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(202) 234-4433

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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MATERIALS, METALLURGY AND REACTOR FUELS SUBCOMMITTEE

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WEDNESDAY

MAY 6, 2020

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The Subcommittee met via Teleconference, at 9:30 a.m. EST, Ronald Ballinger, Chairman, presiding.

COMMITTEE MEMBERS:

RONALD G. BALLINGER, Chairman

DENNIS BLEY, Member

CHARLES H. BROWN, JR. Member

WALTER L. KIRCHNER, Member

JOSE MARCH-LEUBA, Member

DAVID A. PETTI, Member

JOY L. REMPE, Member

PETER RICCARDELLA, Member

MATT SUNSERI, Member

ACRS CONSULTANTS:

MICHAEL CORRADINI

STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

CHRISTOPHER BROWN

ALSO PRESENT:

PAUL DEMKOWICZ, INL

MADELINE FELTUS, DOE

EDWIN LYMAN, Union of Concerned Scientists

SCOTT MOORE, NMSS

JOHN SEGALA, ENG

ANDREW SOWDER, EPRI

BOYCE TRAVIS, NRR

DEREK WIDMAYER, ACRS

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P R O C E E D I N G S

9:30 a.m.

CHAIR BALLINGER: Okay. By my clock it's 9:30. Time to start. The meeting will come to order please. This is a meeting of the Advisory Committee on Reactor Safeguards, Metallurgy and Reactor Fuel Subcommittee.

I'm Ron Ballinger, Chairman of the Subcommittee. Members in attendance today by my record would be Dennis Bley, Charlie Brown, Jose March-Leuba, Pete Riccardella, Joy Rempe, Matt Sunseri, Dave Petti. If there are any other members that are now logged in, please identify yourself.

Okay. We also have consultants Mike Corradini and Steve Schultz present. Christopher Brown and Derek Widmayer are the designated federal officials for this meeting. Chris and Derek can make sure our court reporter is on. I assume that's happening.

The purpose of today's meeting is for the Subcommittee to receive a briefing on staff's Safety Evaluation for Topical Report EPRI-AR-1, Uranium Oxycarbide Tristructural Isotopic Coated Particle Fuel Performance. Today we have members of the NRC staff and industry to brief this Subcommittee prior to my ship's bell.

The ACRS was established by statute and discovered by the Federal Advisory Committee Act, FACA. That means that the Committee can only speak through its published letter reports. We hold meetings to gather information to support our deliberations.

Interested parties who wish to provide comments can contact our office requesting time. That said, we set aside 10 minutes for comments from members of the public attending or listening to our meetings. Written comments are also welcome.

The meeting agenda for today's meeting is published on the NRC's public meeting notice website as well as at the ACRS meeting website.

On the agenda for this meeting and on the ACRS meeting website are instructions as to how the public may participate. No request for making a statement to the Subcommittee has been received from the public.

Due to the COVID-19 issue, we are conducting today's meeting virtually. A transcript of the meeting is being kept and will be made available on our website.

Therefore, we request the participants in this meeting first identify themselves and speak with sufficient clarity and volume so they can be readily heard.

All presenters please pause from time to time to allow members to ask questions. Please also indicate the slide number that you're on when moving to the next slide.

We have a bridge line established for the public to listen to the meeting. The public line will be kept in listen only mode until the time for public comment. To avoid audio interference, I request that all attendees make sure they are muted while not speaking.

I should also note that we have two members probably that have conflict of interest. They can tell us what that is. One would be Dave Petti, who probably everybody knows what conflict of interest he has -- he's almost an author of the document -- and Joy Rempe.

MEMBER REMPE: And, Ron, mine is limited to just the instrumentation for AGR-1.

CHAIR BALLINGER: Yes, that's what I thought. Based on our experience from previous virtual meetings, I would like to remind the speakers and presenters to speak slowly.

We will take a short break after each presentation to allow time for screen sharing as well as at the Chairman's, that would be me, discretion during longer presentations.

We do have a backup call-in number should Skype go down, and it has been provided to the ACRS members. If we need to go to this backup number, the public line will also be connected to the backup line.

Lastly please do not use any virtual meeting feature to conduct side bar technical discussions. Rather contact the DFO if you have any technical questions so that we can bring those to the floor.

Also I might add that we have a hard stop at noon so we've got to probably try to be careful about that. Also note that there is a full Committee meeting scheduled on this topic for June 3.

Let's see. What else do I have to have here? We will now proceed with the meeting. And I think Andrew Sowder will be sharing his screen now with us while John Segala, Chief of the Advanced Reactor and Policy Branch, Division of Advanced Reactors and Non-Power Production and Utilization Facilities -- boy that's a mouthful -- for any introductory remarks that they would like to make before we begin today's discussions.

So I'm not sure who all is on. I can't

see. But, John, would you like to make comments?

MR. SEGALA: Thank you, Dr. Ballinger. Can you hear me?

CHAIR BALLINGER: Loud and clear for me.

MR. SEGALA: Thank you. I'm glad you introduced me and announced my division name for me. It is a mouthful. So as you indicated we're here today to brief you on our safety evaluation of the EPRI TRISO Coated Particle Fuel Performance Topical Report.

Since it has been a while since we've briefed ACRS on NRC's advanced reactor readiness activities, I wanted to take a moment to step back and provide some context for the subject of today's meeting.

Back in 2017, we briefed the ACRS on NRC's vision and strategy document for advanced reactors and our implementation action plan that enhance our readiness to effectively and efficiently review and regulate advanced reactors.

For the near-term implementation action plan activities, they are grouped into six strategies. Strategy 1 is training of the staff. Strategy 2 is developing computer codes and models. Strategy 3 is developing guidance.

Strategy 4 is facilitating industry consensus codes and standards. Strategy 5 is identifying and resolving policy issues. And Strategy 6 is communications.

At the time we briefed ACRS, you all recommended that we focus our near-term activities on Strategies 3 and 5, which we have been doing. This Topical Report is a high priority for NRC, and it supports Strategy 3 for the high temperature reactor designs that plan to use TRISO fuel.

The data supporting this Topical Report is built off of a long history dating back to 2005 as part of DOE and NRC's work on the next generation nuclear plant, or NGNP and DOE's Advanced Gas Reactor Fuel Development and Qualification Program, which is still continuing today.

We are looking forward to hearing from the ACRS on this important topic and any insights and feedback that you all may have. Although the NRC is not asking for the ACRS to write a letter, we understand that ACRS may be planning to write us a letter.

As you mentioned, June 3 will be the full Committee meeting. If ACRS writes us a letter following the full Committee meeting, the NRC will finalize its safety evaluation after we address any issues identified by the ACRS.

And, therefore, this completes my

introductory remarks.

MEMBER REMPE: John, this is Joy Rempe. And a couple of days ago Christopher Brown sent us an updated version of the SER. And his intro said, I think there's not any technical stuff. It's mainly stuff that was from OGC. And I only had time to briefly skim through it, but there were some technical changes that I picked up.

I assume if we were to write a letter, you want it on the updated version. And so today when the staff gets up, I've got some questions on the items I did pick up. But I just want to confirm, you want us to write a letter on the updated SER, right?

MR. SEGALA: Yes.

MR. TRAVIS: Yes. Dr. Rempe, this is Boyce Travis. I'll be presenting on behalf of the staff. We'll be happy to address any questions you have.

But because of the timeline for this meeting, for all practical purposes, that initial draft was an OUO, like, early draft of the document that was provided for ACRS for preparation.

The draft that exists that you have, what you've heard is the updated version, is the staff's draft safety evaluation that's being used for the purposes of this meeting.

MEMBER REMPE: So be prepared. And, again, it would even help me more if you would tell me all the technical changes because, again, I did not have time to go through all the markups and say, oh, this is a technical change.

But there was one I picked up that implies that someone from EPRI or INL gave you some additional data to make this change. So, please, you know, if you could make a list of those changes and go through them even though it's not on your slides, that would help.

CHAIR BALLINGER: Okay. I guess hearing -- I'll apply the 10 second rule that we've been doing for virtual meetings. I guess we should pick it up. And I guess, Andrew, you're next online and your slides are up on the screen as far as I can tell.

MR. SOWDER: That is correct. And can everyone hear me?

CHAIR BALLINGER: Yes.

MR. SOWDER: Okay, good. Thanks. Just good to know.

So I am Andrew Sowder. I am with the Electric Power Research Institute. A quick just brief on EPRI. We are a not for profit charter for public good. And so just to preface any remarks on really this project that we do not advocate and we do not endorse any particular products.

The purpose of this effort was, again, as was stated earlier by NRC, was really intended to basically benefit the public and the industry through, you know, development and demonstration and eventual commercialization of beneficial new technologies.

I do want to just kind of make a quick remark that this would not have been possible without the collaboration and resources provided by many partners, and I will go into that further.

But particularly the NRC, the Nuclear Regulatory Commission, should be commended for their engagement and also, of course, the willingness to review this off key as a generic topical.

Again, I'm Andrew Sowder with EPRI and recognizing time is really short today, I will move on and try to be concise with my remarks as the meat will be provided a colleague at Idaho National Laboratory.

I was going to say next slide, but I have control. Okay. A little too much control. Okay.

So the topic of today's discussion as well as the NRC's review is EPRI's TRISO Fuel Topical Report.

At a high level, this document was intended to basically capture and consolidate research to date from the AGR-1 and AGR-2 experiments, demonstrating the UCO, uranium oxycarbide, TRISO fuel performance.

I will also just emphasize that this is a public report. And from the very beginning, we intended to make this report public so everything in the report's data analysis has been reviewed for expert control and other purposes. And, again, it was made public for the benefit of the community.

Next slide. I just want to make recognition of the growing stakeholders engaged in developing and bringing high temperature reactor technologies to commercialization. I'm not going to read through all the participants in the high temperature reactor technology working group but that EPRI has been engaged with NEI. The Department of Energy gained from the very beginning by engaging with the community along with the other technology working groups.

Of course, interest in high temperature reactors is due to the fact that with the higher temperatures and greater safety margins that are essentially the main focus of this Topical Report from the fuel, new missions, markets and opportunities that come with the higher temperature, higher outlook temperatures, as well as potential for expanded siting options, et cetera, that come with each a more inherently safe reactor technology.

And I should just say, these missions would certainly extend beyond just electricity to include uses of the heat output for direct use for process heat, some energy storage and other applications.

CHAIRMAN BALLINGER: This is Ron Ballinger. I don't know if there are people that are just dialed in and not on Skype. But could you remind folks of the slide number that you're on?

MR. SOWDER: Thank you. I apologize. Good point. We are now on Slide 5, which is U.S. and international experience. Thank you. My apologies.

So as was stated earlier, it's important to recognize that the historical and global context of the subject matter here, TRISO-coated particle fuel. While the international experience is not technically the focus of the Topical Report, it was included for the very purpose of providing historical perspective.

TRISO is not new but rather has been the result of a long evolution from earlier fuel forms. But really the focus of today and the Topical Report is on the U.S. Department of Energy Advanced Gas Reactor

Program and the results from specifically two of the experiments, AGR-1 and AGR-2.

Again, you'll recognize the names on those reports. There's already quite a bit of public information available on the performance of TRISO fuel.

So a quick refresher on what is TRISO fuel. Basically, as shown on the left, you have a fuel kernel, which is what most people think of as the fuel meat in let's say a Light Water Reactor, for example.

And historically that has often been a UO2, which again is the ceramic UO2, also used widely universally in Light Water Reactor fuel. However, there are other forms that are possible as well.

And the AGR program is focused on development of uranium oxycarbide, UCO. That fuel kernel, if you will, is then surrounded by a coarse carbon buffer layer and then comes the triple structure, the namesake of the fuel, an inside layer of pyrolytic carbon surrounded by silicon carbide and then an outer layer of pyrolytic carbon.

Again for the purposes of this report, it's important to focus on the fact that we are just addressing chiefly the performance of this fuel kernel, but obviously the fuel kernel has to be embedded in some usable form and on the right shows the two principal forms out there today.

There are others as well, but these poppy seed size fuel kernels would then be embedded in a broader carbon matrix either pressed into fuel compacts which then go into a more traditional fuel element shown on the far right there, a prismatic block, if you will. And then the other common variant is being introduced into a spherical carbon form known as a pebble. And those are then being introduced into a reactor as either flowing, moving or static pebble beds.

MR. CORRADINI: I have a question, Andrew. This Corradini.

MR. SOWDER: Yes.

MR. CORRADINI: The AGR-1 and AGR-2, I assume, will be discussed. They were tested in a compact geometry?

MR. SOWDER: Correct, correct.

MR. CORRADINI: So does that --

MR. SOWDER: That's correct.

MR. CORRADINI: So the reason I ask the question now is there a future plan by EPRI to discuss the path forward to essentially qualify what I'll call the surrounding matrix beyond just the kernel?

MR. SOWDER: So, Michael, that's a very important point that came up early in the development of the report. Clearly, the fuel particles have to be tested, evaluated in some matrix. And so, again, there is a nominal matrix that was drafted for the NGNP program.

We did limit it as much as possible to just the particles recognizing that once you start getting into the actual fuel matrix, that starts getting into exhaust specific forms.

Currently, the EPRI perspective is once we start getting design specific forms that starts getting outside of our comfort zone. And we believe that, and I think most of the developers have expressed it, as they move forward with their own development activities, they will be basically addressing those on a design specific basis through topical and other engagements of their own.

MR. CORRADINI: Okay. That helps me. Thank you.

MR. SOWDER: So right now -- okay, great. Thank you. That was a very important point.

CHAIR BALLINGER: This is Ron. But was the matrix carbon IG-110-U?

MR. SOWDER: I will defer to Idaho National Laboratory. I am not the expert on the actual fuel and the AGR testing itself. In fact, maybe Dave Petti, certainly, for example is as are many of my colleagues. But I would defer to the others.

CHAIR BALLINGER: Okay. Thanks.

MEMBER MARCH-LEUBA: Well, we are -- this is Jose by the way, a member. While we're talking about this, this report qualifies particles, right, and not the form or the shape of the compact of the sphere.

Will the coolant make any difference to your conclusions? You know, we have anything from helium all the way to molten salts. Would that affect at all the conclusions of the report?

MR. SOWDER: Again, in terms of -- specifically for this Topical Report, the performance of the fuel has to be understood in the context in which it was tested.

So if that was specifically tested in a compact for NGNP and for specifically a helium-cooled thermal reactor, that said it is applicable obviously to other applications of these fuel forms, for example, in molten salts, high temperature cooled reactors.

But I did not want to go too far but other than to say it is up to each developer to explain how this Topical Report applies to their fuel form. And obviously each developer has their own path that they will have to develop with the NRC on applying this high quality data to their design.

So I don't want to speak too much about how the nuances associated with different coolant forms other than heat removal is heat removal.

MEMBER KIRCHNER: This is Walt Kirchner. Appropriate to Jose's question is the spectrum that the qualification was done. I would assume using compacts as the fuel form, you had a thermalized spectrum for the actual radiation testing. Is that correct? Not a FAST spectrum.

MR. SOWDER: Yes, no. My recollection is that is correct.

MEMBER REMPE: It was done in ACR, Walt. And, Jose, there's a limitation that the staff had about the actual conditions that it kind of acknowledges that yes, they have not started to consider coolant as well as the fabrication of whether it's in a sphere or a compact.

And I would even note that in one of their tests they had trouble with some chromium and nickel migrating in and failing the particles early. And so remember when we talked about this type of fuel in another design, that was one of the concerns we raised is that you need to be careful about iron and chromium and nickel and things like that that could attack those particles because they tried to keep that from happening in the ACR.

MEMBER MARCH-LEUBA: Yes. But I like the response from EPRI that -- this is Jose -- that the reactor manufacturer, the designer, the applicant, we used to call it, he will be responsible to see these tests are applicable. And if they are applicable, they can use them. If they're not applicable, they cannot use them. The staff would have to review that evaluation.

MEMBER BLEY: Yes. This is Dennis. I wanted to jump in, too. I certainly agree with Jose on this one. But, Joy, to your point those limitations and conditions are kind of vague. You know, they aren't dealing with the specifics that were brought up here. We'll get to those in this presentation.

MEMBER REMPE: We'll get into the next couple of slides. I'm real puzzled on what a foundational basis is. And I think if you look at the staff, it sounds like they were struggling with how to deal with this. And I've got some questions coming up on the next couple of slides. It's a bit of a puzzle this report.

MR. SOWDER: Okay. And this is Andrew coming back in.

(Simultaneous speaking.)

MEMBER PETTI: I wanted to answer Ron's question that you couldn't, Andrew. One, the matrix is not a graphite. It is more of a carbonaceous material. It's not graphitized.

CHAIR BALLINGER: Okay.

MEMBER PETTI: It's a graphitic flour in a binder.

CHAIR BALLINGER: Got it.

MEMBER PETTI: Okay? It's very similar to what the Germans did.

CHAIR BALLINGER: Got it. Okay. Thanks. Okay.

MR. SOWDER: And to the comments on getting deep into technical discussions about, we do have Paul Demkowicz from Idaho National Laboratory. I would defer many of the detailed questions to Paul because he will probably make better use of your time in addressing the technical questions associated with the Topical Report.

MEMBER MARCH-LEUBA: This is Jose. See at the start of the discussion, I wanted to throw in another concept, just the same concept.

I see this report being very positive for the future applicants because they will have to do some work to ensure this report applies to their design.

Once they can convince us that this report applies to their design, then they can use it and this report exists. So I wanted to make sure that I was not throwing stones at you. I mean, I think this is a valuable exercise.

MR. SOWDER: Great. Thank you. But I do understand, it's important to clarify the applicability of the data and the report. No controversy to your question here.

I'm on Slide 7. So this is put up -- I'm putting it just from the obvious that many of the developers in the high temperature reactor community, especially the hydrogen gas cold reactor community, look to TRISO fuel and its performance.

Joy, you mentioned our foundational basis. What is referred there is essentially a lot of the safety benefits, safety margin benefits, are derived directly from the TRISO fuel structure and performance itself. So that's essentially what is, I believe, meant by that statement.

The obvious fact that the TRISO fuel is designed and has been demonstrated to perform well at high temperatures, I believe, you know, at the AGR-1 and 2 at 1800 degrees Celsius. We've documented that performance in a report.

Reactivity and power decrease with increasing temperature, I believe the AVR reactor in Germany, they achieved shutdown by shutting off the actual power cooling to the reactor. And then the fact that it's up to the designers to design their reactor around the fuel for fully passive heat removal.

MR. CORRADINI: So, Andrew, this doesn't have to be answered now. This is Corradini. But just to put it in context, I thought what Joy Rempe, Dr. Rempe, was trying to get at was if I look at the matrix that the particle is surrounded in or the surrounding coolant, is there some sort of physical feedback that would defeat what I view as very positive characteristics of this fuel form? So that's the first question and you don't have to take it up now, but that's how I would frame it.

The second thing I would frame is there a particular recipe that must be followed that is part of this topical report that therefore once followed, applicants can say we're following this recipe and therefore we can take the positive characteristics of the TRISO fuel?

And that can be answered by Paul when he gets up. But those are the two things that I'm trying to couple in to what was asked before.

MR. SOWDER: Sure. I would speak to the first question because, again, this was discussed at length when we were developing the report.

And I think one of the members put it the best is in order to do an experiment you actually have to somehow get the TRISO fuel particles into the reactor. They cannot be suspended in helium or some -- they had to be put into some kind of a compact or some kind of a matrix.

So we are dealing with basically the reality that they had to be inserted in some matrix, and, again, Dave Petti and others from INL will know much more in terms of how that matrix was decided upon.

But the point is, I think on your second one, yes, obviously what matrix is put into and how it's put into will have an impact. We consider that to be to a large degree outside of the scope of this Topical Report because the focus was on evaluating based on what we knew about the matrix and its impact, what the performance of the actual fuel particles and cells are.

But I would not -- you cannot discount the effect of the matrix. Obviously, you want to put it some things and not others. You know, obviously, you know, it could be interactions.

So that's where I'll leave it. I would leave it to Paul Demkowicz and others who know much more about the actual experimentation and have the depth technically.

MEMBER KIRCHNER: Andrew, this Walt Kirchner. Just a side comment. You mentioned AVR. That was not -- what you described with AVR was not due to the TRISO particle itself. That reactor was designed thermospectrum with a low SS reactivity.

It was a pebble bed reactor. And because of the strong moderator temperature co-efficient that's why it shut itself down. It was not the TRISO particle. So we need to keep the particle performance separate from the reactor design.

MR. SOWDER: You are correct. I was mixing apples and oranges there. I apologize. I was speaking to -- but again the TRISO fuel as part of a foundational basis, the TRISO fuel can withstand and ride out the thermal excursions is what I essentially was referring there. I should have said that. Yes, exactly. You're right. I was mixing as well. Okay.

We're on Slide 7. I'm going to move on to Slide 8 here. Now just going into the details of -- just a little bit on the report itself because again

EPRI, we don't have a dog as they say in this fight. But we do try to do generic pre-competitive work that benefits as many developers, as many technologies as possible.

So this opportunity arose. It was, you know, over a course of discussions with INL and the Department of Energy on wouldn't it be great if we were able to take data off the shelf and provide it in a package that could be reviewed by the regulator before designs were being submitted to kind of bring the regulator up to speed and also to support the industry as a whole.

The collaborators on this project, which again I need to call out, that provided any kind of support on developing the topical, reviewing the report as well as helping us with the request for additional information responses were and are Framatome, StarCore Nuclear, X-energy, Kairos Power and BWX Technologies, BWXT.

MEMBER REMPE: Andrew?

MR. SOWDER: Yes.

MEMBER REMPE: There was an eighth experiment, AGR-8, that was supposed to be completed as part of this program. And I think the report said that was eliminated due to budget constraints and the absence of a reactor design effort going forward.

In this slide, it sounds like you've got a lot of interest in design efforts going forward. Is DOE going to a reconsider and finish what they started here?

MR. SOWDER: Well, that's a great question. It's just one that I cannot answer. So that's really DOE's call and certainly not EPRI's call.

I would leave it to maybe the industry partners, you know, who can advocate to that as well as the Department of Energy and INL who have some more information. I cannot, no.

MEMBER REMPE: Is someone from -- is industry going to answer it or is someone from DOE there on the line that could answer that? Because it would be helpful to know how important that last omitted test is to this whole program.

MR. DEMKOWICZ: This is Paul Demkowicz. And I can't answer it for DOE in terms of plans on AGR-8, but I will just clarify.

AGR-8 was a vision product transport validation experiment. It wasn't a fuel performance experiment. And it was, you know -- and Dave Petti can chime in, too. But it was predicated that we had a, you know, single design going forward under the NGNP program, which, you know, I would say we're still not in that position.

