are limited.

The pathways for qualification also include the need for quality assurance. This is something that isn't discussed nearly as often as probably should be. There is a difference between setting up a well-designed experiment and being able to acquire the data that is going to be eventually needed for qualification. But if you don't have some sort of quality assurance plan in place, that will limit the ability for vendors to be able to do testing.

If you can't back up where you got your data or how you procured your data, essentially handing someone over a blueprint of how they could do the same thing, and normally, we get the same data as you, or in the same ballpark at least, then the questions are going to come, particularly when it comes to regulation which is well, how good is your data, what processes did you go through, how can we allow a vendor to go forth with a full design and deployment if the data structure of which their design structure was built really doesn't hold up to our regulatory standards.

And as I mentioned, actually a couple of slides ago I guess, that this is a cyclic event in that you are going to go through the cycle several times. Testing and development of materials is an iterative process. And when you are looking at developing materials for new applications, you are looking at new materials itself, whether they are different alloys or alloys that are being tested in the environments with limited testing capabilities. Now, you are looking at a very expensive endeavor, in terms of money, in terms of time, and in terms of resources.

In many cases, these are shared resources that multiple entities are trying to access. If you happen to be fortunate and you work for a company or a university department that has a research reactor, well, maybe there are some preliminary tests that could be done there. But eventually, you are going to have to go to a full-scale irradiation test facility or say a transient testing facility. And every other vendor that is managed at that point is going to be looking to do the same thing, who are vetting their own materials. And so, this is where the idea of bottleneck starts to come in, so you are either on the waitlist or might be you're putting forth to design your test, it can just be very taxing. And so, what we would like to discuss a little of a strategy on how you can move through that process a little more smoothly.

A little bit of historical background, I mentioned this number already. For the process of fuel and material developments, this has actually come from a paper not quite 15 years ago, from a couple of [Unclear] that discussed the pathways that you go through for material development. So, you are looking at selection of potential candidates, the lab scale developments, then scaling up. In other words, being able to take your testing again from design to small scale, moving up to something that's beyond the bench scale to, I'm going to use the word prototype, or something on those lines, and then towards the qualification of particular materials or designs that go into the development and then eventually on to demonstration.

For a scheduling for new fuels and for some materials, you are looking on the order of 20-25 years. If you were to look historically at some of the work that was done in the 1950s and 1960s for reactor development, you will see that those numbers are much, much smaller, but then again, it was a very different time throughout the world, and just the world we live in right now is the time scale is much more extended than it used to be. For some reasons good, and for some reasons maybe there could be questions.

As a recent example, I bring a point that was actually just in the news very recently Alloy 617, that was added to the B&V Code, just actually earlier this month. The qualification though took 12 years and about $15 million investment from the Department of Energy. And again, this is for structural. But it still had to go through the same sort of vetting process that many other materials have to go through, but still, that's even on a lesser scale than you might have for a candidate fuel for your particular reactor design.

And this was the first addition to the Boiler & Pressure Vessel Code in 30 years, which sort of demonstrates that either for your own reactor development, your own pet design, whatever it might be, you are either going to be trying to leverage the use of a material that's already been vetted, and trying to adapt your design to get to it or you are going to try and take in your material, try to better and try to qualify it so that you can use that particular material. Either way, you are still fighting a bit of a battle when it comes to going from the design to deployment.

Now, I realize that everything that I've mentioned so far, a lot of it is either bringing up historical facts or bringing up my own opinion, and I want to sort of stress on that a little bit. If, as an industry, we really want to get to the point of deploying advanced nuclear reactors, in my opinion, we are looking at changes in our paradigm, changes in our thought process, and so the reimagining or optimizing all possible uses for that. In other words, sort of a cross-cutting approach where say for a material that's being vetted, could it be used in multiple reactors or could it be used in multiple places within a particular reactor so that the data that you are collecting can be used in multiple vendors.

And earlier, I mentioned the idea of 'all the above strategy' and well, okay, great that's a soundbite. That's really what it comes down to. What exactly does that mean, though? And so, the graphic that's on the right-hand side of the screen there, from USNC, a presentation that they gave sort of goes from the fuel kernel all the way to actually developing a graphite fuel block through the reactor.

As I mentioned, TRISO fuel, in particular, is one that's been studied for one application for 40-50 years, but other reactor development teams are actually looking at different ways to be able to utilize this process, just using different working fluids or different configurations. So, that's kind of the idea is, is there a way to be able to leverage the qualified data that's already out there or maybe even data that's leading up to qualification, so you are not starting from scratch.

In particular, the TRISO fuel particle is an interesting one because in many cases, it's the fuel kernel that can vary, whether it's CO2 or whether it's showing a carbide, there are discussions of other material mixes that could serve as the fuel kernel. But the layered structure for containment actually would stay similar or exactly the same as you might see here. And so, the idea is could you look at designs that have a more interchangeable fuel kernel type, knowing that, say, the discussion of the silicon carbide layers, the pressure bandwidth versus the interaction of the graphite layers, or the pyrolytic carbon layers on the outer structure of the TRISO particle, you might just have to consider their interaction with particular cooling needs as opposed to going all the way from the fuel kernel out and having to justify every process of every step along the way. And that's kind of what I mean by all the advanced strategy is that there may be cases of information that you have to procure through your own particular design, your own concept, but there may be other pieces of information data that's out there that is already demonstrated in a particular use that your design can fit within.

Trying to implement in all the above strategy, and again, I'm taking this from an editorial point of view, but informed from a variety of folks that I've talked to over the years. And what's the best, and I should probably put 'best' in quotes because I am assessing this as my best, but how to best approach these challenges? The biggest – in my opinion, the most significant challenges that we run into are trying to reduce the hazards that come from irradiation testing, reducing your footprint. In other words, are you able to try and develop a concept that would fit into a warehouse as opposed to a city block? Trying to automate some of your processes, both for design and construction, but also for operations. And then, the correlations in the models that are developed to better predict scale-up processes.