MEMBER REMPE: So it's something that each gender will need to -- or design developer will need to do on their own in order to go forward to get source term information. Is that what you're telling me, Paul?

MR. DEMKOWICZ: I wouldn't go that far as to say at this point what they do or don't need to do.

MEMBER PETTI: In principle, you're right, Joy. But it depends on how the design evolves and what the strategy is in terms of how they guide and develop their source term.

MEMBER REMPE: Thanks.

MR. SOWDER: This is Andrew. We're on Slide 9. And I'm not going to dwell on this, but from my perspective this is my primary interest as EPRI. We felt this was a model collaboration and a good model for good public/private partnership where EPRI and the Department of Energy were able to pool funds to bring together all the players to actually make what we think is a high quality product and will benefit many -- it will float many boats if you will in terms of the technology community.

Again, emphasizing at EPRI we were really here to package and be the applicant of record. EPRI has submitted many topical reports in the past. Again, this being generic and there not being an actual fuel supplier marketing their fuel yet or being ready with their fuel yet, it would seem that EPRI would be an appropriate vehicle for preparing the Topical Report.

Recognizing that EPRI is not a fuel supplier, we did bring aboard BWXT also to help us craft the Topical Report itself from the perspective of a fuel supplier.

At the same time recognizing that Idaho National Laboratory and Oakridge and others, they were the ones that developed and owned the data. And so they were really critical in terms of actually developing the core technical content.

And that's, again, why we have Paul Demkowicz on the line because they really are the repository for the technology knowledge and have the depth and experience with the experiment.

As I mentioned before though, we also had the High Temperature Reactor Technology Working Group serve as our reviewers of the Topical Report as we developed it and also as an essential resource for answering the request for additional information.

Again, the intention here was not to be

out of touch with or to impact the developers' own efforts because, as you have heard, it's really up to the developers and the fuel suppliers to take the fuel and designs forward. We also subjected this to the independent reviewers who were familiar with the technology.

In the end, I also have to call attention again to the NRC staff for engagement, receptiveness and the regulatory review off the fee basis, which again is essential here with the hope of eventually having an approved Safety Evaluation Report.

So at this point, I want to go quickly just through the Topical Report. I don't intend to dwell, again, due to the limits of time, but just to kind of a review for everyone on the line the structure and content of the report.

I'm on Slide 10, a transition slide. Now we're moving on to Slide 11. I'm just going basically through the Table of Contents, Section 1, a high level introduction.

Section 2 was intended to provide the regulatory context for TRISO fuel current and past.

Section 3, we deliberately included a section on the non-U.S. AGR program experience for coated particle fuel in the U.S. as well as internationally because, again, we feel like this will serve as a great historical lesson as well as provides the broader context for how the AGR program was executed.

Section 4 provides the basis for particle design and test conditions. So, again, many of the questions that have been asked, hopefully those questions are covered in Section 4 of the topical.

Section 5 then provides overview of the AGR program itself, including four fuel irradiation campaigns around which this overall program is structured, keeping in mind that the Topical Report itself is focused on AGR-1 and 2, which is Section 6, irradiation response of fuel particles in the AGR-1 and AGR-2 campaigns.

Section 7 provides a summary of safety test performance in post-irradiation examination data for AGR-1 and AGR-2 that were available at the time of the report. All of AGR-1 and most of AGR-2, I believe, were available at that time.

And then Section 8 summarizes the report, including most importantly the conclusions drawn from the work and what we are asking of the NRC to review and approve.

MR. CORRADINI: So, Andrew, this is

Corradini. You actually made a point about Section 4. But if I read the report properly, the summary of the performance parameters that have to be checked so that somebody can say that I followed the recipe is Table 5-5. Is that not correct?

MR. SOWDER: Table 5-5, I believe that's the intention is to basically summarize the parameter, the key parameter envelope.

MR. CORRADINI: So from the standpoint of a licensee with their particular reactor design using TRISO fuel with this kernel, they have to show that their manufacturing technique can be within those specifications?

MR. SOWDER: Actually, this came up early in -- this is also an important that, again, I want to leave it perhaps even to some of the developers to respond to. But the intent here was not to develop a manufacturing spec.

MR. CORRADINI: No. I didn't mean it to be a manufacturing spec. I was trying to get at you're showing the UCO kernel, which shows superior characteristics of performance based on testing and then --

MR. SOWDER: In the envelope.

(Simultaneous speaking)

MR. CORRADINI: -- if you meet these ranges, you ought to get this same sort of performance.

MR. SOWDER: Correct. That's the envelope for which, you know, specifically, on the report the conclusions apply to that envelope described in Table 5-5.

MEMBER REMPE: When I try and understand points that are important from this report, one thing that I thought was important was you were trying to show that a manufacturing scale capability, the particles obtained from that manufacturing scale capability were similar to the performance of particles from a lab scale capability. Is that true, Andrew?

MR. SOWDER: Yes. Because -- okay. Yes, because AGR-2 represented a scale-up of, I believe, the particle production in terms of the process from kind of a bench scale to what I think they would call an engineering scale.

The other important aspect is the fact that because there is obviously variance in these particle properties, that these are not single point parameters.

They do, in fact, inherently reflect a range of particles -- a normal range -- well I shouldn't say normal -- but a range of particle capabilities and of properties that should, again, if you produce something within that range, it should display equal performance.

But from the standpoint of the manufacturing, there was scale-up for AGR-2 versus AGR-1. And that is a point that's made within the report.

MEMBER REMPE: Okay. So if that's true, then as I look through this report, it looked like AGR did a longer test. They had more instrumentation or whatever. But you were also trying to say you did the scale-up, but the performance of the particles was still good with the engineering scale capability and it matched what occurred with AGR-1.

So it's important that you have confidence that the similarities of the irradiation campaign was much shorter for AGR-2 were similar and you can apply some of the data from AGR-1 that you don't have from AGR-2. So you need to have confidence that the conditions were similar for AGR-2 as they were for AGR-1. Is that a true statement?

MR. SOWDER: Yes, I believe that is a true characterization, a true statement.

MEMBER REMPE: Thank you.

MR. SOWDER: I'm on Slide 12 here. I do highlight because it's useful the way this is structured that Sections 5 through 8 essentially these are really the sections that we were asking the NRC to review and make their conclusions and approval based on.

Again, it's important to recognize that the earlier sections with respect to the history, we were not including the past performance as part of the actual conclusions associated with performance of the TRISO fuel. We are speaking specifically to those TRISO fuel particles that were generated and tested under the AGR program.

The last slide here, I'm on Slide 13, basically, you know, references an additional appendices provided that expand upon sections that are already in the report.

The intent of the report was to try to keep the main body as concise as possible but also allow for providing additional information in appendices.

So Slide 14, the bottom line, I'm coming to the conclusions. So obviously we submitted the Topical Report. We have to then have -- we have to be very clear as to what we are asking the NRC to review and provide approval of.

I'm not going to read the whole slide. But basically coming back to, I think, Joy's earlier statement, we are stating that based on the performance demonstrated in AGR-1 and AGR-2 that this testing and the results and analysis should provide a foundational basis for using the particle design in fuel elements of TRISO fuel high temperature reactor design including pebble/prismatic fuel forms and helium and salt coolants.

Now going back to what I think Jose and others made a good point on is that doesn't mean the results stand on their own but that this provides the first foundational basis for subsequent interactions, engagements, studies of possible additional Topical Reports that each developer will have to decide on their path forward.

Moving on to Slide 15 is Conclusion 2. Again, I'm not going to read it. I'm really focused on the last sentence there, the operative sentence, which is UCO TRISO-coated fuel particles that satisfy the parameter envelope in Table 5-5, again going back to Mike Corradini, I think what you were pointing out, can be relied on to provide satisfactory performance.

Again, clearly, we were limiting the statement here to what parameters were actually covered in the testing and then it's up to each applicant and developer to then apply and demonstrate that their fuel palette relates to that parameter envelope.

MEMBER REMPE: So here's where I had a question because it relates to the foundational basis. But this last sentence, it sounds like this is all on need. And if that were true, why do you have AGR-5, 6 and 7?

There's a lot of statements in the EPRI Report that talk about you're still doing a PIE even for AGR-2. You've got these other tests that are going to be produced. And if you add a modifier in front of this and saying with the additional data coming, it appears the particles -- if they satisfy this parameter envelope, you can rely on them to provide satisfactory performance.

But I have problems. This sentence is just kind of over the line when you still have a program to evaluate these particles in my opinion. And I was a little surprised the staff even seemed to buy off on this one.

MR. SOWDER: Well, I will make a kind of clarification or an interpretation and then I think Paul in his -- because, you know, I think certainly all of these conclusions were thoroughly reviewed by the NRC and were addressed in a number of RAIs. I will say the focus here is on satisfactory fuel performance as measured by fission product retention, et cetera.

I believe the other AGR programs are looking at other aspects of fuel irradiation. But the focus here was exclusively on performance. I think it will come down to the interpretation of that word fuel performance and what is encompassed in that.

And you are correct. We do not intend to say that this covers every single thing. What we say is this provides kind of the building blocks upon which additional results testing as well as analyses conducted by the applicants, for example, can provide the basis for fuel qualification and design certifications and licenses.

That's why I feel comfortable saying. I think, Paul, if you want to say something now or maybe we can wait until you cover additional work. I would rely on -- because again, these were carefully considered and your point is well taken. So words matter, and we want to make sure these words are correct. But we felt strongly that we could stand behind it based on AGR-1 and AGR-2 scope.

MR. DEMKOWICZ: Yes. This is Paul. And I know and I apologize. I'm having some connection issues. I spoke up a little bit ago, and I think I was already disconnected.

Yes, the issue with subsequent

irradiations like AGR-5, 6, 7 is that those are really a qualification of the full fuel form at the engineering scale fabrication. So our defect specs for this fuel form is only applicable at the compact level, which is why we didn't bring those into this report.

What this report essentially says is that these particle designs, under these irradiations conditions perform as demonstrated in AGR-1 and AGR-2. AGR-5, 6, 7 would be an experiment that is going on to demonstrate that you can scale-up the entire fabrication, the fuel compact fabrication and that you are not having a problem with your defect specifications and that you are not introducing any attributes into the particles that are going cause poor performance in-pile.

MEMBER REMPE: So I thought AGR-2 was at engineering scale. B&W did a 6 inch scale, whatever, device. And what's the difference in what's being done in 5, 6, 7 versus AGR-2?

MR. DEMKOWICZ: AGR-2 was engineering scale particles in the 6 inch coater with compacts made still at the lab scale at Oakridge. So it was an intermediate step in the phased approach to going through a full pilot scale fabrication.

AGR-5, 6, 7 had compacts that were made

also at BWXT.

MEMBER REMPE: So what if you find out there's a problem with the -- oh, so you're basically saying the compact is now going to be at engineering scale, but you don't think there will be any differences in the way the particles are done?

MR. DEMKOWICZ: I'm not sure what you mean by done. But fabricated essentially in the same way the particles are. It's the same coaters. It's the same process for the particles. The argument is that, again, under these conditions those particles are going to perform as demonstrated in AGR-1 and 2.

MEMBER REMPE: And the PIE for AGR-2 that was still underway when this report was written, does that affect any of the conclusions in this report?

MR. SOWDER: It does not. We stated when it was submitted that we didn't see -- enough of the PIE was completed that the picture was fairly complete. But we couldn't say that it was all complete. Of course, we are more complete now and that still hasn't changed so.

MEMBER REMPE: Okay. Because I thought there was even one slide where they were talking about in this report about an updated version of this Topical Report. And so I just kind of thought it was kind of stepping over the line.

But you're very confident is your response to me, and EPRI's response to me, that this is an update that you feel comfortable with that if somebody can get it within these parameter envelopes that are shown in Table 5-5, you're good to go.

MR. DEMKOWICZ: Again, it's a demonstration of the particle performance. If your fuel compact or your fuel pebble fabrication process is introducing defects into the fuel, that's another matter. And that's what we are qualifying in AGR-5, 6, 7 and that any manufacturer would have to qualify for how they are making the fuel.

MEMBER REMPE: Thank you.

MR. CORRADINI: So, I'm sorry. Excuse me, Joy. So this Corradini. Paul, so 5, 6 and 7 are benefitting a particular geometrical matrix that you had expected would come to the fore. But other geometrical matrices with different matrix material would still have to go through a similar sort of testing. Am I understanding this correctly?

MR. DEMKOWICZ: Essentially. I mean, again, I'm not the regulator. I'm not the one who is going to say that would have to be qualified separately. But, you know, all we can say is what we're doing in the program so.

MR. CORRADINI: Okay. That's fine. That's fine. So let me ask the question in a reverse manner.

What does the 5, 6, and 7, what design or type of fuel geometry does 5, 6 and 7 benefit? A prismatic, I assume?

MR. DEMKOWICZ: Right. That was the baseline design going into the program. So it was mainly focused on prismatic design.

MR. CORRADINI: Okay. Thank you. And then last thing, where did AGR-3 go? I have forgotten what -- I used to remember all these things, but I can't remember. What is AGR-3 and how does it fit in?

MR. DEMKOWICZ: So if it's okay with you if we waited until --

MR. CORRADINI: That's fine. If you're going to cover it, then I'll be quiet.

MR. DEMKOWICZ: Yes, yes.

MR. SOWDER: Thank you, Paul. I'm going to go on to Slide 16. And, again, Paul is going to cover the AGR Program and then he will also be addressing, I think, some more in-depth requests for information that hopefully will shed some more light on questions that have been raised so far.

So the last conclusion is that the overall combined experience with AGR-1 and AGR-2 fission product release data and fuel failure fractions that were presented and described in the Topical Report do support licensing of reactors employing UCO types of coated fuel as long, again, as the irradiations occur within that parameter defined by Table 5-5.

Again, this is not saying, you know, this is totally sufficient in and of itself because, again, we're just speaking exclusively about the particle performance itself and not the actual fuel form, compact, what have you, which needs to be further evaluated.

And so Slide 17, and this is in essence what we ask the NRC to do, basically, consider Sections 1 through 4 as a historical background and overall context of the report.

We ask for a review of 5 through 7 as the actual AGR program content and core scope. And then we ask for approval of the conclusions in Section 8 with issuance of a Safety Evaluation Report.

Slide 18, just to close, the project to date, again, this just highlights the amount of engagement. We've had positive engagement with the NRC. The Topical Report was published publicly and simultaneously transmitted to the NRC on May 31.

And you can see we went through a number of engagements, an in-person audit at INL, giving the staff a chance to actually ask questions face-to-face of the actual technical experts first person, the RAI process and here we are today, May 6, with the Subcommittee meeting.

The hope here is, and I think a positive example this sets and precedents it sets, is actually close to a one year turnaround on a Topical Report for an advance reactor fuel qualification subject.

So, again, it assumes that we continue on this path. But we have been very pleased with the response from the NRC, the engagement as well as the proactive and positive and beneficial comments and questions.

And with that, I believe that's it. That is my presentation. Again, thank you for the questions and listening and your patience. Paul will follow I believe and/or the NRC. Paul Demkowicz and I will now be able to answer more detailed technical questions.

CHAIR BALLINGER: Thank you. This is Ron Ballinger, again. The staff will have to correct me if I'm wrong, but I think since this is a public meeting, we're scheduled for a break at 10:30 on the agenda.

And are we required to adhere to that?

MR. BROWN: Ron, you can actually run the meeting as you choose to.

CHAIR BALLINGER: Okay. Okay. So we're not bound by that.

MEMBER BLEY: But it would be wise.

CHAIR BALLINGER: That's right. That's right. Okay, Dennis. So, Paul, is up next. It's a convenient break point.

So I'm going to say that we should recess until 35 after, which means also 25 until 10. So we'll see you at, well, see in parenthesis, everybody at 25 until.

(Whereupon, the above-entitled matter went off the record at 10:29 a.m. and resumed at 10:35 a.m.)

CHAIR BALLINGER: Its 35 minutes after the hour. So absent some glitch or anything, Paul, you're on.

MR. DEMKOWICZ: Okay. Thank you. And good morning, everybody. Thanks for this opportunity.

So this presentation is going to give a very brief overview of the AGR program and then talk about the AGR-1 and AGR-2 results in summary form. All of this information is covered in much more detail in the topical report.

So we're on slide number 2. The overall high level objectives and motivation for the program has been to provide data for fuel qualification to support reactor licensing and to establish a domestic commercial vendor for TRISO fuel. And both of these put together are intended to reduce market entry risk for fuel vendors.

Our approach, of course, is to pursue the development of UCO TRISO fuel. That has a pretty long history in the U.S. And we do have five different program elements of fuel fabrication, irradiation testing, and advanced test reactor under a range of conditions, post-irradiation examination and safety testing, fuel performance modeling, and some experiments that look at fission product transport behavior. Next slide please.

MEMBER REMPE: Paul, before you leave this slide, I wanted to make a comment and then ask a question. And I, the comment, I -- and this is actually for EPRI and the staff more than you, obviously.

But I really like Table 4-2 in your, this report that compared the differences in gas reactor fuel that was produced by various sources. And I think that this will be very important for other types of technologies, like the sodium reactor fuel that may be coming to the staff. And I hope that other working groups do a similar type of thing.

And then I had a nit. And I don't know where to ask this. But I was curious about it enough that on page 58 out of 192 of the EPRI report, it refers to some information that's supposed to be in a Section 4.2. And I think that's a typo.

But if somebody, and it doesn't have to be today, could find out where that information is, because I don't think it's in Section 4-2, and send a note to Chris Brown and let him pass it to us, I sure would appreciate it.

MR. DEMKOWICZ: Okay. Yeah. Thanks for the comment. I hesitate to try to pull that up right now for fear of losing connection again.

MEMBER REMPE: Not important enough to waste time on, but I just was curious. I think it's a typo.

MR. DEMKOWICZ: Yeah. Okay.

CHAIR BALLINGER: Copy that.

MR. DEMKOWICZ: Okay. Slide number 3. So this is a timeline and an effective overview of the programs based around four irradiation experiments.

The first, AGR-1, was an early test of lab-scale UCO fuel. The kernels were always made at

BWXT for all of these. But the particles for AGR-1 and the compacts were made at Oak Ridge National Lab. It was also a shakedown of our test train design.

AGR-2 was engineering-scale particles, as we've discussed already, and lab-scale compacts. It also included UO2 fuel as well.

AGR-3/4, Dr. Corradini, this goes to your question, so for the combination of two experiments that were originally planned for smaller locations and APR. And it was all about fission product transport.

So we had DTF for designed-to-fail particles that would release fission products during the irradiation. And the intent of the PIE was to assess how those migrated through reactor graphite and fuel matrix material.

AGR-5/6 --

DR. CORRADINI: So Paul, I'm sorry. This is Corradini. But it was, again, a compact.

MR. DEMKOWICZ: Yes, that's correct.

DR. CORRADINI: Okay. Thank you.

MR. DEMKOWICZ: AGR --

CHAIR BALLINGER: This is Ron again. Just so for the record, nothing that you've seen so far in the PIE of AGR-3 and 4 has a negative impact on the results from AGR-1 and 2?

MR. DEMKOWICZ: That is correct.

CHAIR BALLINGER: Thank you.

MR. DEMKOWICZ: AGR-5/6/7 is the fuel qualification test, again, engineering-scale everything, UCO particles, and engineering-scale compacts, all fabricated at BWXT.

That experiment is nearing completion. You can see in the blue on the timeline. And we are nearing the end of the AGR-2 and 3/4 PIE. And we'll be starting 5/6/7 next year. Next slide, please.

And again, this table lays out the progression of fuel fabrication for AGR-1 and AGR-2 and 5/6/7, transitioning from lab-scale fabrication to complete engineering-scale.

Just a couple of bullets on the AGR overall fuel fabrication campaign. The program essentially reestablished this capability after about a decade and a half hiatus in the U.S. from the late '80s, the early '90s and has made some significant improvements to the fuel fabrication processes and the quality control measurement techniques.

We've talked a little bit already in the meeting about how different particle designs were used not only in different fabrication scales, but different designs. AGR-1 was a 350-micron diameter kernel with

19.7 percent enrichment. And there were a couple of coating variants that were explored to see what the effect was on performance. And AGR-2 was a 425 nominal diameter kernel with 14 percent enrichment. And --

MEMBER REMPE: Why was the lower enrichment used in AGR-2? What was the reason? And in fact, why did they go through the larger diameter kernel? Were there some insights from AGR-1, or what was the reason?

MR. DEMKOWICZ: That was more being driven by reactor design considerations. The AGR-1 particle, it was the fissile particle of an earlier two-particle system from GA that was a fissile-fertile particle. So you'd have -- this would be your fissile particle, and then you would have fertile particles as well.

And it was chosen at the time, early 2000s, as the starting point. But in subsequent design efforts, it led to looking at a larger kernel with smaller enrichments.

We talk a little bit about that, especially in answering some of your RAIs as to this relationship between kernel diameter and enrichment and burnup. So as you go through a larger kernel, you're going to be more limited on your peak burnups.

DR. CORRADINI: Why, Paul?

MR. DEMKOWICZ: I'm sorry. I didn't catch that.

DR. CORRADINI: This is Corradini. Could you just finish the why about that? You said limited, why?

MR. DEMKOWICZ: Oh, yeah, if we want, we can get into it in the RAI discussion, because it was brought up there. But it's -- what you're looking at is, you know, as you have a larger kernel diameter, you are going to have more fission products, more fission gas produced. And so you are producing more gas in the plenum and the buffer layer, which is, again, it adds stress to the SiC layer.

And so generally speaking, you don't increase the kernel diameter and still go for these very high burnups because you're going to get a very high gas pressure in the particle that can stress the SiC layer.

DR. CORRADINI: So it's a mechanical stress limitation?

MR. DEMKOWICZ: Yeah. If you look at the German particle design, it's a 500-micron diameter UO2 kernel. And their peak burnups are a little over 10 percent. So --

DR. CORRADINI: 10 percent of all the

uranium, or 10 percent of the enriched uranium. That's what I didn't understand also.

MR. DEMKOWICZ: Oh, 10 percent xenon, so it's ten percent of the initial metal.

DR. CORRADINI: Thank you.

MR. DEMKOWICZ: Yeah. Okay. Next slide, slide 5. So now talking about the irradiation tests, both AGR-1 and AGR-2 were performed in the large B positions on opposite sides of the quarter in the advanced test reactor. They both have very similar designs. There were six capsules in each. Each capsule had 12 fuel compacts.

So for AGR-1, there was about 300,000 particles. Again, these are smaller particles, so there was more per compact. AGR-2 was about 114,000 UCO particles and 3 US capsules.

We irradiate for approximately two years of effective full power days. And that simulates a three-year reactor lifetime. So it's a slightly accelerated irradiation as we say.

The temperature is controlled in each capsule independently and with the helium/neon gas mixture. And that gas mixture also sweeps the fission gases that are released from each capsule through detector systems. And that's how we assess the health of the fuel during the irradiation.

The plot on the right is just showing the four key irradiation condition metrics: burnup temperature, power density, and fast fluence. And we've plotted AGR-2 capsule 2 separately. That's in green. And the reason is it was intentionally operated at a much higher temperature. It was a temperature margin test. And so you can see that it was time-averaged peak temperatures of about 1360.

MEMBER REMPE: So Paul, how did you get any sort of indication above 1100 C in AGR-2 since you only had Type N thermocouples?

MR. DEMKOWICZ: Right. So we never measure the actual temperature of the fuel. As you know, we are measuring temperatures out in the graphite holder at various locations. And those are going to be at lower temperatures than the fuel.

MEMBER REMPE: Yeah. But if I look at some of the plots in the actual EPRI report, it shows temperatures that are higher than 1100 C. And I know you only had Type N thermocouples, which actually the EPRI report doesn't even distinguish that you had different types of thermocouples in AGR-1 than you did in AGR-2.

But in AGR-2, I believe your intent was

to run it above 1200 C. And again, there was no indications above -- in fact, you had even lost all your instrumentation toward the end of AGR-2 as I look at it. And so I'm real puzzled on that.

And I know in the past we used from ATR from my years of INL, they say, well we kind of know because of our experience with the reactor, and we do analyses that -- they did see a lot of swelling and things like that in AGR-1 that assessed the gap. And that affects your ability to predict temperatures. So I'm real puzzled about some of these temperature indicators in the EPRI report.

MR. DEMKOWICZ: All right. So for both AGR-1 and AGR-2, we did a fairly extensive temperature uncertainty analysis. And there are I know reports that go into that.

And in both cases, the approach was to look at all of the factors, including the graphite dimensional change that you mentioned, all of the factors that go into the fuel temperature. So these are things like the heat generation rate in the fuel, the gap size because of dimensional change in the graphite.

And it looks at all of those. And it establishes uncertainty in those input parameters.

It looks at a sensitivity coefficient for each one of those to see which one is the, has the biggest effect on fuel temperatures. And so we, as a result of that, have published the uncertainties on the temperatures based on all the analyses.

And the short answer is that one sigma, it's around 50 degrees C. At two sigma, it's in the neighborhood of 100 degrees C for both AGR-1 and 2, slightly higher for AGR-1. And so we know that we have an uncertainty in temperature --

MEMBER REMPE: I'd say I think it's a little underestimated, especially when I look -- I mean I know you've said that you've tuned each of these capsules individually. And sometimes you start off at the beginning where, even with the tuning, you're off by sometimes I thought it was 100 degrees. I don't have the report up in front of me right now with that page. So I'm a little bit suspicious of that. And I'm interested in how well the staff investigated that.

Plus, it looks like in AGR-2 you started off with one capsule or one position. And then because of the palm cycle, when you took it out and you put it in an I position, which means the flux is going to be a lot different and the fluence. And well I know you had flux wires in it for AGR-2.

I'm real -- I think the uncertainties are a little underestimated from what I saw. In fact, I thought the report was saying 100 degrees. It said that you only had like 30 or 40 degrees uncertainty.

So when you try and justify the behavior of the engineering-scale manufactured particles being similar based on the similar irradiation conditions for AGR-2 to AGR-1, I'm not sure that the uncertainties were properly considered. And I'm interested in how carefully the staff delved into that question. And did they review all of these supplemental INL reports in the RAI? Paul, I think we've lost you.

MR. DEMKOWICZ: No, I'm here. I was waiting to see if the staff was going to answer any of those questions.

Yeah, interesting comment. Again, they are, the uncertainty analysis was outlined, you know, fairly thoroughly. And those were forwarded. So I don't know what the review process, if it included those in detail or not.

MR. SOWDER: And was there any -- in the audit as well, right, we had the trace audit.

MR. DEMKOWICZ: Right.

MEMBER REMPE: Is that from the staff, or is that from someone from industry or EPRI or some --

MR. SOWDER: I'm sorry. This is Andy Sowder, EPRI.

MR. TRAVIS: Dr. Rempe, this is Boyce Travis from the staff. We'll discuss a little of this. It's not part of the presentation. So I'll be happy to address some of the questions during the staff's presentation.

MEMBER REMPE: Yeah, I really am curious, because I want to make sure the staff did understand that, for example, the temperature sensors differed between the two tests, because that EPRI report was silent on that.

CHAIR BALLINGER: Okay. This is Ron Ballinger. I need to remind folks that we do have a hard stop at noon. And we are, shall we say, running a bit behind.

MR. DEMKOWICZ: Okay. I will continue. Slide 6 please. So this just summarizes the approach for getting fission gas release from the experiments.

Each capsule, again, has its own detector system. The top plot is an example from AGR-1 capsule 6 of the fission gas release of several different isotopes of krypton and xenon. You can see at the end of the irradiation the top had about 10 to the minus seven.

The plot on the left is the historic comparison between the AGR results and the historic U.S. and the historic German results. I'll go ahead and move on. Just the main point is that the R/Bs for the U.S. on AGR-1 and AGR-2 are similar to what the Germans had accomplished at roughly twice the burnup with the UCO fuel.

In post-irradiation examination and accident safety testing, our main objectives are to measure the fission product release during irradiation. In other words, we are looking at the capsules to assess what the release was during the irradiation.

It's to measure fission product release during high temperature post-irradiation heating and also to examine the fuel, in particular, the kernel and coating microstructures so that we understand what the irradiation and the exchanges are that can impact fuel performance.

And we use both conventional and specialized equipment for TRISO fuel exams. As you can imagine, some of the tools are very conventional that you would use on any sort of PIE, and some are very specialized because of the nature of TRISO fuel.

Okay. Next slide. So I have a few slides that give a summary of the results. I just try to hit on some of the key points. In terms of the fission product release from the AGR-1 and AGR-2 fuel compacts, this is a plot that summarizes that for cesium, strontium, europium, and silver.

In terms of cesium, the release from the compacts is very low when all of the particles retain intact SiC layers. And so at the lower end of that range, you can see down around 10 to the minus seven. And those were all capsules where there were no SiC failures.

And then at the upper end is where you have capsules where you had a small number of SiC failures. And so you can get up to around 10 to the minus four.

For strontium and europium, the behavior is generally similar. And you get a modest release a little bit through intact silicon carbide, which is why those levels are a little bit higher.

And I separated out AGR-2 capsule 2, which was the higher temperature irradiation, just to show that in-pile you get a significantly higher strontium in your OP release when you have higher in-pile temperatures.

And then, of course, silver release is fairly high for TRISO fuel, which is consistent with historic observations. Next slide.

DR. CORRADINI: Paul, this is Corradini. So --

MR. DEMKOWICZ: Yep.

DR. CORRADINI: So when you do AGR-3 and 4 analysis, you drove at the failure, and you would then use that to determine the source term under severe accident conditions? I'm trying to understand the relationship between this data of 2 and what you're doing in 3 and 4.

MR. DEMKOWICZ: Yeah, the data that I'm showing here from AGR-1 and 2, this is essentially the release that you would expect from good fuel. AGR-3/4, and it wasn't even so much a derivative failure as it was designed to fail. That's what the DTF is. It was coatings that were just designed to fail very quickly in the reactor.

DR. CORRADINI: Oh, so you manufactured them in a failed state so to speak.

MR. DEMKOWICZ: Yeah, essentially. They were intact, you know, during fabrication, but they failed in-pile. And it was 1 percent of the particles were like that. So you, you know, essentially had 1 percent exposed kernels, and so much higher releases of these fission products, and an experiment design that was much more tailored to doing those kinds of measurements --

DR. CORRADINI: Okay --

MR. DEMKOWICZ: -- 1 and 2, they were designed just to get as much fuel into the reactor as you can. Whereas AGR-3/4 was a whole different objective.

DR. CORRADINI: Okay. Thank you.

CHAIR BALLINGER: This is Ron Ballinger, again. Back to slide 8 I guess, the silver release, we have to be a little bit mindful I think, unless things have changed, that we're pretty well understanding how the cesium, strontium, and europium and other fission products get released.

But silver is kind of still the wildcard in this, right, in that in some cases you get no release. In some cases you get release for nominally the same fabrication conditions. And that's the one isotope that's the least understood. Am I still -- is that still correct?

MR. DEMKOWICZ: I guess I would take exception with the comment that it -- I guess what you said kind of implies that it's random, that, you know, some fuel does release and some doesn't. We've seen, you know, a reasonable correlation of higher temperatures with higher silver release.

And that was one, you know, thing that we were in a decent position to examine with AGR-1 is we had two different kinds of silicon carbide that we fabricated. And during irradiation and during heating up to as high as 1700 degrees C, we didn't see any difference in the silver release from our silicon carbide variance.

But if you get to 1800, which I'll, I can talk about on our next slide, if you get to 1800 after 100 hours, we do start to see a difference. So in other words, you have to really drive it fairly hard to start to see these nuances in the SiC performance as far as silver. But understand it can't -- it's something that the international community is still working on.

CHAIR BALLINGER: Thanks. Just, yep.

MEMBER REMPE: Paul, before you start on the next slide, there's a nomenclature that never was even defined in the report. You have like a bunch of lines. And you'll have like X, Y, and Z that are numbers. And I guess that X is the capsule number, but I'm puzzled about Y and Z. Which one is the location in the out contact, and which one is the stack number? Okay. And this was on slide number 9.

MR. DEMKOWICZ: Yes, let's go ahead and go to slide number 9. That's correct. The X, Y, Z is the capsule/level/stack. So it's the -- first is the capsule number. The next is the vertical level in the capsule. And the third is the stack. So it's a locator identification.

(Off mic comments.)

MR. DEMKOWICZ: Okay. So --

MEMBER REMPE: Someone else said something that I couldn't hear.

MR. DEMKOWICZ: Yeah, I didn't understand that either. So let's just talk real quickly about the safety test results. This is one of the figures from the report. It just summarizes the results for cesium, silver, europium, and strontium for the AGR-1 tests. Just a few points, I've tried to highlight the key items here.

So cesium release fraction is very dependent on whether or not you have a SiC layer failure. If you don't, the other release is extremely low. If you do, it's a bit higher, about 10 to the minus four at 1600 and about 10 to the minus three at 1800 after 300 hours.

And that's determined through extensive PIE of all those compacts that were tested. They were deconsolidated where we could actually find individual particles with failed layers.

For europium and strontium release, the only thing I'll point out is that it clearly, if you look at the plots, it is increasing as a function of temperature. Again, the temperature is color-coded there. Blue is 1600. Green is 1700. And red is 1800.

The cesium release is high again, as we have seen already. And it is dominated in these tests by silver that was already released from particles during the irradiation but was stored in the matrix. This is the reason why we don't see much of a correlation with temperature on our release.

And then krypton, which I don't show here because most of our tests, it had no measurable krypton, at least in a lot of them. It's related to the level of the TRISO failures, which we just didn't observe very frequently. There was, it was observed in two of our 1800 degree C tests.

MEMBER REMPE: So Paul, when you do these TD tests after the irradiation, have you ever included an unirradiated contact with the particles, because I'm just curious how much it degrades because of the actual irradiation?

MR. DEMKOWICZ: We have not.

MEMBER REMPE: It would be interesting to see. If it's not much different, it would be an interesting point that might be useful.

MR. DEMKOWICZ: Yeah, the compacts do see pretty significant temperature during fabrication above 1800 degrees C. But it's not for these sorts of durations.

So okay. Next slide. I think we're almost done. So this has got some animation. So go ahead and give me one click.

So one of the big successes of the program was developing an ability to essentially find one particle out of 100,000 or so that had a failure so we could study it and understand what's going on. This is something that was not really available in the PIE campaigns of some days of yore.

And as an example, if we take AGR-1, there were 72 fuel compacts and six capsules, about 300,000 particles. And if you could give me a click.

We start by identifying which compacts are suspected of having particles that are leakers, so compromised coatings. And we do that by looking at a gamma scan of the empty graphite holders so we can identify which compact is the suspect. Next.

Then we send those off to the lab for a destructive examination. We deconsolidate those, get all the particles out, which is anywhere from 1,500 to 4,000. And gamma count all of the particles using the MGA machine at Oak Ridge that can count all the particles and sort them based on the inventory.

And then we can take that particle and do all sorts of detailed microscopic exams, including non-destructive exam of the particles, which is at the top there, by x-ray, find the exact location on the particle that has a -- or where the SiC layer is comprised, and then go in and do a very detailed study of that area with SEM and TEM, et cetera.

So it has really improved our ability to understand coating failure. And this is something that you just didn't see in the past. It's the reason why we didn't have as good of an understanding of some of these more -- or some of this minutiae when it comes to how coating layers are failing. Next.

Using these techniques, we were able to look at both failure of the SiC layer alone. So this is the failure of the SiC layer where the outer part of that carbon is still intact. So it would not release fission gas during the experiment. So you wouldn't know about it online during irradiation, but you'd find it in the PIE, and TRISO failure, which is where you lose all the layers when you release the gas.

And the plot shows the upper limit on our failure fractions at 95 percent confidence, which we calculate using binomial statistics. So you take the number of observed failures and the number of particles in your sample population, and then you can calculate this upper limit.

The blue is the SiC failures. The red is the TRISO failures. So historically, reactor design specs only included numbers for TRISO failures. And part of this is that quantifying SiC failures would be very difficult in the past.

And so the plot just shows the margin between our 95 percent confidence values for TRISO failure during irradiation and during accidents at 1600 compared to the historic reactor design specs. It's about a --

DR. CORRADINI: Paul.

MR. DEMKOWICZ: Yeah.

DR. CORRADINI: Paul, so I -- this is Corradini. I think I don't appreciate the red dashed line. This is the prior design and their performance specs.

MR. DEMKOWICZ: That's correct.

DR. CORRADINI: This is not what would be in advanced reactor design currently. They would be lower. Am I understanding this correctly?

MR. DEMKOWICZ: That all just comes out of reactor design and safety analysis, you know. So for, back in the late '80s, early '90s, the MHTGR -- and this was the same, by the way, for the German HTR-module design, the Siemens design. It was both about the same. It was about 210 to the minus 4 in-pile failure during normal operation. And 610 to the minus 4 during accidents.

DR. CORRADINI: Okay. But again --

MR. DEMKOWICZ: That's really based on your reactor design and your design specs. I don't anticipate them being lower for any of the current designs.

DR. CORRADINI: Thank you.

MR. DEMKOWICZ: Yep. Okay. Next slide. I think we're just about done. Yep.

So the key points, just to summarize, the AGR-1 and 2 fuel met the key fuel product specs. Both irradiations are completed.

The end of life R/B for AGR-1 was acceptably low. For AGR-2, we had good results at the beginning of life. But as detailed in the report, we lost our ability to measure the R/B unfortunately toward the end of the irradiation. So we're looking at the PIE to help us quantify the number of failures that could have occurred in-pile.

We have safety testing data at temperatures between 1600 and 1800 with very good performance. And we have quantified both SiC and TRISO failure fractions. And those are below the previously established design specs for allowable failures.

I believe that's it. Yep.

MEMBER REMPE: So you're not going to go through any of the rest of your slides you've got, right, Paul?

MR. DEMKOWICZ: I think in the interest of time, yeah, the idea was to have those to address any specific questions. But I wasn't going to go through them unless you wanted to.

MEMBER REMPE: Well, it's not really, maybe you could use one of them to answer the question. But it's associated with Table 5-5 and the QA.

You have a range for these particles. And you don't go through and measure every particle. And there's a lot of confidence limits applied. And if you, you know, you constantly in these reports, you're saying if you meet what's in --

(Telephonic interference.)

MEMBER REMPE: --- are good. But you don't measure everything.

And so I guess what I'm interested in is when a vendor makes fuel, there's a lot of fuel that just is rejected off this in the fabrication process because they just know something's not going to be to spec because they don't even include it in their fabrication products.

So when you do the QA for these particles, how many of them are rejected? Would the process be that you go through and like B&W would manufacture it, and there's going to be a bunch of rejects that don't even make it to the final product? And then they're going to do some spot checking on the final product to meet Table 5-5, or how would the values in Table 5-5 work?

And then the other question I had was: was the reject fraction that B&W had for the engineering-scale fabrication capability similar to the reject fraction that Oak Ridge had with their lab-scale fabrication process?

MR. DEMKOWICZ: Yeah, okay. So application of Table 5-5, we did talk about that in some detail in the response to the RAI. It's not in this presentation.

But yeah, the QC methods are basically how you would approach when you have extremely large populations, and you are doing statistical sampling to verify that your population means and your population critical in this are acceptable, right.

So we -- all of our specifications for those properties in Table 5-5, there are specs on the means. And the requirement is that you demonstrate that the mean is within that range at 95 percent confidence.

And there are critical limits that I will specify is basically the outer 1 percent fails of the distribution on the critical side. So some properties have two critical sides, and some only have one.

You know, so all of our sampling is intended not to measure every particle, which is obviously infeasible. It's to demonstrate those specs at those statistical limits. And so all of the methods, the statistical methods, that's what they are geared at.

And so the Table 5-5 values, we attempted to show that. You know, so the ranges are the ranges of the 95 percent confidence levels for the mean. The tolerance limits are the ranges of these 1 percent fails for these populations. Does that answer your question?

MEMBER REMPE: So are they allowed to throw out some things before they do the measurements and see if their statistical sampling meets these requirements --

MR. DEMKOWICZ: So --

MEMBER REMPE: -- don't roll down a table showing they're spherical when they throw out the rejects? Are they allowed to just test what they find to be the good ones?

MR. DEMKOWICZ: Well no, you wouldn't do that. I mean you want to test the population that's going to go into the reactor, of course.

There are some stages during fabrication where you can upgrade the fuel, you know. For example, particles get sieved at BWXT to rule out the extremely small or the extremely large particles. And so there are stages in the process of doing upgrading.

And this gets down to, you know, a fuel fabricator question. They obviously want to limit their amount of rejected material. And so you want to limit that as much as possible and have a process that is very precise and gives you narrow distribution.

But they will -- you know, so in that case, you are rejecting particles based on size if it's a sieving operation. And then you're doing your test on that population, which is what would go into the reactor.

MEMBER REMPE: So it would -- for example, if they can reject based on size because of sieving, then this thing about the kernel size or the thickness, are they allowed to also reject based on size after they apply the buffer and the coatings?

Are they allowed to do that? Because I'm just kind of wondering if you could just keep rejecting the ones that don't meet and then test your final distribution, and you could meet this table a little easier than if you had to take the sieve on all of the particles you produce? And so I'm just kind of wondering how you apply this table in the process and provide confidence.

MEMBER PETTI: So Joy?

MEMBER REMPE: Yeah.

MEMBER PETTI: The upgrading is usually done at two steps. But again, different fabricators could do it differently. It's done at the kernel stage, and it's done at the final coated particle stage.

Yields are generally above 90 percent at the steps in the process. So they're not throwing away a tremendous amount of material --

MEMBER REMPE: Is that documented in this report, Dave?

MEMBER PETTI: No.

MEMBER KIRCHNER: No, I don't think so. Joy, this is Walt. That's -- Dave has it right. That's typically what would be done. Once you get to the actual coatings, you don't stop after each coating, although you could. But I don't think that's --

PARTICIPANT: Well, they used to.

MEMBER KIRCHNER: They used to at some --

(Simultaneous speaking.)

MEMBER KIRCHNER: -- and then the final product.

MEMBER REMPE: So I can remember GA as well as Holtec in Germany rowing them down the incline table. And they would reject based on that.

(Simultaneous speaking.)

MEMBER REMPE: And there was a bunch of different places that different vendors can do it.

MEMBER KIRCHNER: NUKEM, you're referring to what NUKEM did. NUKEM made their kernels. And then they put them on a table and tested for sphericity.

MEMBER REMPE: Right. And GA --

(Simultaneous speaking.)

MEMBER KIRCHNER: -- dominant factor in getting uniform coatings. Then the next step was to do it as Dave indicated, once you had your final product, or as Paul was talking about, you sieve. That gets the gross mismatch, so to speak, of the spec out of the final product that goes into the reactor.

MEMBER REMPE: So my question, though, is, is all of this -- I mean if you keep adding more QA to it, it's going to be pretty easy to meet Table 5-5. And is it documented you only get two shots to upgrade? Or I mean I'm not sure how --

MEMBER PETTI: So Joy, just a couple things, just a couple things. We tried, the program tried to do a tabling and found that it really wasn't, they felt they were throwing away good material. And that's why they weren't, to this decision, sieving. It's also up-to-date technology if you will. It's done, used in many, many instances.

And second, what -- the question that I thought you were going to ask and the program specifically prohibits is what's called salting. That's where you have a batch that doesn't meet all the specs. But I had five batches that are good. And if I mix them all together, I still meet. That's --

MEMBER REMPE: Yeah, that's another way to game the system --

MEMBER PETTI: That's prohibited.

MEMBER REMPE: Is that --

MEMBER PETTI: That's prohibited. Again --

(Simultaneous speaking.)

MEMBER REMPE: -- in this EPRI report, Dave?

CHAIR BALLINGER: Folks, this is Ron. Again, this is all I'm sure a very fruitful discussion except for the fact that we are now penalizing people that will be presenting going forward because we're running out of time. So I would, again, remind people that we don't want to penalize subsequent presenters. So please be careful about the time.

MEMBER REMPE: I just, I understand your concern, although the staff only has 15 slides, Ron, if that's all that's left. And I just am curious on how this is enforced based on what the --

CHAIR BALLINGER: Joy --

MEMBER REMPE: -- document versus the staff document.

CHAIR BALLINGER: I'm sure we can manage to do -- we can manage to make 15 slides into effectively 50 if we want to.

MEMBER REMPE: You're right. I agree. Anyway I'd like to hear from --

(Simultaneous speaking.)

MEMBER PETTI: Joy, there would be a topical report on fabrication that we cover all of this. But because there's more than one fabricator, it's not generic. And that's why the whole thing was structured the way it was.

MEMBER REMPE: Well, okay, again, I'm looking at Conclusion 2 that said if you meet the requirements in Table 5-5 without any caveats, you've got confidence in the performance of the particles. And I just am kind of wondering about all this. But anyway --

MEMBER PETTI: Well if you can meet those, if you can make particles that fit inside that box, then you know that they will perform well. That's what that means.

MEMBER REMPE: But okay, we'll go forward with the staff. I just am curious if that's been covered with no review.

CHAIR BALLINGER: Doctor, we still have not discussed the RAIs. We have a lot of material to cover.

MR. SOWDER: Do you want us to give the RAI presentation, Dr. Ballinger?

CHAIR BALLINGER: Well I think we ought to at least run through it quickly because, you know, we have questions there, and there may be some. But we ought to really be mindful that -- let's see. We have to hard stop at noon. The NRC presentation is slated to be 11:15 to 11:50, which is otherwise known as now.