And so, this graphic design here on the right is one, it's not actually even from a nuclear publication, but it came out in discussing material performance. And you may recognize several of the different portions of the cycles as you might have it. You start up with some particular material. It's going to go through some physical testing to assess what may have happened. That then is then used to help to significantly add to your model, which then goes back into your design. It also goes into the process to determine the lifetime, the performance of your material that goes along with it. So, this is where the experimental data and the modeling and simulation sort of meet up to help develop the data and the justification that is needed for your particular material.

Being able to speed up that cycle by looking at materials on different scales might actually be a great advantage. So, for instance, and I'll discuss this in a little more detail, if you have a material that when irradiated actually has some significant radioactive byproducts or retains, say, neutron activation for quite some time, you either have to wait for some of the byproducts to decay, or you have to try and put it through a much more rigorous process for shielding, for analyses. All of these things are things that could take up time and money and your materials, and the testing facilities that go along with it, and there are so many things that can be backed up with it. What if you were able to justify looking at properties that describe a bulk performance of a material by looking at the microstructure?

And again, this is not something that's new. This is more recent, but it's not new. There are researchers internationally that have been considering these ideas for quite some time, but it's certainly something that needs to be considered as sort of all of the above strategy is looking at how you can better and more efficiently assess your performance. And it doesn't necessarily have to all reside in the bulk property of performance so long as you have a way to be able to discuss how you get from the microstructure on the nano-scale up to the bulk property scale.

And so, different ways that we consider this is through the specific figures of merit that we are interested in, whether that's swelling or density or whether that's fatigue, whether it's creep, whether it's the strain that's on a particular material. These can vary based on application and material type, and previous work which has been done. If there is the ability to take advantage of research that was done for vetting a particular alloy in a high temperature environment, even if it wasn't nuclear application, there may be some of those metrics that could be utilized for a nuclear design.

For being able to develop new materials or I'll say novel materials, one of the methods that are used to be able to differentiate between some of the alloy developments, and this kind of plays along with the graphic that's on the right-hand side, where if you are able to use modeling and simulation, to be able to say, well, if I replace a certain atom in my microstructure at this point, how could that change the behavior and mechanical and thermal mechanical properties of my material? And maybe you can determine very early on without ever having to go to the point of alloy deployment, so you could do this through first-principle development in DFT that can determine the materials is not going to work, it's going to have a failure point, you are going to have problems in bringing down, you are going to have chemical interactions that are adverse to the performance of your material. Those are things that could be assessed without ever having to do an experiment in the lab as far as the performance value goes.

And then moving on to performance, looking at multiple venues for when it comes to testing methods and facilities. And when I talk about testing methods, I am thinking more from the perspective of microstructural testing versus the macroscale or the bulk property. But again, if there is no way to be able to discuss and properly assess how you can go from the microscale to the macroscale, then that's something that has to be developed along with it.

And then post-performance assessment. Again, this ties into the ability to look at materials, maybe you are looking at them in parallel, maybe you are looking at them on a smaller scale to be able to describe something on a larger scale, maybe this is where you introduce the idea of process automation, for being able to take the place of - particularly for irradiated materials where you need to have currently, you are looking at very monolithic hot cells and operators that are using manipulators to be able to sort of process the analysis of your materials. That's a very costly concept. If it is something that could be automated, then that might be something to explore, to help reduce cost, and also to reduce stress, which also is something that isn't discussed as much.

I've mentioned it maybe once or twice, but I did not spend much time on it. The risk of that is concerned for people who are doing the work, particularly for irradiated materials, is something that also has to be incorporated as part of the strategy, is how to reduce those hazards, how to reduce those risks. That can also help speed up time, that can speed up your time to market, if you will.

Let's jump right into testing because I mentioned that – I will say with complete bias, I am an experimentalist. While I appreciate the work that is done by folks in the modeling and simulation world, the ability to go between those two worlds is a very valuable thing, but you have to be able to have a foot in each of them. And so, while I value modeling and simulation, again as I mentioned, the testing that goes along with it is also a very key thing, especially for our industry.

So, you can look at operational testing which is something that could be done depending on what material it is you are actually analyzing. If you're looking at structural material, particularly alloy, maybe you can do further tests that don't have to be in pile per se.

You can look at setting up a high pressure way to be able to try and look at fraction or fatigue for thermal recycle material. That's not something that's sort of required an in pile in reactor test. But eventually, that's something that you do have to consider because that's the model that we have chosen to work in. And so, you have to look at irradiation testing. You have to look for facilities that can provide whatever metrics you need to qualify your material, and those will vary greatly, saying that there is one particular plan to go from Set A to Set Z for your material is just not realistic because it's very different for a non-pressurized molten metal system than it is for high pressurized aqueous and water system.

So, sort of analyzing and identifying the facilities that you are going to need to perform testing is very important.

Also, there are concerns for safety testing. So, as I mentioned, if you are looking at high pressure, if you are looking at corrosive materials for your coolants, if you are looking at fuels that are fuels more evolved over the time but will do so in very unique ways depending on the constituents of the fuel, the form in the fuel, the arrangement in the fuel within the core structure, and those are all things that need to be considered. And then, of course, there is the system considerations that go along with it. There is testing that needs to be considered for design-basis and beyond design-basis accident scenarios that may not have anything to do with the core. They may have to do with your steam generation system, they may have to do with your coolant supply, and the ability to try and develop those testing techniques and systems can be very challenging.

I'll break this up a little bit as far as operations testing, I'll delve into each one a little bit just to show you, not to try and define a qualification list or something like that, but just to demonstrate the variety of things that need to be considered along the way. And couple of the graphics that are up here, if you are considering looking at, say, furnace testing, mechanical testing, you know, the scale and size and scope of your materials, are you looking at, say, dog bone samples that are a few inches or dozens of centimeters big, or you're looking at something that's hard, say a TRISO particle which is only about a millimeter in diameter. And so, you are talking about trying to perform thermal mechanical testing on something that needs to be cut out very precisely using, say, like a focused ion beam. And again, these have nothing to do with the irradiation of the radioactive material. I mean, this is just the performance of the material itself.