And so we need to be -- again, I think we should try to quickly skim through the RAIs and make sure that we don't ignore something which is very important, but be mindful that we really need to give the staff the presentation. I would say that we have a hard stop on the RAI presentations at 25 after.

MR. MOORE: Member Ballinger, this is Scott Moore. And Chris, please correct me if I'm wrong. As Chair, if you choose to go past noon, that's your prerogative. But you can't go past 1:00 obviously, because we've got a full committee meeting then. And you're also eating into any break time that any of the members have between then and 1:00. Chris, is that correct?

MR. BROWN: Absolutely, Scott.

MR. MOORE: So it's your prerogative.

CHAIR BALLINGER: Okay. I -- okay. Let's do it.

MR. DEMKOWICZ: Okay. This is Paul Demkowicz again. I will run through the RAIs. I think that we can be quick. Lest you panic, there are not 28 slides in this deck that we're going to talk about. Most of them, we've reviewed this and pushed them off to an extra slides section.

So just the overview, the NRC staff submitted four RAIs that had to do with the technical content of the report. We felt that these reflected the very careful reading of the report and a good grasp of the key issues that impacted the conclusions.

We have provided additional information and some technical discussions. And a lot of that information is going to be worked into a revision to the topical report.

RAI number 1, and I am paraphrasing these. They obviously were much longer. But especially are there important operating conditions for the fuel beyond burnup and temperature, which were called out explicitly in Conclusion number 1?

The answer is yes. And we are adding fast neutron fluence and power density to this list. And so we have calculated ranges for those for AGR-1 and 2 and added those in tabular and graphical form, which I will hit just very quickly on the next slide. And we changed some of the supporting discussion related to Conclusion 1. Next slide.

So this is the information that has been added. Again, tables and a plot, which we saw already, that show the ranges for burnup, fast fluence, temperature, and the power in the fuel.

The power in the plot is the compact power density. And in the table, we've also added, because different size particles and different packing fractions will result in different individual particle powers, we've included both here. Okay. Next.

So RAI number 2 is: are there important fuel properties that are in addition to what was listed in Table 5, which focused on coating properties? And some specific items that were mentioned were the ratio of the kernel-to-buffer volume, the SiC microstructure, the kernel stoichiometry for the UCO fuel, and whether or not an uninterrupted coating process was required. So I'll hit each one of those on a slide here.

We pointed out that the report did talk about kernel and buffer volume ratios in the context of this SiC stress metric sigma. It's a proportionality that showed the important factors that can affect stress in a silicon carbide layer.

And the important point is it's not just the ratio of the kernel and buffer volumes. You also have burnup and then some other particle geometry factors.

So what we did is we went ahead and calculated values for sigma for AGR-1 and 2. And we provided those in graphical and on tabular format just to show the ranges of values for sigma that essentially were irradiated in these two experiments. Next.

SiC microstructure, we discussed that the AGR-1 and 2 fuel specifications used a visual standard for silicon carbide microstructure. The idea was to avoid excessively large grains and unfavorable orientations, which means highly columnar grains that span the entire thickness of the SiC layer.

Those are known to be poor performers based on the historic database. And so this spec, the intent was to get folks, or to get the program in the right range of silicon carbide microstructure without overly specifying that for fuel fabricators. And that visual standard is shown in these two micrographs. It's been added to the report for reference. Okay. Next.

On the issue of kernel stoichiometry, our response includes a discussion of thermochemical analyses of kernel chemistry as a function of the starting composition, meaning oxide/carbide ratios and the ultimate burnup that you achieve.

And the conclusion is that, this again is from the historic database and calculations that have been done in the past, that there's a wide range of oxide/carbide ratios that will work to both limit the

CO gas formation and to immobilize lanthanide fission products, which is really what UCO fuel was designed to do is to take advantage of the benefits of UC fuel and UO2 fuel combined, and that we are well within the range given our peak burnups of about 20 percent FIMA.

The AGR fuel has about 30 percent carbide. And you'd have to be significantly outside this range based on the thermochemical calculations to fail to accomplish these goals. And so some material from this response was incorporated into the part of the report that talks about the fuel description. Okay. Next.

There was a question about uninterrupted coating, if that's a requirement. The fact is it is a de facto standard in modern TRISO fabrication. Most of the historic data sets that we refer to have used this process.

And AGR-1 and 2 both use this process. And so we are considering it essentially a process requirement when applying the results of the topical report.

Okay. The next one, this is probably the most involved and difficult in terms of a response. But it was to clarify the acceptable ranges for fuel in order to apply the topical report conclusions, specifically what are the differences between the specs and the measured ranges of fuel in Table 5-5. It was really asking for some more clarification on Table 5-5.

So we did revise the data in Table 5-5 to a certain extent. We have changed that to give confidence intervals for the means. And we have tolerance limits that indicate the outer edge of the distributions. And we picked the extreme of those. The intent is to show essentially the ranges that bound what was irradiated in these two experiments.

And we have included -- so we, again, we have revised Table 5-5. And we've included some of this in our discussion. Okay. Next. Here's the new Table 5-5. We don't need to dwell on that.

And finally, RAI 4 was to clarify any limitations on the fission product release data. So there were a couple questions.

The original effects in the conclusions stated that those data can be used to, essentially that they can be used for licensing reactors. We just wanted to clarify and added this edit that says it can be used to support licensing reactors. In other words, it was never the intention to imply that the data in this report necessarily are all that one would ever need for that purpose.

And then it was also called out that there weren't data from PIE on short-lived fission products, and therefore, doesn't the data apply to that. And we just clarified that this conclusion only applies to fission products that are specifically talked about in this report.

So we don't have data on something like iodine-131, for example. And therefore, this conclusion doesn't apply in this particular case.

I think that's it. That's the end.

CHAIR BALLINGER: Okay.

MEMBER KIRCHNER: This is Walt Kirchner. Ron, I'll make it quick. It just seems to me that the Table 5-5 is incomplete without some of this information you just shared. I'm particularly thinking of impurities, materials going into the actual coaters and such.

So it's not just enough to have the physical dimensions right. You've got to be worried about transuranium. You've got, you have to have the right chemistry going into the coaters. It's not just physical dimensions. That's just an observation.

Some of the points you just made address some of the concerns I would have of just relying on Table 5-5.

MR. DEMKOWICZ: So just one comment on

that, you know, the specs that you allude to, there are things like transuranium. Those all come in at the compact level. And so we have this discussion, you know, in depth that compact specs were something that we did not want to get into here because that gets into fuel form, and it's not technology neutral.

So we tried to focus just on particles in this report, and therefore, you know, didn't get into that.

Now, things like the impurity specs for making your kernels and things like that, I mean that's all relevant. But that gets into a process and specification, which again we are talking about our product specs and not our process to get there.

MEMBER KIRCHNER: I would disagree. I'll make this short. If you don't have those material properties correct going into the coater, you're not going to get particles that perform like you measured in AGR-1 and 2.

MR. DEMKOWICZ: I have no argument with that. That's true. But you know, the report is basically giving leeway to fabricators to achieve those particles in the manner that they see fit.

DR. CORRADINI: But I -- this is Corradini. I guess Walt's point is: don't process specs have to be in some sort of specification?

MR. DEMKOWICZ: Yeah, sure, they are. And they were for the program, too.

MEMBER KIRCHNER: Yeah, that's my point, Mike. You need both. You can't just rely on physical dimension to get the same performance that I now and the team were able to get in AGR-1 and 2.

MEMBER REMPE: Paul, this is a real quick question since we're going to go a little bit beyond the time.

On Figure 5-1 in the discussion, you talk about the skin of UC that's a light ring between the kernel and the buffer layer. And maybe it was just the way the cross section was performed, but there's discontinuity showing in that figure. And do you know what it is? And if you don't know just off the top and say it was just the way we did the section, can you have someone talk about it and send a response back to Chris after this meeting so we can understand it?

MR. DEMKOWICZ: Yes, sure. So I don't have the figure in front of me. But so it's a carbide layer that forms when you coat and compact. It's a reaction of the kernel with the buffer layer. And it's a brittle layer, and it can often be discontinuous.

But also it can be a pain to prep

metallurgically because you've got a discontinuity in material properties between that and the buffer --

MEMBER REMPE: It doesn't matter that it's discontinuous. It's just something that happens. But it's not important whether it stays as a continuous ring is what your response is. And if that's the case --

MR. DEMKOWICZ: Yes.

MEMBER REMPE: -- then never mind. I just thought it was an interesting artifact.

MR. DEMKOWICZ: Yes. That's correct.

MEMBER REMPE: Thank you.

CHAIR BALLINGER: Okay. If we can quickly transition to Boyce's presentation, and we'll be sure to give Boyce the time that he needs.

MR. TRAVIS: Can everybody hear me?

(Off mic comments.)

MR. TRAVIS: All right. I believe it is up on my screen. I cannot see the Skype window. So just let me know if there are any issues at the moment.

CHAIR BALLINGER: I can see it fine.

MR. TRAVIS: Okay. Well, then I'll go right into my presentation. For those of you who don't know, I'm Boyce Travis. I'm a technical reviewer in the Advanced Reactor Technical Branch in DANU and NRR.

I'll be presenting on behalf of the staff for this presentation. I'll introduce the rest of the members of the team here shortly. This presentation covers our safety evaluation on the topical report we've just discussed.

And so at a high level, the stated goal of the topical report is to provide a foundational basis. And I'll get into foundational basis here briefly. And I'll go into a little more detail on a later slide.

But we view foundational basis as this report lays the building blocks for applicants who want to use TRISO fuel to use the data that's been presented for our AGR-1 and 2 tests as part of the topical report for use under an umbrella or an envelope that's defined by the topical report, which includes Table 5-5.

It includes the limitations and conditions documented in the safety evaluation. And it includes other aspects of the topical report that are discussed in the report itself, such as the performance characteristics, burnup temperature, time and temperature, power density, aspects related to like the stresses that we have enumerated directly in the limitations and conditions.

But fundamentally, this report is confined to the particle. And it's going to be the responsibility of a future applicant or licensee that's referencing this report to justify how their TRISO particles perform in their reactor that will meet this inflow.

So when we say foundational basis, that's kind of what we mean. This is the first building block. But there are other pieces for a future applicant or licensee to show how either they meet this report or for areas that go beyond it, like the compact and what not. And so this topical report lays out those performance criteria for TRISO particles based on the AGR-1 and 2 tests and irradiation. And so --

MEMBER REMPE: Is this the first time you've run into somebody wanting to have you guys approve a foundational basis?

MR. TRAVIS: Using those words, yes, not as such. But, I mean, this is a fairly unique approach for a topical report in that it is not the entire story.

And in effect, we were provided with the topical report. We felt there was a reasonable basis. And so we worked with what we have, because there is a strong desire to do things somewhat differently for the advanced reactor -- advanced reactor and the non-Light Water advanced reactor designs. And so this is, in some sense, this is part of a staged process for TRISO fuel reactor events.

MEMBER REMPE: Thank you.

MR. TRAVIS: Yeah. And so, moving on, I tried to keep the presentation short. I tried to keep it focused on specific findings the staff made as a result of the report and the limitations and conditions, because those will be following the report, and I felt that's where the discussion would be best focused.

So we'll move on to the next slide, briefly talk about the technical review team. Jordan Hoellman was the project manager. My name is Boyce Travis, I'll be presenting on behalf of the staff. Also involved in the technical review were Jeff Schmidt, Chris Van Wert, and Antonio Barrett, all part of the Advanced Reactor Technical Branch in the Division of DANU -- sorry. I'm not going to get into the mouthful of our divisions.

So the next slide, I'm on slide 4 now. And so I've kind of prepared this slide to hit on the, what we mean when we say foundational basis. The topical report represents one stage in licensing a TRISO-fueled advanced reactor design.

And so, for that advanced reactor design, there's going to be a license application, and that's kind of symbolized by the blue oval, the safety demonstration, which we expect to make up a large part of that license application in justifying how the applicant will, you know, conform to the safety expectations and regulations that we set forth.

And then for our TRISO-fueled design, we expect fuel qualification to form a large portion of the safety demonstration, because of the unique aspects and features that the TRISO particle presents.

And so this topical report is a piece of fuel qualification for a TRISO-fueled design. But it is not the end point.

And how much of that piece is going to depend on how much that designer wants to push the envelope with regard to reactor characteristics, with burnup temperature, what fuel form that they use, whether it's, you know, fairly well-defined or new, and other aspects that are design-specific.

And so we're looking at, again, just a piece of what's going to be involved in licensing a TRISO-fueled reactor design. So I'll move on to the next slide, slide 5.

And to your point, Dr. Rempe, the regulatory basis for this topical report is, I will say, almost wholly unique in my experience at the NRC.

It is a non-traditional topical report in that it's directly -- difficult to directly tie to a regulatory basis.

Generally speaking, this, if this report were for a Light Water reactor design, we would be tying something to a GDC for fuel performance, or something of that nature.

As you know, we've presented to the ACRS on this a few times, most recently I think related to Reg Guide 1.232, which is the staff's published principal -- or, advanced reactor design criteria. It is to be used as guidance for developing principal design criteria that would replace the general design criteria in Appendix A.

And so, based on the use case that we expect to see for this topical report, we reference MHTGR-DC 10, Reactor Design, and MHTGR-DC 16, Containment Design, from that Reg Guide 1.232.

Again, that report is guidance, it's not a requirement. But it is a requirement that an applicant for a reactor design have principal design criteria. And we expect something similar to those design criteria to be used as the reference for this topical report.

DR. CORRADINI: So, Boyce, this is

Corradini. I'm trying to understand your thinking here.

MR. TRAVIS: Sure.

DR. CORRADINI: Are you basically saying that this essentially -- or, this -- if an applicant were to be able to fit within -- I'll keep on going back to the Table 5-5. I'll expand it or as it is now. And they can fit within those specifications, then they're showing that at least this portion of their fuel design meets DC 10 and DC 16?

MR. TRAVIS: So --

DR. CORRADINI: I'm still struggling as to understand what's in and what's out.

MR. TRAVIS: So yes, in part. I think what we're saying is, if you can manufacture a set of particles to the values in Table 5-5 and the other parts of the report that envelope what's going on here, so like Table 5-6, the radar plot that was shown in the RAI discussion, the limitations and conditions, the other aspects of the report that the conclusions draw attention to, if you can remain within all of the bounds of that and you can, you have a QA program that says yes, fairly I have manufactured the particles to the statistical specifications in Table 5-5, we think this report says that if your reactor is going to operate within all those bounds, and you've done that manufacturing, your TRISO particles themselves are sufficient and demonstrate performance in accordance with what's here in the report.

And so how you -- the step beyond that, in that how you reference that as part of a reactor design, i.e., if you're using a functional containment approach, are you assuming some sort of dose release from the failed particles that the statistical sampling would show, those are questions for that application.

What we're saying here is that if you do everything that I just said, you can use the data for a failed fuel fraction and fission product releases that are discussed in this report from the particle itself. Does that make sense?

DR. CORRADINI: I think so. Can I say it with less words --

MR. TRAVIS: Absolutely, I apologize.

DR. CORRADINI: No, no, maybe more words are better. What I hear you saying is that if I have a particular design that employs the TRISO particles and I can stay within the confines of 5-5, or some modified 5-5 table, I'm on the way to showing that it can perform with my design to satisfy a functional containment if I so choose to use that approach, or it satisfies the reactor design parameters under DC 10. So it's one step of a multi-step process.

MR. TRAVIS: That is correct, yes. It is a -- like for a TRISO-fueled design, we expect it to be a reasonably large step. But, yes, it is only one step.

DR. CORRADINI: So that leads me -- so the only reason that you would reevaluate the TRISO fuel with a particular design is if their design, their operating envelope, would start challenging what was tested under these test sequences AGR-1 and 2.

MR. TRAVIS: Yes, to an extent. So I'll limit that a little bit. What we're talking about is particle only, not a final fuel form. So, again, they'd have to address their compacting process and all that.

And we did lay out some, as part of our limitations and conditions -- I mean, we think that the designer is going to have to justify that they fall within the bounds of this test specification.

And so, if you're pushing the envelope in one area or another, using data from the safety testing to justify what's being done here, we think that demonstration is going to require some extra steps on the analytical side or testing side from the designer.

But, yes, in essence if they're going to rein fully within the envelope as defined by this report, they have done the necessary steps for the TRISO particle.

DR. CORRADINI: Okay. Thank you. I think that helps me. I think -- well, let me ask this question. It's not appropriate for you to answer, but is there an application coming forward using the TRISO that will -- that is trying from a pragmatic standpoint in getting you to clarify the other steps that are necessary?

MR. TRAVIS: I'll say, yes, we have applicants in-house that were reviewing other pieces of, that we expect to reference this report. No, we don't have an idea exactly what those other pieces are at this stage, because, again, they're more a function of the full design dependency.

DR. CORRADINI: Okay. So last question, are they customized so that every one of them is a new custom review plan for you, or are they going to develop into some sort of for TRISO fuel under these -- under a range of conditions there is a series of steps that you guys understand how you need to walk through to certify the design?

MR. TRAVIS: Okay. So right now they are customized because we are working with what we have.

But as part of the legislation in NEIMA, we are preparing guidance for fuel qualification that is more general in nature, that is not just for TRISO fuel but for all fuel.

And we hope that, to some extent, that's going to do some of what you just said in that it will walk-through the series of steps required to qualify any fuel, not just TRISO fuel.

DR. CORRADINI: Okay. The only reason I bring it up right now is I think Ron's committee, as Chairman, this would be a logical place to, when the time might be right, to try to test drive it.

MR. TRAVIS: And -- yeah. And I will agree with that. And I'll just say that we're moving with the changing landscape as much as possible. And if we get to the point where we have a process like that, we will, absolutely we will be engaging you too.

DR. CORRADINI: Okay. Thank you.

CHAIR BALLINGER: As somebody has once said, these are -- we are living in interesting times.

MR. TRAVIS: And so are there any other questions on this slide at the moment? If not, I'm going to move on to slide 6.

So slide 6 kind of paraphrases the conclusions. I thought it was important to restate them here because that's fundamentally what this report is approving.

Ultimately, and I'm going to paraphrase this slide even further, what we're saying with this report is that the AGR-1 and 2 data is valid and useful for the performance demonstration for TRISO particles, that the particles that were manufactured for AGR-1 and 2 were done in a variety of different ways, you know, through a couple of different engineering -- or, excuse me, a couple of different processes and subject to the conditions that are laid out here in limitations and conditions.

They have a performance demonstration that shows that they perform very similarly and have a strong statistical basis for it that's documented in the report.

And then the big conclusion, number 3, is that if you can manufacture the particles to the values in Table 5-5 and subject to the limits that are laid out in the report, the conclusions and the limitations and conditions of the safety evaluation, you have demonstrated performance that can be used to support your TRISO particle for your fuel qualification and development.

And so I'm moving on to slide 7. This is just kind of a background on the staff's review. And I'm going to kind of hit on a couple of things from Dr. Rempe's discussion here after I get through this slide; hopefully to address some of the questions and allow, open up for questions.

So, and this, the first bullet gets to what I just discussed with Dr. Corradini. In effect, what we're trying to say here is that applicants who reference this topical can use the AGR data and the associated conclusions for particle performance if they follow the envelope that's laid out in the specifications in Table 5-5, the operational performance ranges that are defined by the report, and the limitations and conditions that we've laid out in our safety evaluation.

And so, as part of our review, the staff conducted an audit. I'll emphasize the utility of that audit. We got great support from INL, EPRI, folks from the lab.

We went into that audit with a bunch of questions, a bunch of broad questions. We left with a much narrower set of questions. It was a pleasure working with the folks from the lab. And it greatly accelerated the process for this topical report. So that was a very useful tool.

We have five RAIs. The previous presentation noted four. Four of them were technical. We asked a fifth RAI, related to quality assurance, that's documented in the other response there that's listed on the slide.

And then as a result of the review, as was noted in the previous presentation, the scope of the topical report was narrowed from the Table 5-5 that's proposed in the, I'll say the PDF version, Rev 0 of the document, to the Table 5-5 that was shown on the -- in the slide of the previous presentation. And additional performance parameters were defined as limits as you saw in the radar plot.

And so going to something that Dr. Rempe asked earlier for uncertainty, we did evaluate the supporting documentation, that is referenced in the report and the RAI responses, and agree with the assessment in Section 6.4 and 6.5 of the report that there's a roughly 100 degrees C uncertainty based on the statistics.

I'll note that we were not aware that they used different sensors to gather that data. And so, you know, we will go back and take a look at that again.

Also, the staff conclusions are much narrower for the safety margin testing at the very high temperatures that were used in the report in that -- and near the boundaries for the envelope, which we'll define later in the limitations and conditions, as we expect the applicants who are pushing those boundaries to justify reactor performance, versus the test measurements, and directly show how these values could be used such that they aren't -- that the high temperature and performance is not independent of the specific design considerations for transient performance, particle temperature, et cetera.

There has to be a demonstration that the specific designed TRISO particles will be -- will fall within the envelope as defined by this topical report.

And again, we're a little less concerned with the lower temperature ranges for the portions that show no failures because that's fundamentally a feature in the TRISO particle. And so, subject to the uncertainty that we discussed earlier, we believe that the report was appropriate in developing those bounds.

CHAIR BALLINGER: And this is Ron Ballinger. From the standpoint of margin and things, I think we should recall that if it's plus or minus 100 degrees, that's plus or minus two to the fifth in kinetics.

So the fact that these particles all

performed quite well is, with that kind of uncertainty in temperature, which would translate into a huge uncertainty in thermodynamics and kinetics, is kind of a testament to the margin that actually does exist.

MR. TRAVIS: I think we agree with that statement. And again, I think that, as part of an applicant referencing this report, they're going to have to show that including the uncertainty that's involved there, that their design remains within that envelope.

And so that should add a layer of margin, because ultimately that -- our view is that that's going to involve both the uncertainty that's listed here in the report and the uncertainty on the analytical side, which will add to the considerable margin that the particles demonstrated.

MEMBER REMPE: This is Joy. And I'll talk about AGR-2. The fact that it had the control of temperature of the test of neon and helium gases based on the thermocouple response makes the -- it's not just what the particles were exposed to.

If you have a drifting thermocouple that's still giving a signal and you're going to control the test based on a thermocouple that's drifting and you don't recognize it, you could be going in a direction that could be beyond what you anticipated. Okay?

And so that's the kind of thing that you need to be looking at, if you go back and review it. The fact that they -- that there was a change in the report, and I'd like to bring it up here if you don't mind, about your Rev. 1 of your SER --

MR. TRAVIS: Before you go on --

MEMBER REMPE: -- earlier one. Pardon me?