So, keeping in consideration that there are physical and chemical interactions, mechanical interactions, high temperature, corrosion and erosion, you can see the list that's on the left here. When you get past the stress and strain there, you can develop multiple facilities to be able to do this. And by saying that, that means you can go and procure the equipment. But that isn't the only piece of the puzzle that you need to be able to produce the data that is going to help with the qualification process. There needs to be a plan in place to be able to get within the regulatory concerns to vet the performance of these materials and that again is going to bring us back to the discussion eventually of quality assurance.

And being able to say, here is the data that I produced as part of my qualification process, and here's how to a regulator, you can say this is the data and this is how we present it as part of our design. Now, the ability to be able to use, as I mentioned, multiple, maybe even non-traditional facilities, universities or private industry, smaller companies that may be able to do some specialized testing that traditionally isn't thought of for nuclear industry testing, specifically I think of things like thermal mechanical performance, chemical performance. There are a lot of pieces of equipment that could be purchased from vendors, and you can set up your own workstations to be able to vet your materials. But if you don't have a way to be able to demonstrate to a regulator that there was some thought process behind it, then it may all be mute.

Now, when we discussed irradiation testing, now of course, our pool of candidates is reduced significantly. There just aren't as many facilities, and trying to develop one on your own, you know, the small scale is challenging. That said, there are still capabilities out there without having to go necessarily to a testing reactor so long as you have again set up a design plan for how, whatever facility you are going to use, can actually produce the data that it is that will help you in your qualification process. And those are things that have come down to the spectrum that you need, the fluence, as I mentioned the flux density.

And so, there are facilities that can satisfy these, even if there are, say, ion irradiation sources, maybe accelerator systems that can aid in at least looking at the dpa that you need for assessing material degradation due to irradiation gains. The facilities may be out there, but as you might imagine, they are also in very high demand. For instance, two of the three pictures that are up right now are the Advanced Test Reactor that's at Idaho National Laboratory. And the idea behind them is that they are pretty well subscribed. Even for those trying to perform industrial testing, you might be looking at 1 year to 2 years out time before you can actually get into the reactor to do any testing.

There is also the development of advanced, you guys should put that in quotes because again the technology has been around for quite some time, but more advanced test facilities. Now, as many of us recognize, the loss of the holding facility in Europe is one that actually may cause delays for material testing. But at the same time, we are hopefully developing more facilities such as the Versatile Test Reactor, that's being developed for the United States for fast-neutron testing, which will not only help save reactors with vendors who are developing fast reactors, but also, there is more thermal spectrum reactors, it's just that it will allow you to be able to accelerate the amount of damage that you probably impart to your materials. And so, that's again a demonstration of being able to consider the use of one facility for multiple vendors, multiple concepts that should hopefully be able to help us when it comes to accelerating our time to market, our qualification process.

As far as safety testing goes, and again that kind of takes a variety of different angles. So, a couple of the pictures that are up here of the TREAT facility, the Transient Reactor Test Facility that's out here. Again, let me mention something I mentioned earlier on, several of the facilities that I am showing are those that I am familiar with, and those are the ones that happen to be out here at the Idaho National Lab. Of course, they are not the only facilities that are available. Internationally, there are a slew of different test reactors that are available to do this kind of testing. These are just the ones that I happen to be the most familiar with.

Safety testing, again, can be something that's performed in the university setting, maybe not for irradiation testing, but if you want to do safety performance for, say, cladding concepts that have been thermally treated to, say, off-cycle or beyond design temperature ranges, that's an experiment you can design to be done at an industrial, laboratory, it could be done in the university, it could be done at the National Lab systems, here in the US or in Europe, but there are a variety of different ways that you can approach that.

Many times, what that comes down to is being able to best recreate, I guess, or best simulate a particular accident or safety concern that you might have for whatever component it is that you are working on, as I mentioned whether it's cladding, whether it's fuel performance. Now, of course, for the case of dealing with something that has to do with irradiation as part of the safety analysis and, of course, you are really limiting – and by-design in many cases limiting the number of facilities that you have, and they are available to be able to do this testing. And that is part of the world we live in as being part of the nuclear community, but just to know that there are other facilities that could be utilized for doing some out-of-pile testing.

I introduced this a little bit earlier, and this is one of the ideas that I really like to come back to because I think it can be incredibly useful, and I know that there are a host of researchers out there, who are already attacking this, is looking at the importance of scale relative to your materials testing. So, if you've got data that is typically used to assess the performance of a material at the bulk level, trying to get as much information as you can from as small a sample as you can might be a great advantage just because you could use a dozen electron microscopes to assess a portion of cladding that you have, that you put though a single test. And if you only have the ability to analyze them on the bulk scale, then you really only have one device and one sample, and that's it. But you can subdivide that piece of cladding into, say, 12 or 20 or 50 pieces, you can then work in parallel on those different pieces, and then use the collection of data that you have and then reassemble, if you will, all that information to tell you something about the performance of the bulk material.

Now, this comes into greater importance, in my opinion, when it comes to dealing with radioactive or irradiated materials. As I mentioned, the hazard of working with materials that have been irradiated, particularly when it comes to the dose for those who are working with it, that there is a way to be able to reduce that, and typically, the way to reduce the dose is that if you have a sample that is the size of a typical fuel pellet, assuming one inch tall by half an inch in diameter, and you can subdivide that into a thousand pieces, that then means that you've reduced the risk for each one of those individual pieces. Now, it doesn't mean that there's none. There's, of course, irradiation concerns for each one of those individual pieces, but now, maybe you can work with a small laboratory that has mobile shielding, or a small hutch that's used, a shielding hutch, as opposed to having to work with everything in a very large hot cell that is typically meant to deal with much larger capacity and much larger depths. And so, if there is a way to be able to do that physically, then that might be a great advantage. Then, of course, comes the challenge of trying to reconstruct it, taking those 1000 pieces of data that you have and being able to describe how your one fuel pellet is behaving and in different portions of that fuel pellet. That again beckons the idea of how to improve the models that we have as well.