MR. TRAVIS: Before you go on, I need to say something with regard to that. So that initial draft was provided as a courtesy. And that's good, but the changes between -- we shouldn't be talking about changes between the two versions, because that first version is a non-public document that is -- it involves predecisional information.

And so if there's questions regarding the language, not the changes, I am happy to talk about those. But I don't want to discuss changes specifically just so --

MEMBER REMPE: Thank you for that clarification, so I won't step over a boundary.

But the final version of this says that many of the capsules showed an increase in power during the first half of the experience -- the experiment. The applicant explained this is due to the depletion of the boron burnable poison added to the graphite fuel holders.

So, without talking about what was in the original report, I'd note that there was a lot of -- in the ATR, the way they controlled the reactor is with drums that they can rotate that have a hafnium-based plate on it. And that can also affect the neutron flux that a sample is exposed to. So it gets really complicated.

And you do have flux wires in this test that that's an integral measurement. So, as you go back through and review the instrumentation, I'd be looking at that.

And then I'm puzzled. What data did they give you to give you confidence in this statement about the depletion of the boron burnable poison added to the graphite fuel holders? Did they do any sort of investigation?

MR. TRAVIS: So I'm going to have to get back to you on that because --

MEMBER REMPE: That's fine.

MR. TRAVIS: -- I --

MEMBER REMPE: Yeah, it --

MR. TRAVIS: I suspect we'll be revising that portion of the report based on the feedback. So, as you noted, there were changes that took place there, and I suspect we'll be further revising that portion of the report based on what we've heard today. So --

MEMBER REMPE: Okay. And I will do a more careful review of the more recent SER that we've received. And I may have some additional questions that I'll pass through to Chris and Ron. And if they deem them worthy, they may be sending them to you.

MR. TRAVIS: Understood. I guess one thing I will note is that all of the changes -- there was not meant to be any new information as part of those changes, especially information that's not referenced in either the report or the RAI responses or the references in those documents.

If you feel like there were changes, not clarity -- I mean, we do appreciate that kind of feedback, because there's not supposed to be new information in there. I will --

MEMBER REMPE: Yeah. Well, it's difficult, because if I wait till the full committee meeting and there's some differences, it might -- if there's something that can be disbursed of and you don't have to bring it up in full committee, rather if it's something important, then we probably should talk about it in full committee obviously. Thank you.

MR. TRAVIS: Understood.

MR. DEMKOWICZ: So this is Paul Demkowicz. Just a real quick clarification, if there's time, on the power issue. So we did address both of these in the report I believe.

Joy, you mentioned the drum movements. So there are two different types of power changes. One is within each cycle we see something going on, and that's the drums moving. And the other is -- and we judge this to be what the comment was about. It wasn't like on the cycle changes. It was over the course of the entire experiment.

And that was based on the depletion of the boron. And, yes, there was a complete boron depletion calculation done for both experiments.

MEMBER REMPE: And so, again, all of this is underlying. It's not in the EPRI report. And yeah, you did mention the drums.

But again, I'm just -- I'd like to encourage the staff to go through and look at some of these uncertainties, because again the AGR is kind of a different creature with respect to NPRs. And knowing, again, that AGR-2 went into several different positions, I think it gets -- there's more uncertainty involved.

MR. TRAVIS: Understood. And we will take another look at it.

MEMBER PETTI: Joy, one point, it only went into the -- that outflow i-position for one cycle for two weeks. And that was put back in its original position.

MEMBER REMPE: But the EPRI report doesn't give us any sort of a detail. And so this EPRI report is --

MEMBER PETTI: I understand that. But, I mean -- I understand that, right. But the --

(Telephonic interference).

I mean, you can imagine the amount of documentation here is pretty large --

MEMBER REMPE: Yeah. But we're trying to pass a judgment, or the staff is trying to pass a judgment. And today I heard them say, no, we didn't know they used different sensors for AGR-2 versus 1.

And so, again, they need to go through, and -- I understand EPRI had to limit the information, but, and they probably did sift through it, but I just want to make sure that the details are understood if you're going to pass judgment on these two tests.

MEMBER PETTI: And just another thing on the temperature uncertainties, we appreciate the problem in dimensional temperature the program has struggled with. It's one of the reasons the margin test in AGR-2 was done.

Its 100 degrees and higher and see what happens. And if the behavior is similar, then it's sort of a margin in the face of uncertainty, if you will, because that uncertainty is just an experimental fact of life with graphite, these graphite --

(Telephonic interference).

MEMBER REMPE: Okay. Again, I'd like the staff to go through and kind of look through these things a bit more. Thank you.

MR. TRAVIS: Okay. I'll move on to slide 8 now. This is just, the next few slides are just a brief discussion, and so the notable findings that are discussed in the safety evaluation.

The first is something we've already discussed, to some extent, is that the topical report represents a modified approach for qualifying a novel fuel design from what we've done previously.

Rather than the deterministic limit values we've often used for Light Water Reactor fuel, the fuel performance here is characterized statistically across a population of particles based on the provided test conditions. And the conclusions are drawn based on the full population of particles and the statistics, rather than assessing a fail -- a pass/fail condition on the fuel.

The topical report makes justification and draws conclusions for TRISO particles only, not compacts or other final fuel forms. We've discussed this kind of at length, though I want to emphasize it again here.

The particles themselves are the only subject of this report, not how the particles are formed into whatever final fuel form, whether that's pebbles, compacts, or something else entirely. That's the responsibility of the licensee or applicant that's using that design.

A quick note on QA associated with the report, we asked an RAI on this because it wasn't documented in the topical report.

The QA associated with the data gathered here was referenced in the report as part of technology development activities. Those activities were reviewed by the NGNP as part of the -- reviewed by the NRC as part of the NGNP program eight or so years ago. And there's some documentation that references that I believe in the RAI response. Move on to slide 9.

MR. SCHULTZ: Boyce, before -- this is

Steve Schultz. Before you go on --

MR. TRAVIS: Absolutely.

MR. SCHULTZ: -- on the quality assurance, the circumstances then were just an oversight of reference of what quality assurance program was being employed here. There was nothing technical from the audit that caused the NRC to question the quality assurance or the overall program --

MR. TRAVIS: No, that's -- sorry. No, that's correct. We had no qualms about the QA that was being used. It was just unclear to us how that QA had been -- because the report was silent on this, and it was unclear to the NRC how the QA was documented and how that fell into the oversight that the NRC had done in the past.

And so, as part of the audit, we had some discussions with the INL staff on the QA program. And we subsequently submitted that RAI response to make sure we had some information on the docket so that this was all fit correctly.

Again, this -- the QA program was reviewed by the NRC during the NGNP, and we felt that it was being followed appropriately and continued to be followed appropriately.

MR. SCHULTZ: And you're convinced that

that's a robust program that's implemented throughout the laboratories both at INEL and Oak Ridge.

MR. TRAVIS: I believe in this case we're only talking about INEL. I would have to get back to you on Oak Ridge. I don't know to the extent that we've looked at the QA program at Oak Ridge. I don't have any concerns about it, but I don't know the specifics of that.

MR. SCHULTZ: I just wanted to hear that last sentence. There's no concerns. Thank you.

MEMBER KIRCHNER: Boyce, this is Walt Kirchner, just following up on that. So the expectation going forward, though, would be the fuel would be made under NQA-1.

MR. TRAVIS: That is correct. Absolutely.

MEMBER KIRCHNER: Okay. Thank you. I just wanted that in the record.

MR. TRAVIS: Yeah, no, I expect the fuel to be safety related. And I expect that, as such, it would be qualified under NQA-1.

Moving on to slide 9, so this is kind of, the first bullet here is kind of, a fundamental piece of the report that we've discussed a little, that we agree largely independent of the manufacturing process

-- and I use the words largely independent to note the uninterrupted coating that we -- that was referenced in the report and we discussed -- that was discussed in our RAI response that we felt was an important piece.

Largely independent of process, we believe it is possible to establish a set of measurable criteria that can be used to justify predicted performance for the particles themselves.

Much -- so we expect that a fuel manufacturer would have a QA program. That QA program and fuel manufacturing process could be inspected by the NRC as part of, as you noted, the NQA-1 -- it would be performed under an NQA-1 program, and that would be subject to NRC oversight.

We, on the technical side, don't want to be in the business of enforcing manufacturing process specifications as part of a technical review. We'd prefer that to be on the QA program and the oversight of -- our oversight of the QA program. And so that's kind of to put that all under the correct umbrella.

The predicted performance of the topical report is based on demonstrated results from testing. And the test conditions represent an envelope within the, as we've discussed previously, that bound justifiable performance based on the topical report.

So what we're saying here is that the, this is an empirical demonstration of the fuel as part of the AGR program and the conditions that were part of the AGR program, again, subject to the uncertainty we discussed earlier, and that we need to go back and take another look at our makeup at performance envelope.

And the report doesn't provide justification for operating beyond the envelope. That would be the responsibility of a future licensing submittal for an applicant or licensee that wanted to reference this and go beyond those bounds.

And then along those same lines, this topical report doesn't necessarily cover all the accident scenarios. So there are conditions that I expect that certain reactor designs are going to go to that are beyond the scope of this report.

And so an applicant or licensee that was doing that would have to provide some justification for how those accident conditions -- or, how they still have acceptable fuel performance under those accident conditions -- testing analysis. It could be other AGR tests, but it wouldn't be under the subject of referencing this topical report.

And so, if there are no questions, I'll move on to slide 10, which I believe starts the discussion on our limitations and conditions. Limitation 1 applies the scope -- sorry, go ahead.

MEMBER BLEY: This is Dennis Bley. I apologize. I got cut off when you were in your discussion with Dr. Rempe on --

MR. TRAVIS: Yeah, no problem.

MEMBER BLEY: And as you go through the limitations and conditions, it seems to me, vague might not be the right word, but maybe not as thorough as I would have liked. But how would those considerations come up? Where would they fit under these limitations and conditions? Because I can't quite figure that out.

MR. TRAVIS: So, when you say those considerations, what were you referring to?

MEMBER BLEY: The uncertainty issues about the temperatures.

MR. TRAVIS: Yeah, okay. So that I understand. And I'll explain to you how I would see it as part of our review going forward.

The uncertainty, as part of those -- let's say the radar plot that was demonstrated earlier and the performance in the performance demonstration envelope that's been provided as part of the topical report, the uncertainty needs to be considered as part of that and looked at by the applicant or the licensee referencing this report.

So, including their analytical uncertainty and the uncertainty that's documented in this report, they need to justify that their reactor operational conditions for their particles fall within the envelope that's defined, including uncertainty, by this report, if that makes sense.

And so that would be the subject of the future staff review that was referencing this report. So, how the justification of the conditions that that future applicant or licensee met the envelope that was documented here, including uncertainty on both ends.

MEMBER BLEY: That makes sense to me now in hearing you say it. Without some words in the conclusions, I'm not sure -- should you retire tomorrow and whoever is reviewing the first one of these, how they'd really know to think about that.

MR. TRAVIS: Okay. I think we'll discuss that internally, because, I mean, I think it logically makes sense. But I understand the concern. And so we'll take that back and discuss it internally, because I don't -- I mean, I don't disagree that we could be more specific, certainly. So I will take that back as part of the discussion we have.

Any other questions or can I move on to

the limitations and conditions?

MEMBER BLEY: Go ahead.

MR. TRAVIS: Okay. So, going back, this is Limitation 1, fairly straightforward in the sense that we're confining the scopes of this to uranium oxycarbide TRISO particles only. Performance beyond the TRISO particle is not the subject of this report and wouldn't be the subject of a future application.

And I think that's well understood by EPRI, the folks developing the report, the folks that plan to reference the report, that this report is narrowed to only the particles.

And so there is more work to be done. But, how much work? That's going to depend on the specific design.

Moving on to Limitation 2, this -- the report is limited to TRISO particles that fall within the ranges discussed in Section 5.3. And so what we were talking about here specifically was the oxygen-carbon ratio in the particles and the burnup, the associated burnup values with those ratios.

And so we agree with the assessment that's presented in the report and the RAI responses, that there are a range of UOC formulation or UCO formulations that will work, based on the burnup that you have in your reactor design. But we wanted to ensure that anyone that was using this report had an adequate UCO ratio, such that it fell within the bounds that were discussed in this report.

So basically, we want to make sure that anyone that's using particles look similar enough to the AGR particles such that we can draw a clear one-to-one between the data that's being referenced here in the report and the design in the future.

MEMBER REMPE: Excuse me, Boyce. I didn't step up fast enough on Limitation 1.

MR. TRAVIS: Sure, I'll go back --

MEMBER REMPE: Could you go back for a minute on it?

MR. TRAVIS: Absolutely.

MEMBER REMPE: I was looking at the report, and it's not just -- and I know you just have this one for-instance about something in the compact material. But there's also things that might be in the reactor environment. And again, I'll bring up this thing about the chromium and nickel or iron attack. Is there some way for -- if it had instead of gas, for example, some sort of molten salt, and it could come in contact with this fuel.

So, again, if you're thinking of revising the report, it might be good to expand more than just the compact material. If there's any sort of contamination that could, in the reactor design that could affect the fuel performance that would be the responsibility of the vendor or the designer, it would maybe address some of the comments that have been brought up today.

MR. TRAVIS: Understood. I hesitate to add more -- first of all, I 100 percent agree that, we're on the same page with regards to other aspects of whatever the reactor design looks like can influence or may influence how the fuel performs.

And so, honestly, if I had to do it over, I would take out the for-instance and make this even more broad because -- potentially, because I don't want to dwell on specifics.

We kind of want this limitation to be a little more broad in that it's well understood that this is the particle only. And there are other things that are going to impact fuel performance outside of just the particle. It's not just the compact, like you said. There are other aspects there.

And so I think adding more things is not necessarily the way to go. But we will take that into consideration. I just, I think we agree 100 percent though on -- that those things would need to be dispositioned as part of a future review.

MEMBER REMPE: Yeah, again, I'm just one member and you shouldn't do anything to change the report based on one member. But on the other hand, I guess I'd go back to Dennis' comment about, if you retire tomorrow and somebody else takes this up, will the report give enough of a clue of what they should be concerned about.

MR. TRAVIS: Understood. And I think we'll take that back and discuss it internally to figure out what we're going to -- what the best approach to that is.

MEMBER REMPE: Thank you.

MR. TRAVIS: Just for reference, there's a bit of a back -- trying to strike a balance between being sufficiently broad and sufficiently specific on these limitations and conditions, such that we give flexibility versus we don't want to overly narrow it. And so we tried to strike that balance.

But, you know, as we've heard in other presentations, I mean, we've come before ACRS on other topical reports, and we've been either too narrow or too broad. So it's a goldilocks effort here. And we do our best.

MEMBER REMPE: And I know ACRS is always consistent in our advice, right?

MR. TRAVIS: Absolutely, yeah.

MEMBER BLEY: This is Dennis Bley again. Can I sneak in one? It's a comment more than a question.

MR. TRAVIS: Sure.

MEMBER BLEY: But maybe you can respond to it. You mentioned the radar charts -- slide or charts that they've used. I'm assuming the staff is aware of the problems with those kind of charts and how comparisons using them can be badly distorted, especially by the scales and that sort of thing.

MR. TRAVIS: Oh, absolutely. I was more referring to the radar plot as a, let's say, just a visual aid. I think we refer specifically to the table with the numerical values in it in our conclusions. So I agree with you, though. So --

MEMBER BLEY: Okay.

MR. TRAVIS: Yeah. And so I think I've tried to discuss Limitation 2. If there are any questions about Limitation 2, I'll move on to the conditions. Hearing none, I'll move on to slide 12.

Condition 1 is a, kind of a general condition to capture any dissimilarities between the particles that an applicant produces and the AGR particles.

Specifically, we've highlighted stress values, because one thing that's not in Table 5-5 is the kernel size. And so the stress values that were discussed previously we think are a fair proxy for that, and they are discussed in the report. We just wanted to highlight them specifically as something that an applicant or licensee referencing this report would need to justify.

And so we highlight that as a -- this condition is really -- as part of referencing this report, an applicant or licensee needs to justify the similarity, sufficient similarity, to the tested particles so that they can, in the areas that aren't necessarily captured directly in that table, but are discussed in other places in the report, if that makes sense.

And so I'll move on to slide 13, which is the second condition we set out in the report. So go ahead, if there's a question.

Hearing none, the performance limits that are discussed in Section 6 of the report, and again the condition points directly to Table 6-6 and Figure 6-30, this goes to what was just discussed with regards to the radar plot and the tables that are in the report are the results of different tests with distinct samples. And not all of those temperatures and burnups and everything lined up on these same tests.

And so, when referencing this report, we felt it was important to make sure that if an applicant wanted to go, again, push the envelope of where those boundaries lie, that they needed to justify either that the particle -- that their conditions were the subject of a particle in the report, or that they provided some other justification to show how their design fits within the envelope that's laid out in this report.

The other piece in this condition is we've added -- or, we've placed a sentence that says that this is really showing empirical evidence of failure based on aggregate test conditions rather than mechanistic failure.

Obviously, you're not directly measuring the temperature of every single particle in your design. So you can't take out any given particle that you're going to say, oh, this one's going to fail. Based on the conditions that are provided, it's empirical justification for particle failure.

MEMBER REMPE: If someone is on the line without their phone muted, please mute it -- or, your voice or audio. Thank you.

MR. TRAVIS: And moving on to slide 14, the last condition of the report. Data discussed here is only applicable to the fission products that are discussed in the report.

And so the AGR tests only captured the long-lived fission products that are part of the PIE and the short-lived fission products that would have been caught by the gas phase during the experiment -- the gaseous fission products.

And so, as part of a source term, a future source term evaluation of a TRISO-fueled design, an applicant's going to need to disposition the impact, if any, of fission products that aren't part of this report.

And so only the fission products that are specifically discussed in the report, or could have been captured by the gas -- the online gas monitoring that was done, can be justified based on the data in this report.

And I believe that is the last of our discussion. Just as a quick summary of our conclusion, staff felt that the report presented a valid data set. We were given a topical report to review, that the scope is -- was sufficiently narrow such that we felt we could draw conclusions on it.

As we emphasized earlier, this kind of represents an important first step for our TRISO-fueled design. But there are other steps that the licensees or applicants that are using TRISO fuel are going to have to take to justify their final fuel form and how this fits into their reactor safety strategy for the fuel, because the methods that are used by -- or, the features of TRISO fuel are going to lend themselves to different safety strategies.

And so, subject to the limitations and conditions identified in the report and discussed in the safety evaluation, we agree with the conclusions that are presented here.

CHAIR BALLINGER: Well, good. Thank you very much, Boyce. This kind of ends the presentations. I understand that there's a, there is a public comment coming.

But while we're getting the line open, can we go around the table, so to speak, figuratively I guess, and see if there are comments from members while we're getting the line open?

MR. BROWN: The public bridge line is now open.

MR. SCHULTZ: Ron, this is Steve Schultz.

CHAIR BALLINGER: Yes, sir.

MR. SCHULTZ: I had a question for Boyce. Regarding the safety evaluation report, the draft report that we have, the question I have is within the report there is four confirmatory items that are earmarked in the discussion.

MR. TRAVIS: Yeah.

MR. SCHULTZ: And I didn't see them being carried forward to limitations and conditions. One falls in the conclusion section. But, Boyce, could you describe how those are intended to be treated?

MR. TRAVIS: Yes. So I apologize for not addressing that at the start. I inadvertently left that out.

Those confirmatory items are a result of the process that was being used here for the RAIs. As part of the RAIs, the responses that were provided by the applicant, they provided some draft markups of the topical report. However, we haven't seen -- a revised version of the topical report doesn't exist yet. And we didn't want to cycle them through multiple revisions because of the process for a topical report.

And so, ultimately, all we're saying with those confirmatory items is, once we see that the information in the RAI responses is documented in an updated topical report, those confirmatory items will go away. It's more of a process piece than anything else.

MR. SCHULTZ: I understand that now. Thank you very much. Appreciate it.

CHAIR BALLINGER: Any more questions from members or consultants? Okay.

MEMBER REMPE: This is Joy. And I guess I have a question for Boyce about timing. Right now we have -- we've got Rev. 1 of the SE a few days ago -- or, yesterday. And now when are we going to get something updated? What is the version we're supposed to be reviewing for the full committee? And when we will get that?

MR. TRAVIS: So I guess I'll note, to go back to what John said earlier is that we don't necessarily need a letter from ACRS on that. We welcome any comments and/or letter, and we'll respond to them accordingly, but this was hopefully for -- suitable for information purposes.

And the timeline of what we're looking at is an updated version of -- right now the report exists in Revision 0. The RAI responses will be added to a Revision 1 of the topical report that we will get.

Once that happens, we'll strike the

confirmatory items. And then our safety evaluation, depending on any outcome changes from this discussion, will be appended as, to the dash-A version of the topical report.

And so right now the version that you have, that was public in ADAMS, is the version we are using as the draft safety evaluation. If we make changes as a result of the discussion here, you'll get those, you know, before the full committee meeting or whenever we get around to doing -- receiving them. Does that make sense?

MEMBER REMPE: Well, okay, so I heard you say if you make changes, which may not occur, but if you do, you'll get them before the full committee meeting. A day before or a week before, two weeks before, do we know?

MR. TRAVIS: At this point, I'm sorry that I can't tell you the answer to that question. I --

MEMBER REMPE: Okay, okay. Well, if we don't write a letter, it may not be such a big deal. Although, frankly, anything that goes to the full committee in June needs to come out about 30 days before, is my understanding. So we'll have to see what we're going to do here.

MR. TRAVIS: Understood. And we'll try

to keep you informed as effectively as we possibly can on that. If there are changes -- I'll say this. If there are changes, I will commit to providing them as a part of the discussion and presentation at the full committee meeting.

MEMBER REMPE: Okay. Just as part of the discussion at the full committee is what you're saying?

MR. TRAVIS: If nothing else. I mean --

MEMBER REMPE: Okay.

MR. TRAVIS: -- we will endeavor to have them to you well in advance if they happen.

MEMBER REMPE: Okay.

MR. TRAVIS: But I will make sure that they are part of the presentation, if nothing else.

MEMBER REMPE: Okay. Thank you.

CHAIR BALLINGER: Okay. Absent other member and consultant questions, the public line is open. If you're a member of the public and would like to make a comment, please identify yourself and make your comment.

(Simultaneous speaking.)

MS. FELTUS: Okay. Hello, this is Madeline Feltus from the Department of Energy. There was a question about getting the leader for AGR-3/4 and the other results.

We are hoping to have future topical reports -- or, reports sent in in the future, dependent on funding levels. But we really appreciate your questions today from the ACRS.

And the big part of what's going on here again is just the particles, but the question about the matrix and fission products and what happens with transuranium and things like that would be addressed in AGR-3/4 and then the specific fully pilot line may, information for AGR-5, 6, and 7 if that is completed.