Trying to better understand the relationship between the microscale, the microstructural scale and the macroscale or the bulk scale is incredibly important in this effort. The image that's shown here is courtesy of Peter Hosemann at UCAL Berkeley, who has been a pioneer in this field for quite some time, in trying to look at the scale of, if you will, for microstructural analysis up through the bulk property performance. And it's still something that's being developed and, of course, it's something that needs to be vetted for each new material that's being considered. But the process itself is something that we can all get behind as far as scientists go, as far as developing the technical skills to do it.

Essentially, what it means is a large collection of data to support any particular model, whether that's a model for fatigue or for creep, or some other mechanical property, the ability to be able to simulate all of the necessary data to then be able to sort of predict what's going to happen with the performance of the materials is incredibly important. And it's something that could really save on time, and again saving on time and money as your resource that brings along with it.

This also allows for a unique opportunity to be able to discuss automation. So, in the scenario that I threw out there, if you take a fuel pellet and subdivide it into 1000 pieces, do you then want to have 1000 people each with their own sample on 1000 different electron microscopes, each performing their own set of analyses and then feeding back the data in the [Unclear] database or something? Or could you establish a system where you are, sort of, auto feeding your samples into a single device that reduces, maybe not necessarily the time, but it reduces the workload on a particular worker. It allows you to be able to do things, say, 24 hours a day as opposed to having to rely on the operability of a particular piece of equipment. And then the ability to standardize all of that data collection because now you are using an automated system that is on a single device or a single set of devices. It sort of reduces some of the uncertainty that goes along with the data collection as well, which is also very important as part of the process.

In a scenario where you have 1000 different people and 1000 different devices, now you have introduced 1000 different possible sources of uncertainty, beyond the sample themselves, beyond the equipment that they are using. Being able to limit the capabilities but extend the use of those capabilities is incredibly valuable.

And so, the strategy would be the ability, again, to look at something that's a larger scale, say, a sample for mechanical testing, and being able to walk back through the process. Say you start with materials that are not irradiated and they are going to go through their own performance, whether that's strength testing, there's one example here. And then you can perform the same testing on an irradiated material and look at the comparisons between the two and start to assess the differences between the performance of non-irradiated versus irradiated, at the microstructural scale and then use that to predict what kind of performance you are going to get at the bulk property or the microscopic scale.

This is something that through the use of microscale technology, microstructure using electron microscope, something in that order, and being able to do multiple sets of samples allows you to build up that database. So instead of saying you've got one fuel pellet that's not been irradiated and one that has, and looking at both properties on one sample per piece, where you would have to use 20 samples, 50 samples, 100 samples and build up a significant database, now you could take a particular sample, subdivide it, and then reassemble that information on the microstructural scale and then consider what the performance is going to be on the microstructural or the bulk scale.

So, the key pieces that are going in this again from my point of view is the ability to be able to have repeatable methods, the ability to have somebody correlate them, so whether that's through an existing model, or coming up with a premise, if you will. Typically, if you think of a model for a fatigue or something like that, that's already well vetted for a material, you can then try and make adaptations to it based on irradiation effects or thermal mechanical effects, that sort of thing.

And then the largest and probably the most significant portion of this is that I call the large quantity testing, which means the ability to get multiple pieces of data from each single sample, and if that means to the subdivision of that sample into smaller pieces, or if that means vetting it through multiple testing techniques and then being able to suss out particular pieces of data. The important point here is being able to say, I've gotten the most data that I possibly could out of a particular sample. And particularly, as I mentioned before, for irradiated materials, for those that have radioactive materials that are involved, the more data that we can acquire for the least amount of risk is the most viable to us.

And overall, what this should allow for is the ability to do more testing and then also better testing as we start to streamline events. Again, in the 1000 sample, the 1000 device scenario, you could have the inconsistencies in 20 of the devices, and then maybe 20 of those pieces of data are now not going to be fed into a database because they have to be thrown out for being inconsistent or not reliable or not repeatable. That's where I think the greater advantage here of looking up repeatable system is the ability to say that it can also be a better and a more reliable system, and that again is something that goes towards the quality assurance aspect of our process.

There also needs to be some, in my opinion, way of reimagining how it is or where we collect information. And this really was at the Halden Facility in Norway that recently shut down. One of the tricks of the trade that they were really well known for is adapting their ability to collect information from, say, a fuel sample, extracting a fuel sample, and then being able to reconfigure it, re-instrument it, and then put it back in pile to do continued testing. So, the graphic that's up here, sort of again from one of their slides, that's in the ability to say that you have got a fuel rod segment that you can then re-instrument with, in most cases, the thermocouple and pressure transducer.

You've already got material that's already been irradiated, you then can rig it so that it can then be re-irradiated and then taken out and reassessed. And then depending on what the condition of your system is, maybe even reconfigure it or re-instrument it again. This is something that's or this would allow you to assess performance, sort of in situ but also the ability to look at timelines. And for fuel performance in particular and in core material performance, that's incredibly valuable. And so, there is a real present need for similar testing capabilities throughout the world. There was this need obviously before Halden shutdown, but the ability to be able to get these kinds of capabilities is even more pressing now.

There is also the idea in being able to instead of have one device that you move, say, a fuel sample or a material sample from one device to the next, to the next, to the next, is that you can actually configure – geometrically, you can configure multiple examination devices, to be able to consider a single fuel sample or a material sample and get multiple types and sets of data for one piece of material.

This is a demonstration of the MEITNER project out of INL, where they had set up, and I'm going to misrepresent which devices they actually have on here, so I'm not even going to try it, but they actually take a material sample which they place in the center of these devices and then they actually have, again, emission tomography, or again emission scope. They have laser flash, I believe, set up for it.

But the idea being is that around this arrangement, they actually have multiple measuring tools set up to get multiple pieces of information from a single piece of material. And I believe one of the points of interest would be to set up multiple - it's, I think, gamma emission which I mentioned or different cameras that are set up to assess material performance, essentially whether there are cracks or slumping or something like that with a particular material piece, while the material just sits here in the middle. In other words, you don't have to take the piece out from here to go to another device to look at porosity, and then take that out to again to look at grain structure, and then take that out to look at – you can repeat that process as much as you want. It's again trying to leverage as much information at a particular setting as possible, again to coproduce time, and do research and I guess leveraging resources and reduce risk.