So, again, we tried to focus this topical on AGR-1 as a fourth step. So, again, we appreciate your action and look forward to future topicals, if budget permits. That's all I wanted to say. Thank you.

CHAIR BALLINGER: Thank you. Is there another member of the public --

MR. LYMAN: Yes --

CHAIR BALLINGER: Go ahead.

MR. LYMAN: Yes. This is Edward Lyman from the Union of Concerned Scientists. Your comment actually was useful.

And what I'd like to say is we've been concerned about the purpose of this topical report and the language that's used. And in particular, this confirmation or acknowledgment of performance demonstration has been troubling from the start, because those words aren't defined in NRC regulations. But we fear they could be misconstrued or misapplied.

And so, you know, we're encouraged by the limitations that are being put on the application in this report. But my main concern is that words matter.

And we all know that TRISO fuel is being hyped as essentially indestructible or meltdown-proof. You know, the Department of Defense has given public interviews making these claims. And I think that's counterproductive and dangerous.

And so it's really incumbent on the NRC to do a reality check on the limitations, you know, and the realism of what this fuel can and can't do.

So I'm concerned that the staff is still going forward with the proposal, to say that this is a good demonstration, although with all the caveats.

And the concern is that it would be incorporated by reference and applications that would involve functional containment, and that credit, or undue credit, would be given to the limited data from these experiments in justifying functional containment.

And we think that fuel qualification should be more rigorous, rather than less rigorous, if you're going to be taking credit for it in the functional containment.

So with that, we'd say that this report seems premature. First of all, we've heard that the AGR-2 PIE has not been completed, and that it could have a bearing on the data in the report. So we don't see why it's even being considered until all that data is available.

The second aspect is AGR-5/6 or 5 and 6, which was intended to be a formal fuel qualification for the purposes of NRC licensing, and that clearly is still going to need to happen, as we've heard, because the matrix is going to be all important in determining things like the mechanistic source term.

So, again, it seems like it's premature to say too much about AGR-1 and 2 in this context at this point. And so, you know, again, we don't see the purpose of this report.

With all the limitations and caveats, it seems like it's going to be a very limited usefulness for licensing anyway. But again, that's our concern. So thank you for your attention.

CHAIR BALLINGER: Thank you. Are there any other members of the public that would like -- excuse me -- like to make a comment? Okay. Hearing none, can we close the bridge line? And -- excuse me. Can we go around, again, around the table one last time --

MR. BROWN: The line is closed.

CHAIR BALLINGER: Thank you. With members and consultants. Are there any other comments?

I know we have a full committee meeting on, I forget the date, June 3rd. And at that point, there will be a presentation I'm sure. And I'll take comments from Committee members and consultants and work with Chris to try to define what would be important for that presentation. I'm sure we'll have much less time than we had today. And we already went over.

And then I think with respect to a letter or not a letter, that will be decided by the full committee. So are there any other members around the table that would like to make a final comment?

MEMBER BLEY: This is Dennis. I don't see how we do not write a letter on this topical if it's going to come out. I think we're going to have to do that. But otherwise, it was a good presentation and nothing further to add.

MEMBER REMPE: This is Joy. And I second Dennis' remark about we should have a letter. And so

I think, especially, I think we need to make a recommendation now. And then we need to be prepared with a draft letter for the full committee, that you might want to go around the members and make sure all the other members agree a letter is needed, so you feel comfortable that you're not wasting your time preparing such a letter, Ron.

CHAIR BALLINGER: We were kind of assuming that we were going to have a letter and have a draft. So --

MEMBER REMPE: And so, if we are making that assumption, then I would request that you and Chris work with the staff and make sure we can have a copy of the SER if there's any changes as soon as possible.

CHAIR BALLINGER: As always. Other members or consultants?

MEMBER KIRCHNER: Ron, this is Walt. I just have an underlying concern. I like what we heard from the staff. The limitations and conditions that were imposed I think put a little tighter envelope on things.

But to my way of thinking, there's no ignoring that the material property, composition, impurity, et cetera, that goes into actually making the kernels and then applying the coatings is as important as the physical dimensions. And we don't really -- it's not really addressed here. The assumption is that these are very well made, and I'm sure BWXT did a great job.

But without getting into proprietary information and how and process -- production processes for manufacturing and such, there is a lot -- I don't want to call it black art, but there's a lot of experience and skill and control of chemistry and impurities, et cetera, that go into making these particles. And Table 5-5 strictly addresses physical dimensions, not chemistry. And so some of the conditions address some of the issues that were identified by both the -- by the presenters.

But, for example, there's silicon carbide microstructure. I think the Condition No. 1 indirectly gets at the kernel-to-buffer volume and the ratio and what the ranges are these can be. And that gets back to burnup and pressure buildup in the particle.

So I'm just, I just have this feeling that what we have is necessary but not entirely sufficient to --

CHAIR BALLINGER: Yeah, I think I kind of agree. But I also heard the words NQA-1. And so --

MEMBER KIRCHNER: I brought -- that's why I brought that up. That will be a big part of it.

That --

CHAIR BALLINGER: Yeah, to me that means, for example, in the processing side, the precursors for the manufacturing will also have specifications that would be part of NQA-1.

MEMBER KIRCHNER: Yes, that's what I would expect.

PARTICIPANT: Correct, Ron.

CHAIR BALLINGER: Yeah, so I think --

(Simultaneous speaking.)

MEMBER KIRCHNER: Yeah, that would be necessary. So then you would get into things like material impurities, et cetera, et cetera. Gas, the actual gases --

CHAIR BALLINGER: Oh, yeah.

MEMBER KIRCHNER: -- and their impurities, et cetera.

CHAIR BALLINGER: Yeah. Okay. Other final comments from members or consultants? Hearing none, we'll -- half an hour late, but better late than never I guess. Thank you very much to the presenters and the members as well. And we are --

MR. BROWN: Ron, this is Chris. Just to be clear, we are going to full committee?

CHAIR BALLINGER: Yes.

MR. BROWN: Okay.

CHAIR BALLINGER: Yes, yes. Thank you, again. And we are adjourned.

(Whereupon, the above-entitled matter went off the record at 12:32 p.m.)

ELECTRIC POWER RESEARCH INSTITUTE

Topical Report EPRI-AR-1

Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance

Andrew Sowder, Ph.D., CHP
Senior Technical Executive

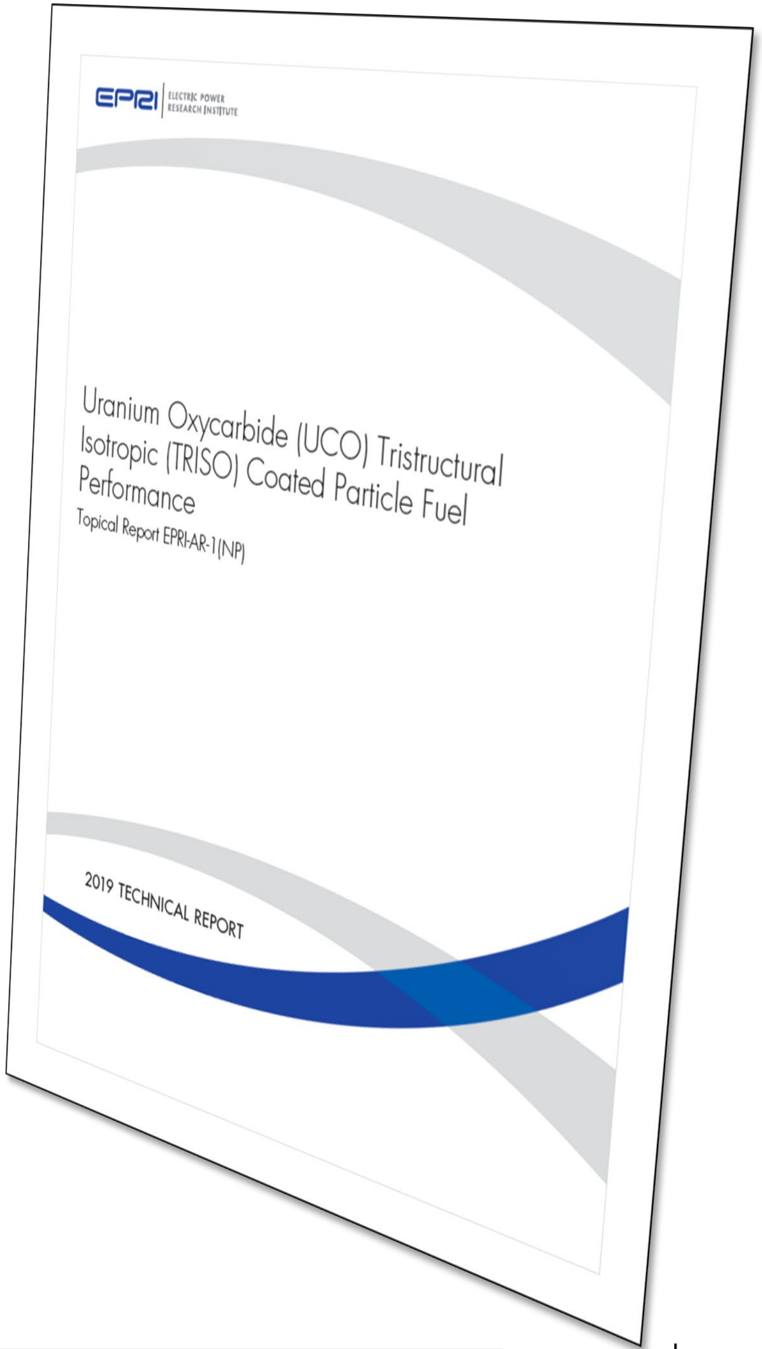
Meeting of the ACRS Subcommittee on Metallurgy and Reactor Fuels
May 6, 2020

TRISO Fuel Topical Report

- Objective:
  Support commercialization of mature advanced nuclear designs to maintain nuclear as a future energy generation option

- Scope:
  - U.S. Department of Energy (DOE)-sponsored AGR-1 and AGR-2 fuel campaigns
  - Global context, history, and experience
  - Performance demonstration of TRISO-coated particle fuel with uranium oxycarbide (UCO) kernels
  - Irradiation, post-irradiation examination (PIE), and available post-irradiation safety testing data

- Publicly available report:
  - Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP). EPRI, Palo Alto, CA: May 2019. 3002015750 https://www.epri.com/#/pages/product/3002015750/



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Key Partners and Stakeholders:

High Temperature Reactor (HTR) Technology Working Group and Supporting Entities

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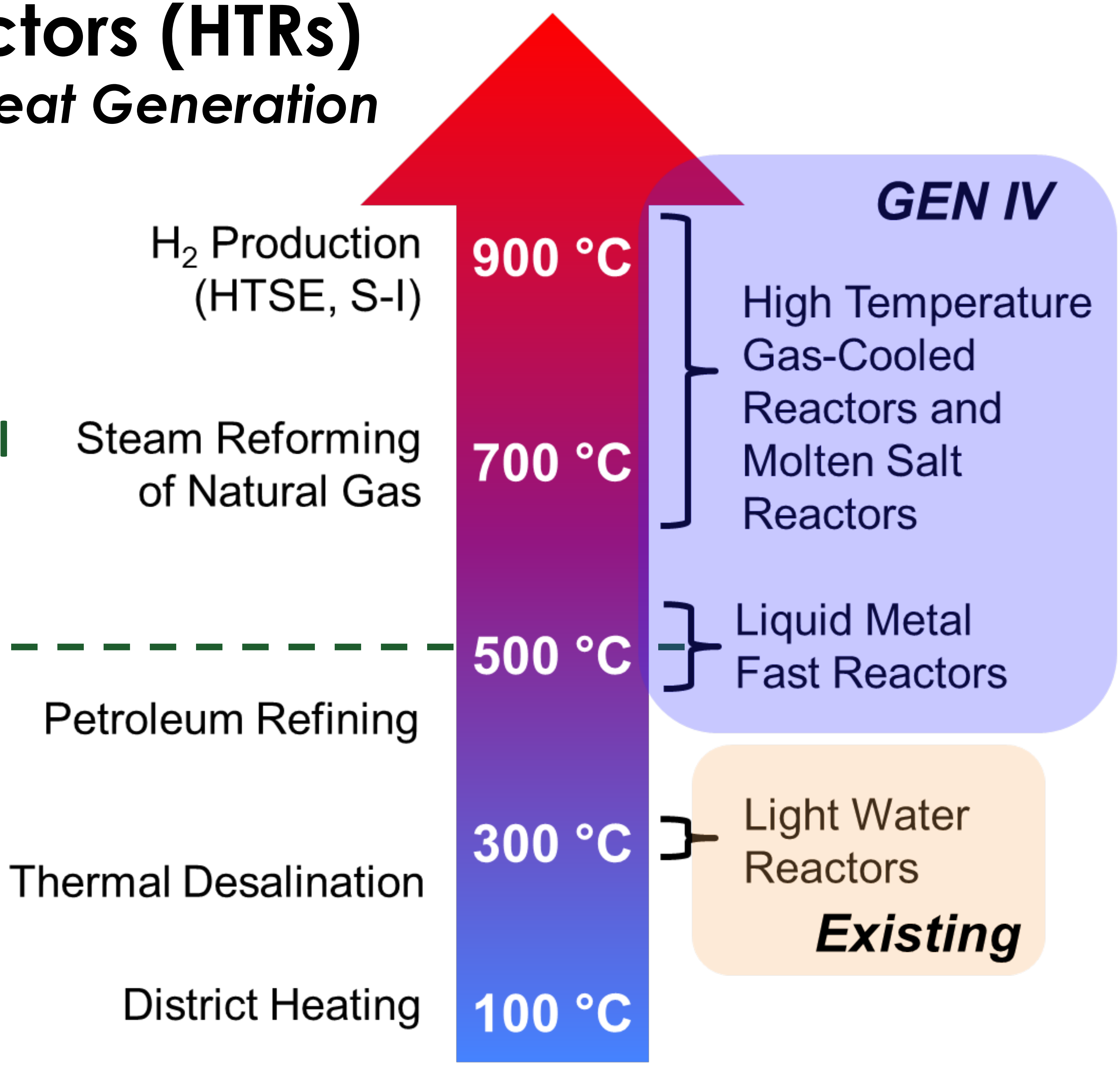
High-Temperature Reactors (HTRs)

Options for Future Power and Heat Generation

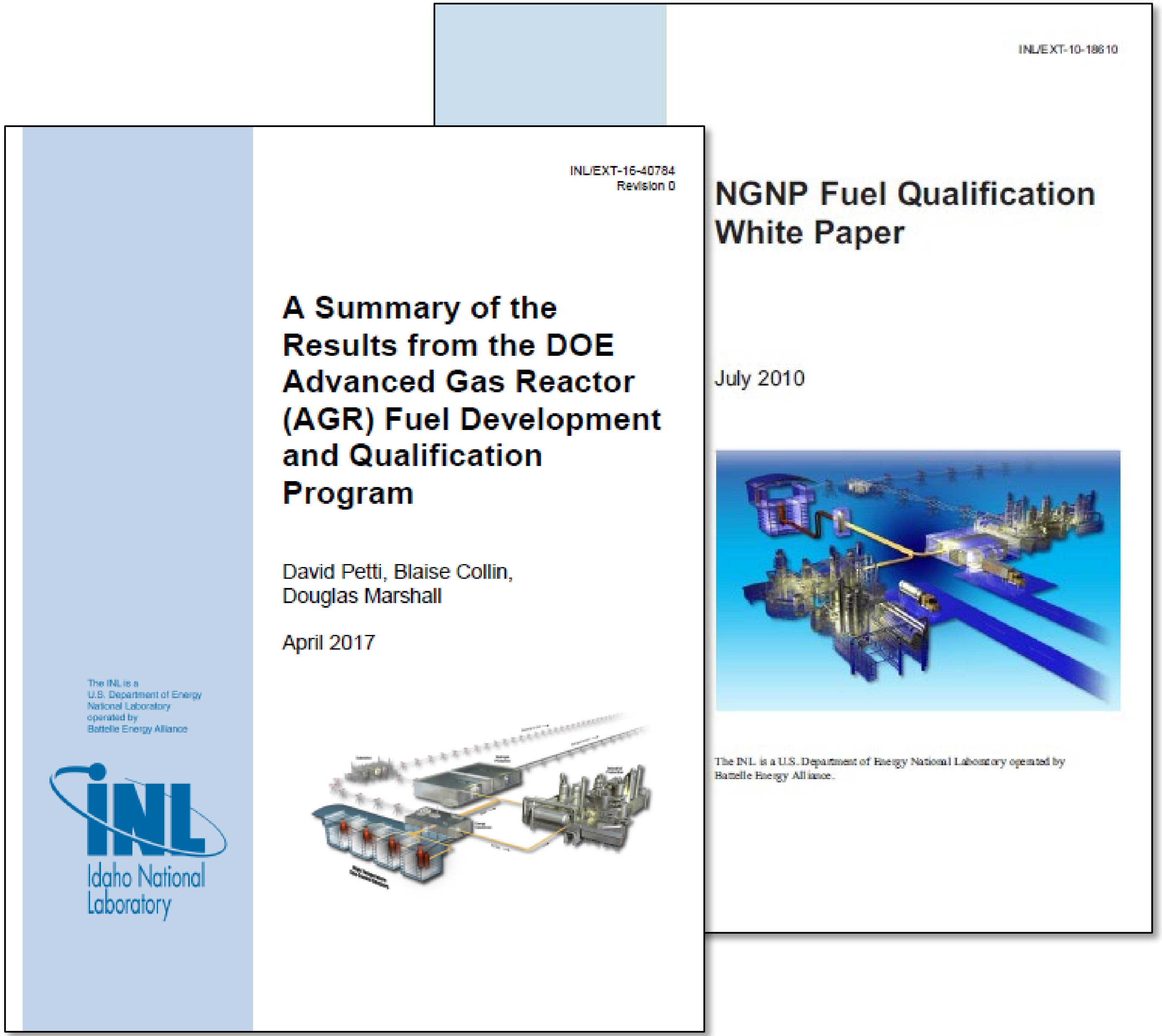
TYPICAL APPLICATIONS:

Electricity and higher-value industrial heat applications for non-emitting, energy-dense sources

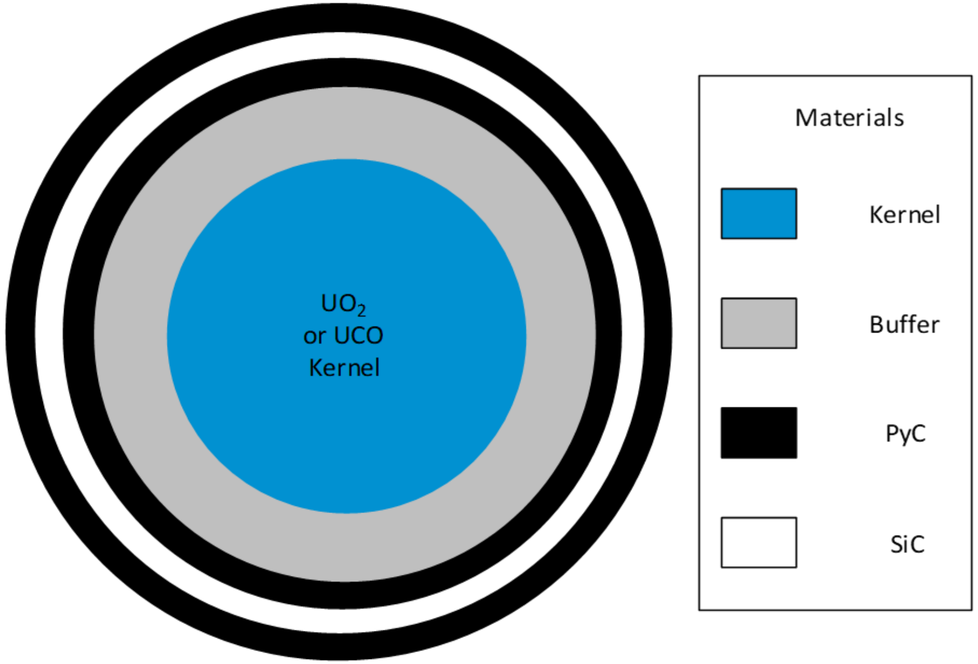


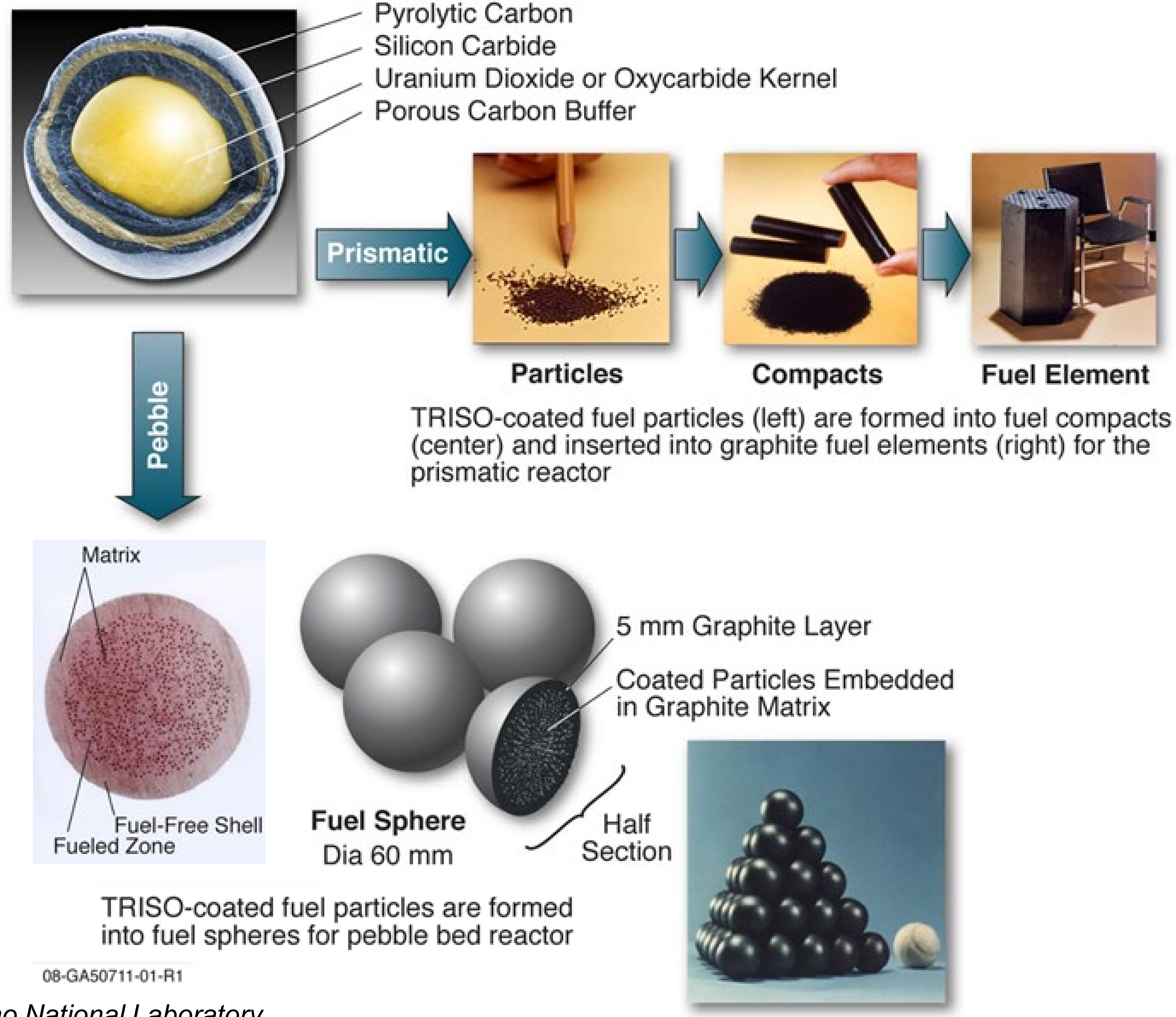
U.S. and International Experience

- International experience:
  - High-quality TRISO fuel can be fabricated in a repeatable, consistent manner
  - Fuel performance with very low in-service failures is achievable under anticipated HTGR conditions
- U.S. DOE AGR program:
  - Fabrication of high-quality low-defect fuel is achievable at industrial scale via stable, repeatable processes
  - Demonstration of excellent irradiation performance of a large population of UCO TRISO fuel particles under high-burnup, high-temperature HTGR conditions