I also mentioned automation as a part of this process, and this was a GIF that I borrowed from the University of Liverpool in one of their chemistry labs that they actually set up an autonomous process to be able to go through a set of samples that needed to go through the gas [Unclear]

The point being is that there's really no reason that you couldn't have these samples being irradiated samples, and they were being sent off to two or three or four different devices that were set up in their laboratory. The laboratory itself would be something as tantamount to a miniature hot cell, but you have multiple pieces that are in there. Where you get the more efficient process going on would be having samples that are, while radioactive, not so high dose that it would cause system damage, and so you could have something like this robot, if you will, to be able to move your samples from one station to the next and be able to collect several pieces of data from these smaller samples.

Again, it's just a different way to consider how to be able to collect this data for your materials based on the ability to utilize automation or to reduce the dose or to try and fit in multiple techniques in the line. That's where most of this discussion goes.

Another process that goes into this and this ties into a little bit of automation, a little bit of a microscale discussion, is the ability to be able to fabricate samples on very small scale, so again, the subdivision of a fuel pellet into 1000 pieces. Well, say, that you are working with something that's on a smaller scale, I mentioned the TRISO particle earlier and its dimensions, looking at about [Unclear].

And so, if you wanted to be able to analyze the interlayer performance of the TRISO particle, that's been the way we do. The idea, that is not new. That's something that's been done for decades, now, when it comes to analyzing whether particles have failed, where they failed, and trying to even determine how they failed. But when it comes to actually trying to develop samples that are then used for subsequent testing, that's a little bit more of a challenge. The radiation concerns a side when you are trying to work with materials that are already on the milli-scale, if you will, and then you are going to have samples around the microscale, trying to do that in any sort of repeatable fashion has been a challenge. But that's something that will be a great advantage is if you could have, say, a line or a stack of TRISO particles and you had a FIB configured, a focused ion beam configured to be able to cut out samples from each one of those particles, which then you could take each one of those samples to be able to be tested through an automated system, so they all have to be scanned in an SEM or they all have to undergo tensile testing.

Those are the sort of things that could possibly be automated, but it takes some time to develop the techniques in order to make it a more efficient process. But these types of processes have been widely used in automotive and medical industries for quite some time, for decades now, and it's something that on a larger scale we should really consider. You may have one university, or one vendor, or a couple of vendors that are working together on this. But if we as an industry as a whole start focusing on how to be able to leverage these different technologies, I think it's going to help us all.

This is just another demonstration on the idea of reducing sample size, especially for irradiated materials, which then allows you to be able to, once you reduce the dose, reduce the hazard, now you can look at being more modular, shall we say, or inventive when it comes to being able to access materials. So, the GIF that I showed a couple of slides back with the robot, that was working amongst three different sites at the laboratory.

Now, imagine if you had a room that was set up with multiple shielding walls, these sort of moving lead shielded walls, there were different places that were kind of shielding a particular device, and the robot was able to go through and, say, put a cartridge of samples into an SEM and then the shielding was placed in front of the SEM to reduce the amount of dose that might be coming your way from it, which then would save the ability, say, for even human access. This is for a large enough facility in Idaho or something like that or reduce the dose that would be imparted to that particular robot that was doing the automation portion.

But the idea that you could have these multiple stations in one laboratory setting and not have it have to be a model which it had. It could be something that looks much more light in an atypical university laboratory, something on those lines. I am just trying to think about things in a little different way and trying to get perspective on how we can use technologies that already exist to make the process go a little faster and a little better.

I mentioned this now in a couple of places, and this is purely an editorial because I think it's something that, admittedly even for myself and that's something I put a lot of consideration into until, say, the past 10 years or so, is the ability to justify the processes that you went through to produce the data that is being used as part of your process for qualification. Developing a facility that's got NQA-1 compliant research programs, nuclear quality assurance designated 1, there are very few facilities that are out there, but they do exist. Actually, there are several that are available in the industry, when it comes to, say, steel manufacturing or materials for reactor use, particularly those that are ex-core.

For in-core and subsequent material development, and especially at the university level, and of course, I again say this with great bias because I've been in academia for quite some time, the ability to, dare I say the word 'prove,' but I'll put that in quotes, prove that the university system that is able to be able to produce the kind of data that is relevant for qualification of materials is a very important thing. And I think resources really can be tapped into with some effort but I think it could be done in a relatively short order. It can really boost the development of our materials program for new kind of materials.

And so, I implore anyone who has any interest in, sort of, jumping into the field of materials analysis, even the automation process in this, should consider going through the qualification process to at least investigate what it would be for you to set up a compliant research program. And there are universities I know here in the US and abroad that actually have done this. It's not a large number. It's a very small number, but they do exist. Anyway, that's something that I think would be of great advantage to any entity – vendor, university, laboratory alike, to be able to help, that just sort of reinforces the processes, the justification of the processes that are used and the data that you collected.

And to be honest, it really helps to save, I don't want to say on scrutiny because there's scrutiny, of course, that needs to be placed on the work that we do, but it provides to [Unclear] little bit of an assurance that you as an entity have taken the time to be able to assess what it is that your team can do, what your program can do and, sort of, provide a demonstration that you have the ability to collect valid data that is part of the qualification program.

How do you get started? I've mentioned a lot of different names throughout this process, a lot of different avenues that can be traveled to be able to go down this path. Really, it's identifying facilities that I think is very important, and there are some names that are up, and particularly I mentioned this, the US contingents will be much more familiar with these, but at least lets international collaborators know that you may have very similar systems set up, whether that's through CEA in France, whether that's through KERI or through KAIST in South Korea. In the US, we have a set of partner facilities that are set up that include National Lab, industry and universities, through Nuclear Science User Facilities, opportunity.