TRISO Coated Particles and Fuel Forms



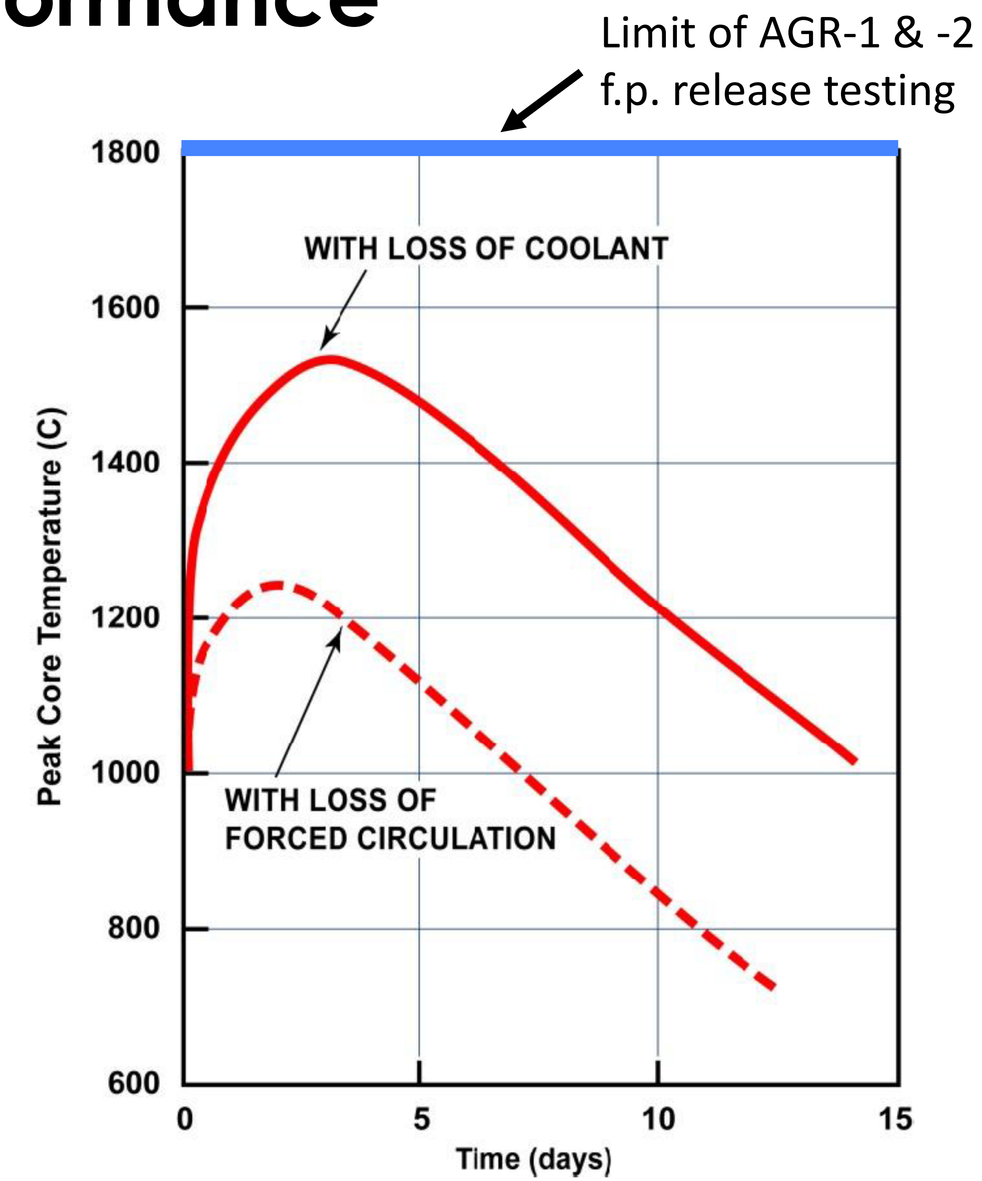


- **International development and use of TRISO fuel has occurred over 60 years**
- **U.S. DOE Advanced Gas Reactor Fuel Development and Qualification (AGR) Program launched in 2002**

Figures courtesy of Idaho National Laboratory

Inherent Safety from TRISO Fuel Performance

- Refractory TRISO fuel tolerates temperature excursions for the most extreme events (~1600°C)
- Reactivity and power decrease with increasing temperature
- Reactor designs can provide fully passive heat removal



Source: IAEA ARIS database, GA Prismatic HTGR design

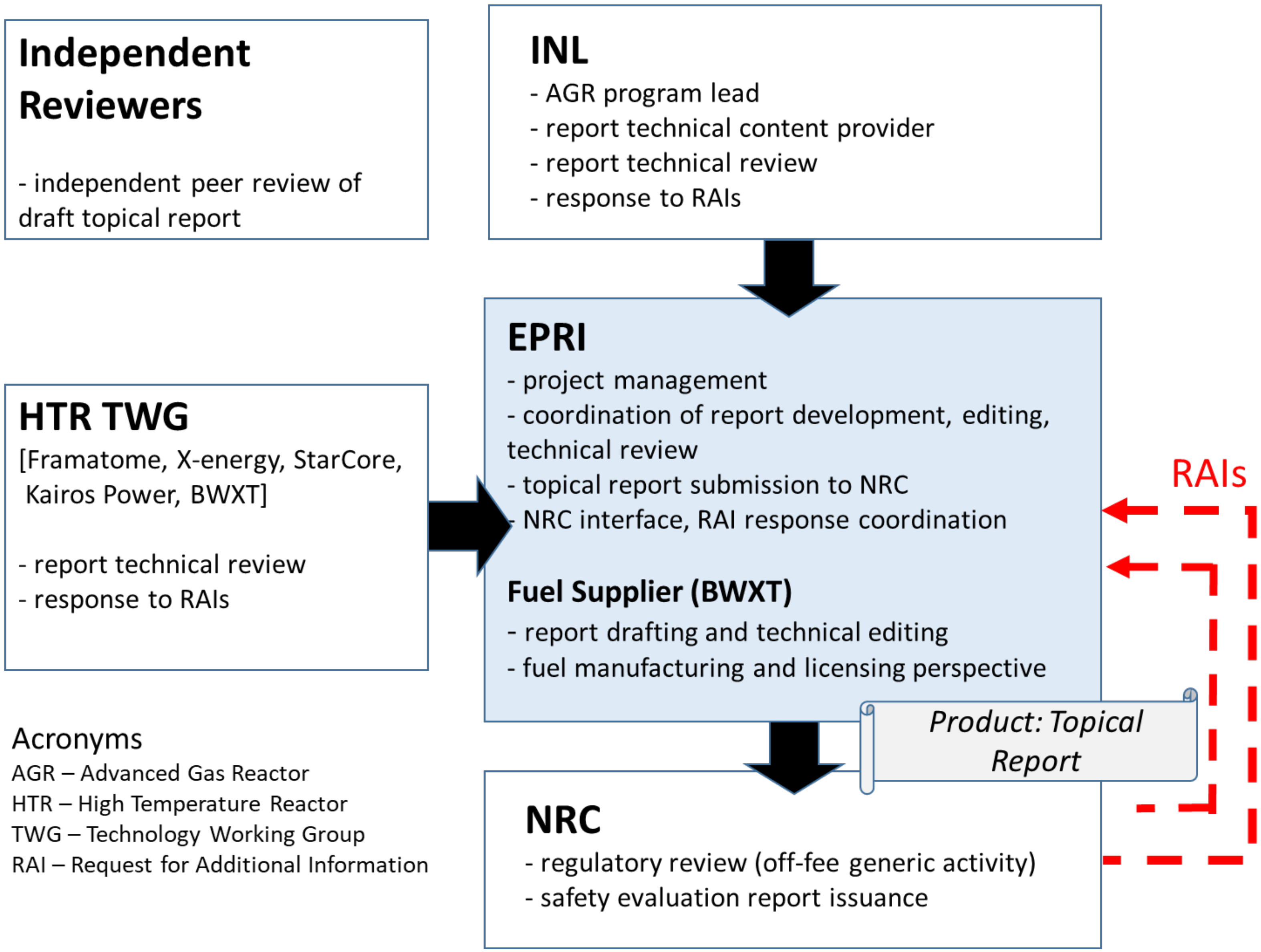
Collaborators from HTR TWG on Topical Report Project

- Framatome
  - SC-HTGR: prismatic core modular HTGR
- StarCore Nuclear
  - StarCore: small modular prismatic core HTGR
- X-energy
  - Xe-100: pebble bed modular HTGR
  - TRISO coated particle fuel
- Kairos Power
  - KP-FHR: pebble bed fluoride salt cooled high temperature reactor (FHR)
- BWX Technologies (BWXT)
  - TRISO coated particle fuel

HTR - Simple Safe Secure

High Temperature Reactor (HTR) Technology Working Group

A Model Collaboration and Public-Private Partnership



Acronyms
AGR – Advanced Gas Reactor
HTR – High Temperature Reactor
TWG – Technology Working Group
RAI – Request for Additional Information

- DOE and EPRI co-funding
- Industry in-kind support
- NRC off-fee review

Topical Report

Content (1 of 3): Background

- Section 1 describes the report scope, purpose, content, and structure
- Section 2 discusses TRISO fuel in the context of past Nuclear Regulatory Commission (NRC) regulatory activities and the current NRC regulatory framework, including a description of how this topical report may fit conceptually into overall TRISO-fueled plant licensing strategies
- Section 3 summarizes the non-AGR experience base for coated particle fuel technology in the United States and internationally
- Section 4 presents the basis for the particle design and test conditions used in the AGR program

Content (2 of 3): AGR Program

- Section 5 provides a brief overview of the AGR program, including the different program elements and the four fuel irradiation campaigns around which the program is structured
  - Fabrication of the AGR fuel described in Section 5.3

- Section 6 provides the irradiation response of fuel particles in the AGR-1 and AGR-2 campaigns

- Section 7 presents follow-on safety test performance and post-irradiation examination (PIE) data for AGR-1 and AGR-2

- Section 8 provides a summary of the report, including the key conclusions drawn from this work in regard to UCO TRISO fuel performance

Content (3 of 3): References and Appendices

- Section 9 provides references for the main body of the report
- Appendix A provides more detail on the U.S. regulatory history related to TRISO fuel
- Appendix B provides more detail on the international coated particle fuel experience base
- Appendix C provides information from the AGR-1 and AGR-2 fuel specifications

Conclusion 1

Testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions. Therefore, the testing provides a foundational basis for use of these particle designs in the fuel elements of TRISO-fueled HTR designs (that is, designs with pebble or prismatic fuel and helium or salt coolant).

Conclusion 2

The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited property variations and were fabricated under different conditions and at different scales, with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2. UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance.

Conclusion 3

Aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions, as summarized in this report, can be used to support licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5 from AGR-1 and AGR-2.

Request to NRC

- Consider Sections 1 – 4 as historical background and context
- Review Sections 5 – 7 as the AGR program content and core scope of Topical Report
- Approve the Conclusions in Section 8 with issuance of a Safety Evaluation

Progress to Date

- May 31, 2019: EPRI topical report submitted to NRC
- August 5, 2019: Topical report accepted for review by NRC
- October 8-9, 2019: NRC in-person audit at INL
- November 19, 2019: NRC shares four draft RAIs
- December 9, 2019: NRC public meeting to discuss draft RAIs, *inter alia*
- January 2, 2020: NRC transmission of formal RAIs to EPRI
- January 15, 2020: Clarification call on project quality assurance
- February 25, 2020: EPRI submits responses to original four RAIs
- March 9, 2020: EPRI submits response to additional RAI on QA
- April 6, 2020: NRC issues draft safety evaluation
- ***May 6, 2020: ACRS subcommittee meeting and review***

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Advanced Gas Reactor Fuel Development and Qualification Program: Overview and AGR-1 and AGR-2 Results Summary

Advisory Committee on Reactor Safeguards
Meeting of the Subcommittee on Metallurgy & Reactor Fuels
May 6, 2020

Paul Demkowicz, Ph.D.
Idaho National Laboratory
AGR Program Technical Director

Advanced Gas Reactor Fuel Development and Qualification Program

Objectives and motivation

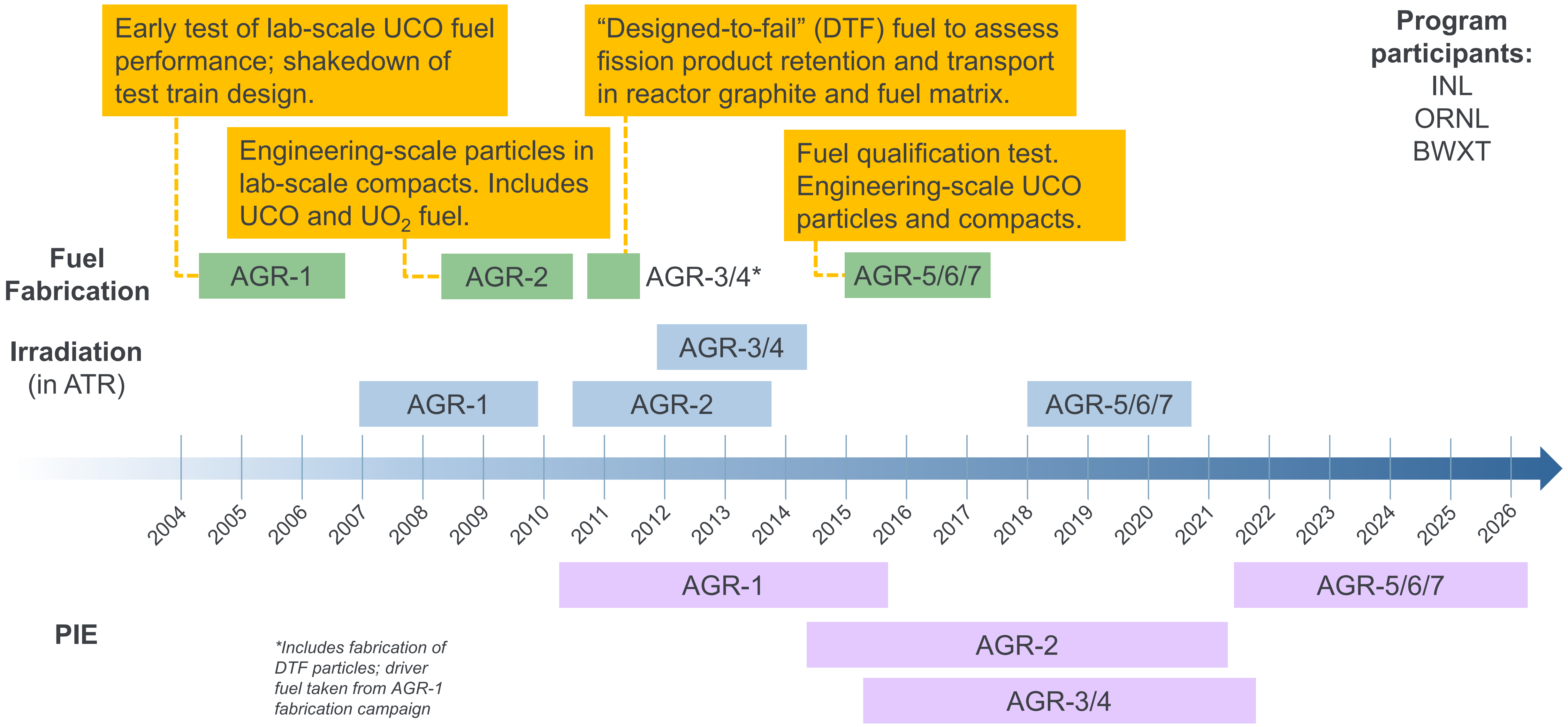
- Provide data for fuel qualification in support of reactor licensing
- Establish a domestic commercial vendor for TRISO fuel

Reduce market entry risk

Approach

- Focus is on developing and testing **UCO** TRISO fuel
  - **Develop fuel fabrication and quality control measurement methods**, first at lab scale and then at industrial scale
  - **Perform irradiation testing** over a range of conditions (burnup, temperature, fast neutron fluence)
  - **Perform post-irradiation examination and safety testing** to demonstrate and understand performance during irradiation and during accident conditions
  - **Develop fuel performance models** to better predict fuel behavior
  - **Perform fission product transport experiments** to improve understanding and refine models

AGR Program Timeline



AGR Fuel Fabrication

Fabrication scale up

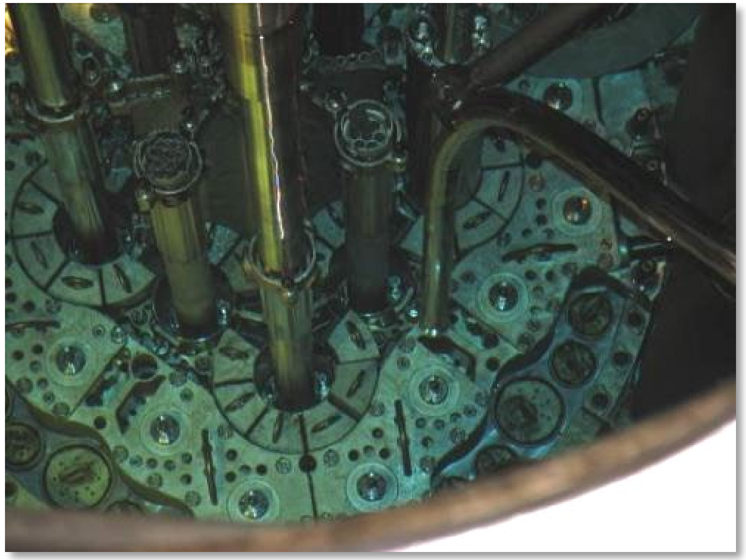
	Kernels	Coatings	Compacts
AGR-1	Engineering scale	Lab Scale	Lab Scale
AGR-2	Engineering Scale	Engineering scale	Lab Scale
AGR-5/6/7	Engineering Scale	Engineering Scale	Engineering Scale

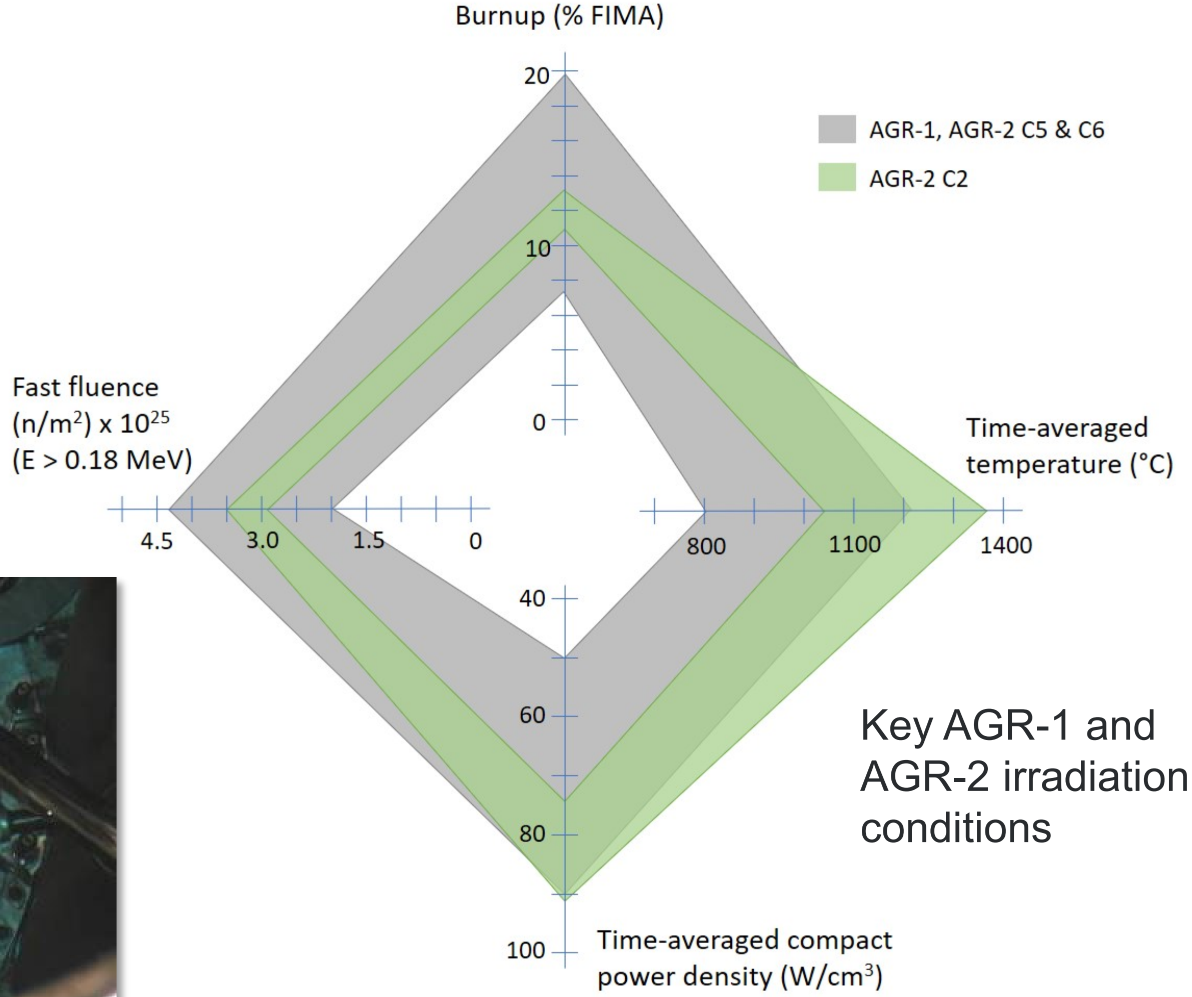
Lab Scale – ORNL
Engineering Scale – BWXT