There are also opportunities for vendors and reactor development teams to be able to access facilities, mostly at the national labs or in the vendor scale, through the GAIN initiative which was recently established in Idaho National Laboratory. And then to really mention that there is a host of collaborators that are available who have very impressive facilities at the university level and industrial collaborators. If one were to consider partnerships, let's say, whether it's Framatome or whether it's GE, whether it's Elano, whether it's with the, say, the partners in the National Labs, whether in the US or abroad, there are a lot of different opportunities that are out there, a lot of people who are interested in doing this work. It's really just trying to make more of a collective effort to identify who has the capabilities and the usefulness in their abilities to be able to do this one.

As a summary, as I mentioned very early on there is a variety of reactor types that are being developed, which really is a blessing for the nuclear community. There doesn't seem to be any shortage of good ideas that are out there, and they should all be explored. But and this is the 'but,' it does put a strain on the available resources for assessment for irradiation and safety testing, and overall for the qualification process. That's not to say there's not a challenge [Unclear], but it is a challenge that needs to be addressed. So, this needs to drive innovative thinking on how to assess materials from new reactor types, and not only the processes that you go through but how the different pieces of data can be assembled into a single qualification package, and the collaborators who are available to be able to help out as part of the process.

With that, I want to take a moment to put a blatant advertisement out here. So, I am employed by the Idaho State University. I've been here as an Assistant Professor for just over 1 year after spending 5 years here as a student. I also want to mention that along with our main campus, which is in Pocatello, Idaho, we actually have a satellite campus which is, as you can see from this picture, there are cars over in the parking lot, so it's probably about 100 yards from some of our classrooms to the INL facilities that are here in Idaho Falls. So, for those of you who may be coming to visit Idaho National Lab at some particular time, feel free to reach out and I'll be happy to meet you.

On that thought, I thank you for your time and open up the floor for any questions.

Berta Oates
Thank you, Dr. LaBrier. While questions are coming in, we'll just take a quick look at the upcoming webinar presentations that we have on schedule. In June, a Comparison of 16 Reactors, Neutronic Performance in Closed Thorium-Uranium and Uranium-Plutonium Cycles. In July, a presentation, an Overview of Small Modular Reactor Technology Development. And in August, an Overview and Status Update on Molten Salt Reactor Technology Development in the US.

So, Dr. LaBrier, there is one question so far in the Q&A pane. It reads, would you suggest an equipment testing roadmap for liquid fuel reactors such as the molten salt reactor materials? Do you have any reference sources?

Daniel LaBrier
That is a very good question. We'll read the question a little bit more in detail. I would say in particular for roadmaps for technology development for molten salt reactors, your first resource, at least as far as the US is concerned, would like would be Oak Ridge National Laboratory. They have been one of the and continue to be one of the pioneers in the field of MSR research. So, if you are looking for a testing roadmap, I can't think of one off the top of my head, but that's not to say they don't have one already. And especially with the resources they've started to reinvest on molten salt reactor technology, I actually wouldn't be surprised if they have one already published or at least have one in development, so that would be my first resource.

There is also, if memory serves me right, a conglomerate for molten salt technical background research called moltensalt.org, I think is what it is. And they have a really broad collection of different activities that have been done. You can actually access these through the GAIN website, the GAIN Initiative that I referred to a few slides ago, and that's kept up by Idaho National Lab. So that's GAIN, which is gain.inl.gov, and then there are references for actually all sorts of advanced reactor technologies that you could use as a reference. So that would also be a good place to follow up. Thank you.

Berta Oates
Thank you. Then next question reads, professor said the development and qualification of nuclear materials needs very long period, around 30 years. How do you young middle researchers have dreams or make careers up for this target? Don't know if you have words of inspiration there.

Daniel LaBrier
The first thing I can say is even though I am finishing up my first full year as an Assistant Professor, I'm not that young. Secondly, let me clarify, for a few qualifications, you are usually looking at 20 to 25 years. In some material cases, you could get by, as I mentioned, with Alloy 617, that's more along the lines of maybe 15 years. But you're right, it can be a very laborious and timely process.

Again, only my opinion, sometimes you have to look at a variety of different materials and, sort of, assess to yourself where you think your time is best suited for attacking a particular material, I guess. And that just comes out of communication; it really does. I enjoy the way this is put, young middle researchers who have dreams or make careers. And you really can do that if there is enough follow through in the industry, you really can make a career out of just, I'll say, assessment of a simple material.

But that said, again, my strategy is one where I like to at least assess as we go what materials are being researched, and then from there, if you need to pivot to looking at more.

Sorry, I'll give you 30 seconds of my background. I actually started off looking at actinide recovery for pyroprocessing, so looking at oxide to metal conversion in molten salt research. Then, I switched to materials research for graphite, then moved into structural materials, particularly seals for advanced light water technology. And now I am starting to revert back to technologies related to graphite for molten salts, and for novel metals, for liquid metal, particularly sodium reactors. So, you may cycle back upon type of researches you've done in the past.

So, in my opinion, it's a good idea to kind of keep your eyes open for different materials and sort of just trying to see how the funding is going, how the industrial interest is going, and that may steer you to what particular area you are going to search for your career, with the consideration that that may change in 5 years or 10 years. It's just the nature of our industry as it is. It can often go through cycles where there is interest, and by interest, I mean financial interest versus times where we are a little more lean as far as our resources go. Thank you.

Berta Oates
All right. Thank you. Does a catalog of test facilities exist with the specific testing capabilities identified, for example size, constraints on samples?

Daniel LaBrier
The first resource I will send to you for that is through the Nuclear Science User Facilities, at least for the US, and so that is nsuf.inl.gov. They actually do have a database of facilities and equipment within those facilities that can be used for your research. As I mentioned earlier, it's part of a process where you essentially apply for time to be able to use those resources. But that said, the database, I think you just need to be able to create an account on the websites, and it's been a few years since I did so much. But I think that's the process. That would be the first place that I would steer you to. Thank you.

Berta Oates
What are the advancements in clad material related to hydrogen management during severe accidents for the Gen III plus water-cooled reactors? When it will be introduced into the commercial reactors?

Daniel LaBrier
That's a really good question that I don't have a clear answer to. I know several folks who are looking at hydrogen management for advanced cladding techniques, specifically here at Idaho National Lab and at Oak Ridge National Lab. I will direct you to their research as far as where the technology is. As far as implementation into reactor testing, that is a little outside my comfort zone, a little bit outside my ability to provide a really good answer for it. So, I apologize for that. Thank you.

Berta Oates
Thank you. What are your opinions on a surveillance campaign to monitor materials inside a demonstration or prototype reactor to mitigate any uncertainties that are covered by testing?

Daniel LaBrier

Is that a question? Oh okay, I see it now, I'm scrolling down a little bit to actually see the question.

Berta Oates
Yeah, it's easier to read them yourself.

Daniel LaBrier
That's okay. Well, I will have to say, my personal overall opinion is it's a good thing if you can develop it properly. The greater challenge is accountability, especially nuclear materials, is how are you going to go about surveillance campaign. So, this kind of brings back the idea of establishing a roadmap for your processes.

My limited experience when it comes to surveillance is actually on the backend of the closed cycle, not on the frontend, again sort of related to developing processes, and in their particular case, it would have been surveillance for, I think, with plutonium. That was one of the greatest challenges is overcoming the uncertainty that goes along with the monitoring system that you have in place. I think that the best approach, and again, you asked for my opinion, so the best approach is to lay out your process literally right up steps A, B, C through Z, and see where your strengths are and where your weaknesses are and try and address the weaknesses as best as you can.

Another consideration might be, as you mentioned, trying to set up a campaign for prototype reactors that, as I mentioned earlier, and this is no deference to the people doing the work now, but most of the research that's being done now for advanced reactors is not new in principle. And so, there may be historical information that's out there for – take for example, a high temperature gas-cooled reactor, there is existing data out there for the past 40-50 years that you may be able to review and leverage for developing a strategy for doing such a surveillance campaign. I hope that is okay. Thank you.

Berta Oates
Thank you. Is there a hierarchy for testing priority, for example, testing, supporting existing fleet of LWRs, for example, for ATF, takes priority over testing, supporting a speculative advanced reactor or is the hierarchy simply who can pay for the testing?

Daniel LaBrier
That's a good question. That's about 12 steps over my paygrade. The short answer is I don't really know what the hierarchy is because I honestly think that – there are two aspects to it. One is what is the current emphasis on reactor fleet development from a funding standpoint,

and that is also tied to the political aspect of it as well. That's one piece of it.

The other piece is that if you ask 10 different people what their opinions are, that you are likely to get 10 different answers. And in my position, I really can't say one versus the other. This is one of the difficulties in trying to sort of push forward any single reactor technology at least here in the US, is that pretty much anything is open game, which means that if you've got a novel concept for fuel development for a sodium fast reactor, if you can demonstrate its viability well enough, maybe it can overtake something that has a little more salvage technology. But again, as far as the actual hierarchy of it, that's a really complicated question that I can't answer with any direction indeed. So, sorry about that, but thank you.

Berta Oates
Thank you. The same person has a series of about three more questions so I am going to read them and post all three, and then you can give overarching thoughts perhaps. How about that?

Daniel LaBrier
Okay. Another option might be if this person wouldn't mind, they could actually reach out to me online, well offline I guess, through my email address, which is supposed to be at the top. We might be able to have a little more dialog about this offline if that's more constructive.

Berta Oates
Excellent point. Thank you. What level of sharing of testing results exists? Is it dependent on the level of subsidizing of the tests? Who ensures testing is not duplicative of prior tests performed by others for the limited availability of the test facilities? And lastly, do you have an example of predictive behavior by a computational model that was not representative of a measured behavior?

Daniel LaBrier
For the first two – actually, I am going to answer the third one first and the easiest way that I can answer that is off the top of my head, no, I don't have an example. But then, again, I wonder if that is directed more towards looking at the microstructure or the macrostructural behavior, and that's still something that's under development. In other words, we can't just make assumptions about what's happened at the microstructural level and assume that that, sort of, propagates towards macrostructural behavior. That was more of a point I was trying to get across, is again from my point of view you can't make that jump about having both the physical data and the correlations to be able to tie them together.

For the first two questions, level of sharing of testing results, that is depending on many factors to be very honest. I am not really sure where I can even start with that question. But that one and the second one, what ensures testing is not duplicative of prior tests performed, many times the actual testing facility itself will, or whoever manages that site, there is a lot of time that is put into researching in what's been done historically. So, it is not a lot of duplication. But I will also point out there that in some cases duplication can be a good thing from the aspect of trying to verify results. And that's even true for historical testing, for, say, molten salt technology, if there is a particular alloy you are trying to vet, that was last researched, let's say in the 1990s, you may want to actually redo an experiment that was done on that particular alloy.

Another example I'd give is when they restarted the TREAT facility, the Transient Reactor Testing Facility at Idaho National Lab, they first brought it back up in November 2017. So early 2018, as they were going through the operations testing, some of their early tests and these were more operations driven than, I'd say, experimental results driven, actually work as best as they could, reproductions of experiments that were done showed that the reactor would shut down. And that was really to get a sense of what kind of condition the operability of the reactor was.

So, that's a very complicated question, or I should say the answer is very complicated, is that some of the impetus is on the researcher to make sure that the work that has been done, that you are proposing to do, hasn't already been done. Or does it need some secondary or tertiary vetting, which means that you could sort of recreate or nearly duplicate an experiment that's been done. There is also the consideration that – and this is something that I've only found through experiences that many times you will have, and I have had this actually happen to me a few times, where I thought I had a good idea for an experiment and walked my way through the process until I got talking to the right person at the right facility, who said, "Yeah, that information is going to be published in 6 months. Is there anything else that you want to look at?" And sometimes there is no good way to know that ahead of time, especially for our industry which seems to be very cutting-edge as far as testing goes. And sometimes going from test development through test implementation to data analysis may be a multi-year process. It may take you 2 to 3 years just to develop the test, and then another 1 year to schedule it, and then another 6 months to 1 year to actually process the data. You could be looking at a 5 years' window from the time you approached the subject to the time that you actually are ready to publish. And that's from an academic point of view. That's very difficult to try and lay out ahead of time. It's probably not the answer you were looking for, but in reality, that's sort of what the answer is. Thank you.

Berta Oates

Thank you. There is a person who wanted to ask, what are the operation conditions of irradiation and post-irradiation experiments? Also, what information do we acquire from these experiments in general?

Daniel LaBrier
That's a really long answer because it can be all over the map. Operation conditions of irradiation, well, what technology are you looking at? Typically, you want to try and mimic – any experiment that you are going to put together, you want to try and mimic your actual operating scenario as closely as you can with regards to materials waste, temperature, working fluid, thermal hydraulics in the system, that sort of thing. So that will vary from one test to the next, depending on what it is that you are interested in studying.

For PIE, Post Irradiation Examination, that really just kind of depends on what information you are looking for. If you are interested in, as this topic suggests, assessment for materials, if you've got metal versus the ceramics versus an oxide, those will usually just depend on what instrument you are going to be using, and I'll say the conditions in which your test material was subjected. So, for instance, if you had a material that was vetted in a sodium-cooled loop, so was exposed to sodium along the way, that will need to be treated with probably a little different mechanism than it would be if you had, say, a steel that was irradiated an inert environment that in other words one could interact with air, eventually the other would need some treatment before doing so.

What information do we acquire from these experiments in general? That is the subject of several classes at the university level. Most introductory material science classes where a lot of you would want to consider the physical, mechanical, and the chemical properties for whatever material it is that you are looking for. Again, depending on what type of material it is and what state it is in, those answers can have a lot of variety to them. Thank you.

Berta Oates
Thank you. Are material test results generally kept as IP, particularly with the number of private companies developing fuels and reactors? I suppose IP would be proprietary.

Daniel LaBrier
I am not sure how to answer that in a general way because that's going to depend. There are plenty of materials that are vetted internally, again my opinion, internally vetted by companies for their own use that the results may not be released. But on the other hand, there are a slew of information that has been put out there in recent years where advanced material and advanced fuel materials, that if it's in the open publication, then that suggests that it's not subject to the IP, at least that portion of it

is not restricted to the IP conditions. But that again is the one that goes with an asterisk along with the answer, under 'it depends.' There may be information that's allowed to be shared publicly and some that's not, and that will vary by technology, by group, by company, but there are a lot of variables other than that. Thank you.

Berta Oates
Thank you. I know we are running just a little bit long today, but there are two more questions so that we don't leave anybody out. The second last is regarding the current design codes, are the current design codes suitable for GEN IV or do we need to develop new ones which could add a number of years out to timelines?

Daniel LaBrier
That is a question that is better suited for the regulatory body of whichever country you have to be in, so in the US, that would be the Nuclear Regulatory Commission. As I understand it, and you can find this publicly on their website, there has been a lot of emphasis in the past few years for getting the regulatory body to catch up to the designs that are being put forth for advanced reactors. And so, there may be evaluation that is based on a particular design, keeping in mind the design codes from previous generations.

I would actually direct you to one example that is being evaluated right now by the NRC, and that is the advanced reactor company called Oklo. They recently submitted paperwork for evaluation to the USNRC, and it's publicly available on the NRC website, to get an idea of what the – I don't want to say the new normal will be, but at least a new process consideration on being able to qualify designs for advanced reactors. Thank you.

Berta Oates
And then if we have ongoing questions after this last one, you can email those directly to Dr. LaBrier, or if you want to email them to me, I can compile them and make sure that we get written responses, and we can post those along with the slide deck on the GIF webinar page with the recording of today's presentation so that everyone can share the information.

Last question we'll take today, and again, I appreciate everybody for hanging in there. We don't usually go this long. We are rapidly approaching 2-hour mark, so I can't believe the level of interest, it's fantastic. How do you take the corrosion and erosion of materials into consideration while modeling the service life of an advanced reactor?

Daniel LaBrier

That is a really good question. I will say from a – because there's a couple of different ways we can approach this, from a baseline level, I'd say if you are going to – the short answer is we are trying to figure that out. The longer answer is you need the experiments to sort of supplement the modeling that goes along with it. So ,say for instance if you – I'll take a publicly available, so it curves through, I don't know whether – well, you could say through like a material performance code like BISON which is developed by INL for thermal mechanical properties of materials. There are models that are established based off of historical data and being augmented based on recent data, for full interaction with properties and that has to do with very complicated systems for corrosion and more for, say, embrittlement, radiation damage, a whole cluster of very different agitators to the material.

For the modeling, that comes down to physically which of the mechanisms are more dominant and at which stages, and that in my opinion, comes down to a combination of separate and integral testing.

So, you would need to do – and again, I make no bones about it, I am an experimentalist by heart. That means you are going to be doing testing in your prototypical environment from a physical and a chemical standpoint to observe corrosion as it may happen through obviously a shortened lifetime, and then, you would have to do consider the irradiation effects, and then if you can start to integrate these in the multiple factors occurring at the same time, then you see how your material performs through, say, microscopy or something like that for adjustments in the structural changes that you might have at the microstructural level.

But the last thing I'd say, it's a very complicated question that I think recently we are still kind of ploughing through. And I realize that I've said that now for probably for every question that's involved. These are all very good questions. They are also very multi-faceted, multi-component, complicated questions, and that's why it's really encouraging to see as many folks that are down here today that are interested in this. Because we need you and your friends, and your colleagues, to kind of jump on board to help with this. So, I think that's where I am going to step off and say thanks to everyone.

Berta Oates

Thank you, Dr. LaBrier. It takes a bit of time I know to put these presentations together. We really appreciate you sharing your time and your expertise with us.

Daniel LaBrier

No problem at all. And thank you to the Gen IV International Forum for the opportunity. This has really been fun, so thank you again.

Patricia Paviet
Yeah. Thank you, everybody. Thank you, Berta.

Berta Oates
Thank you.

Patricia Paviet
Thank you, Daniel.

Berta Oates
Bye-bye.

Patricia Paviet
Bye.

Daniel LaBrier
Bye. Thank you.

END