- AGR program re-established TRISO fuel fab capability after ~15 year hiatus in the US; significant improvements to fuel fabrication processes and quality control measurement techniques
- Different particle designs used:
  - AGR-1: 350-µm-diameter kernel (19.7% ^{235}U); IPyC and SiC coating variants explored
  - AGR-2 425-µm-diameter kernel (14.0% ^{235}U); SiC similar to AGR-1 Variant 3
- AGR-1 and AGR-2 fuel particles met all key fuel product specifications

AGR-1 and AGR-2 Fuel Irradiations

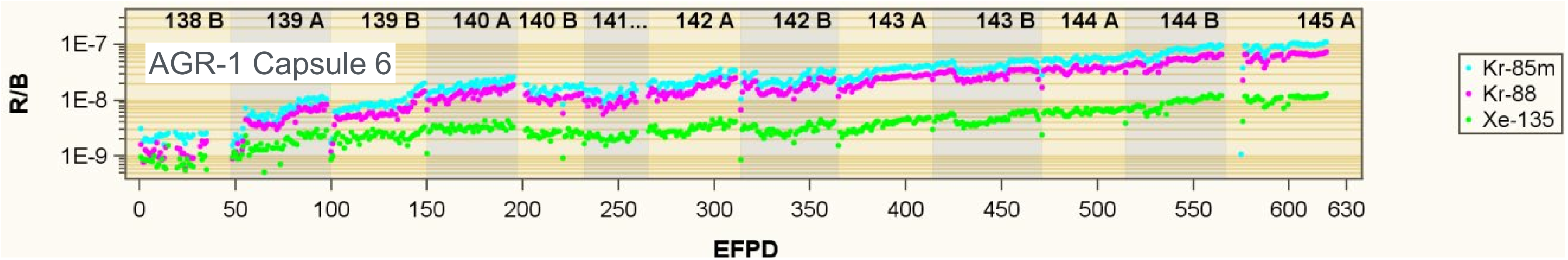
- Advanced Test Reactor – Large B positions
- Six independent capsules; 12 fuel compacts per capsule
  - AGR-1: ~300,000 particles
  - AGR-2: ~114,000 UCO particles
- Approx. 2-year irradiation time to simulate 3-year reactor lifetime
- Temperature controlled with He/Ne gas mixtures
- Fission gas release monitored throughout experiment to assess fuel condition

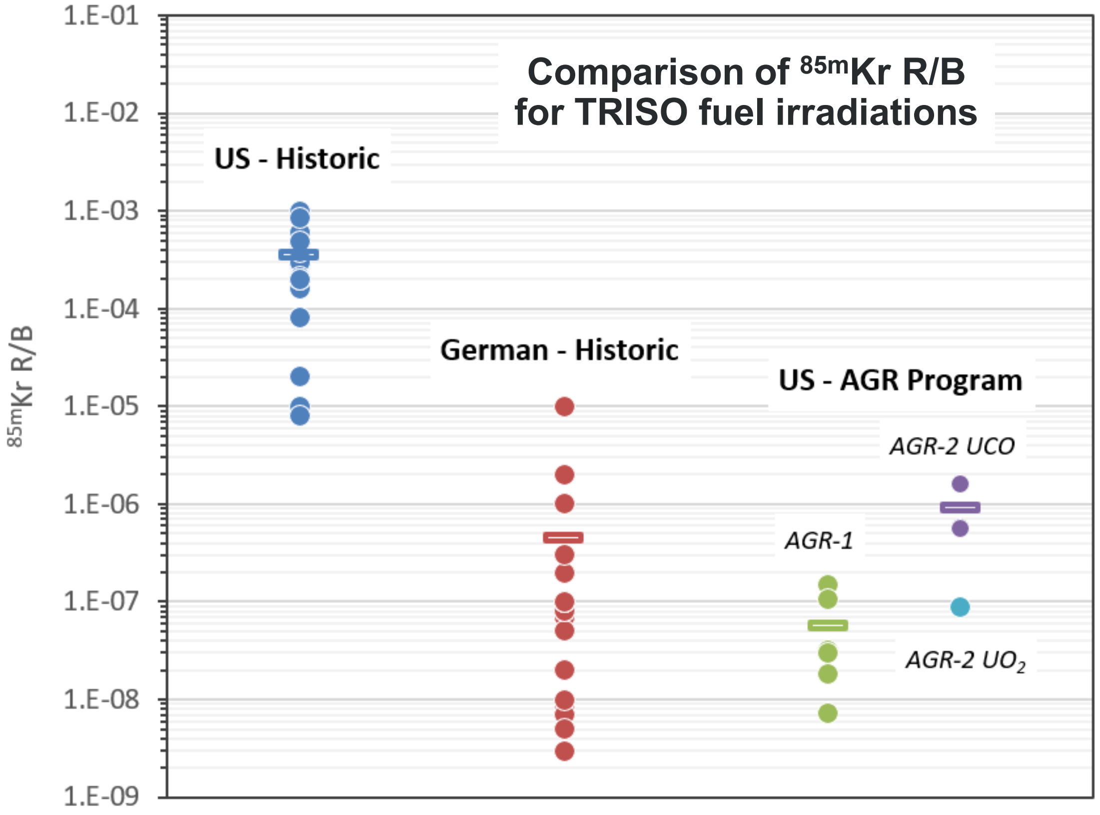




Key AGR-1 and AGR-2 irradiation conditions

Fission Gas Release

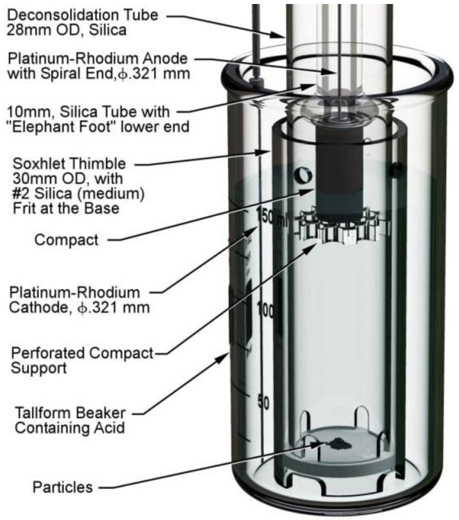




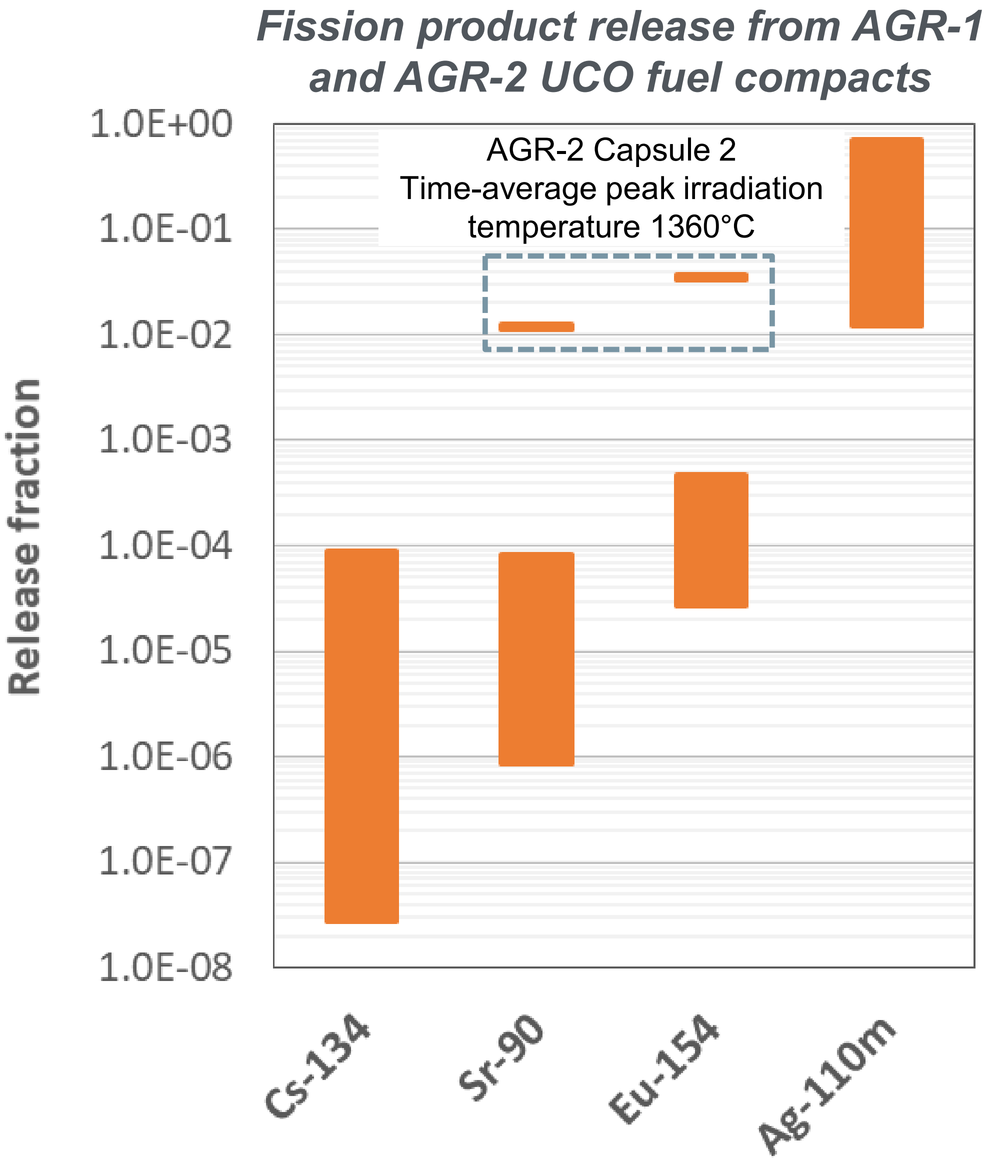
- R/B ratios during AGR-1 remained $<2 \times 10^{-7}$, indicating no failures out of 300,000 particles
- AGR-2 R/B indicated no failures through three cycles; R/B data for remainder of irradiation not qualified because of hardware problems
- Current PIE estimate indicates ≤4 particle failures during AGR-2 irradiation
- R/B data compare favorably to historic German values, but at ~20% FIMA (AGR-1)

TRISO Fuel Post-Irradiation Examination and High-Temperature Accident Safety Testing

- Main objectives:
  - Measure fission product release during irradiation
  - Measure fission product release during high temperature post-irradiation heating
  - Examine kernel and coating microstructures to understand irradiation-induced changes and the impact on fuel performance
- Both conventional and specialized equipment used for TRISO fuel examinations



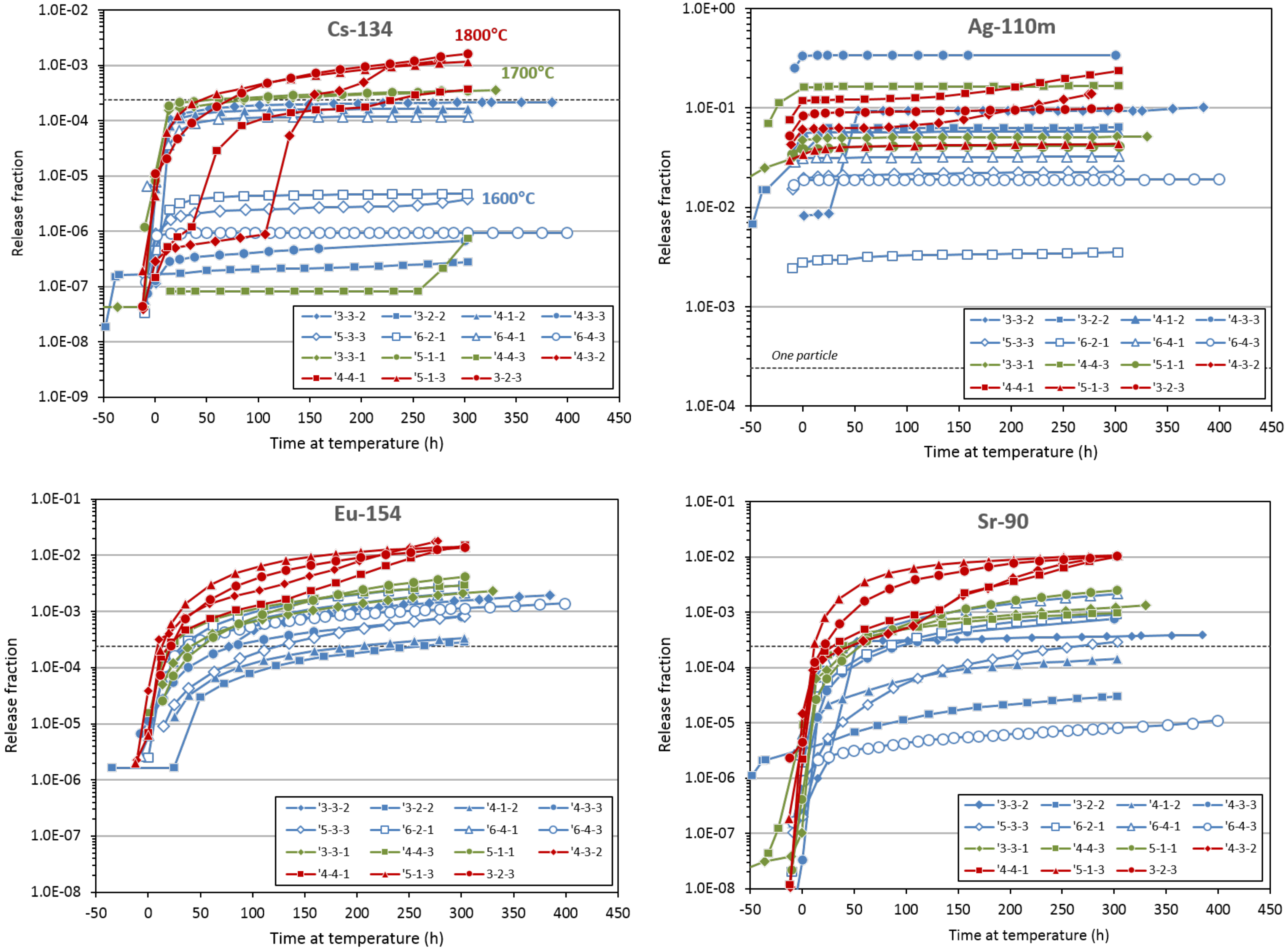
Fission Product Release from AGR-1 and AGR-2 Fuel Compacts



- Cs release is very low through intact SiC; higher releases are associated with a limited number of particles with failed SiC
- Sr and Eu can exhibit modest release; release is much higher with high in-pile temperatures (AGR-2 Capsule 2 time-average peak temperatures 1360˚C)
- High Ag release, consistent with historic TRISO fuel observations

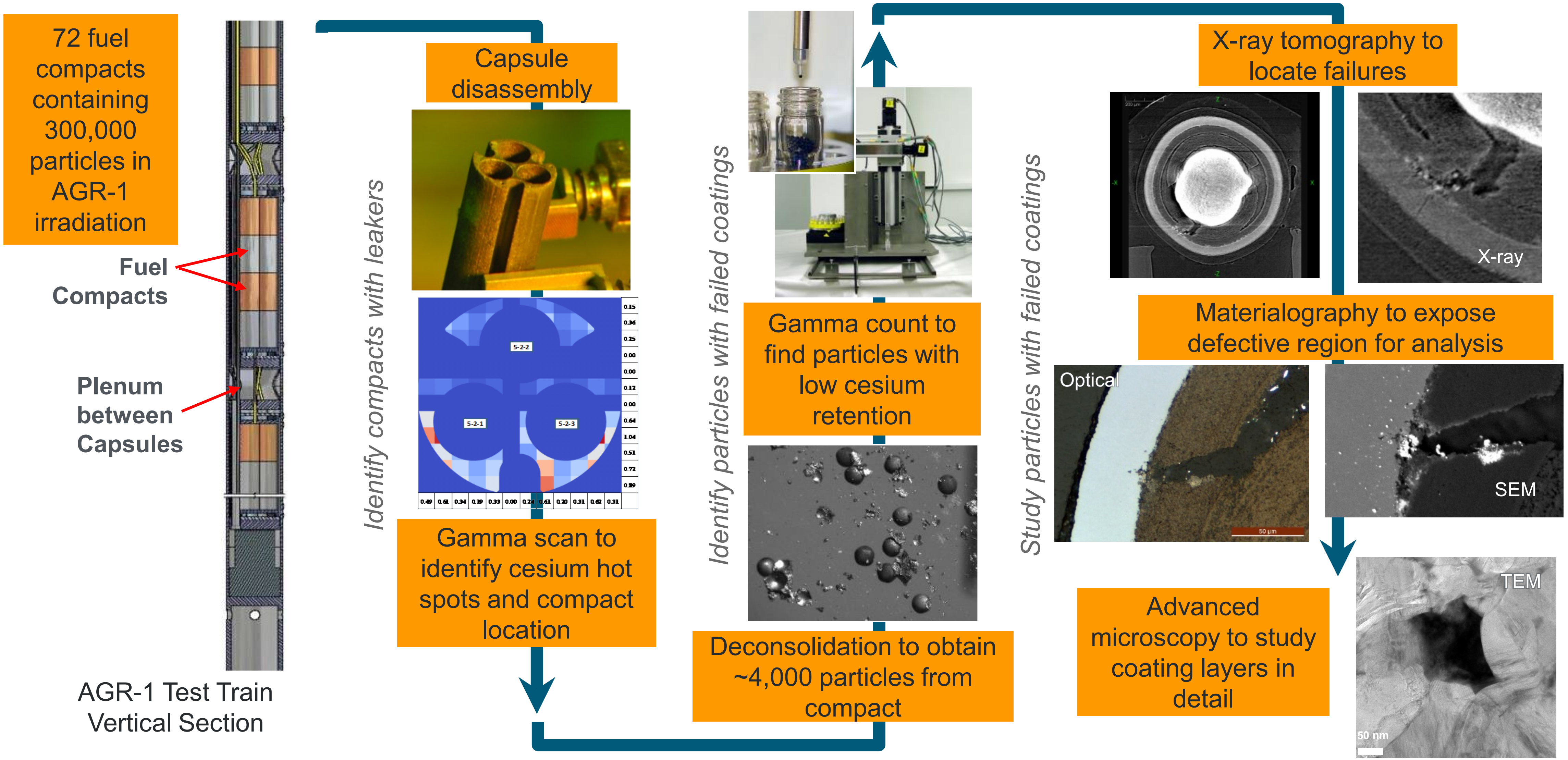
Safety Testing Results

AGR-1 safety test results



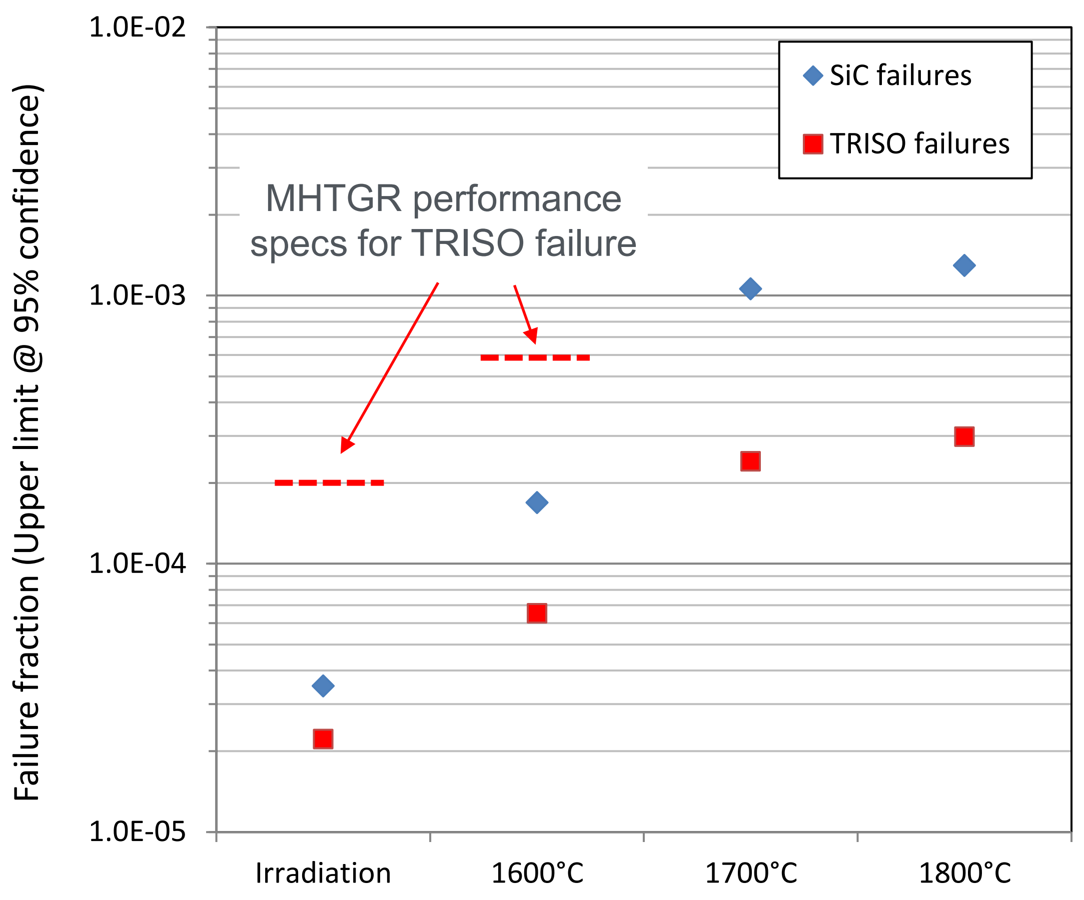
- Cs release fraction very dependent on SiC layer failure; not released through intact SiC
- Frequency of SiC layer failure increases with increasing test temperature but remains relatively low even at 1800˚C for 300 h (~10^{-3})
- Eu and Sr release increases with test temperature; dominated by release from inventory in the matrix at 1600-1700˚C
- Ag release is from inventory stored in the matrix
- Kr release is directly related to TRISO failures (failure only observed in 1800˚C tests)

Studying failed particles greatly improves understanding of fuel performance

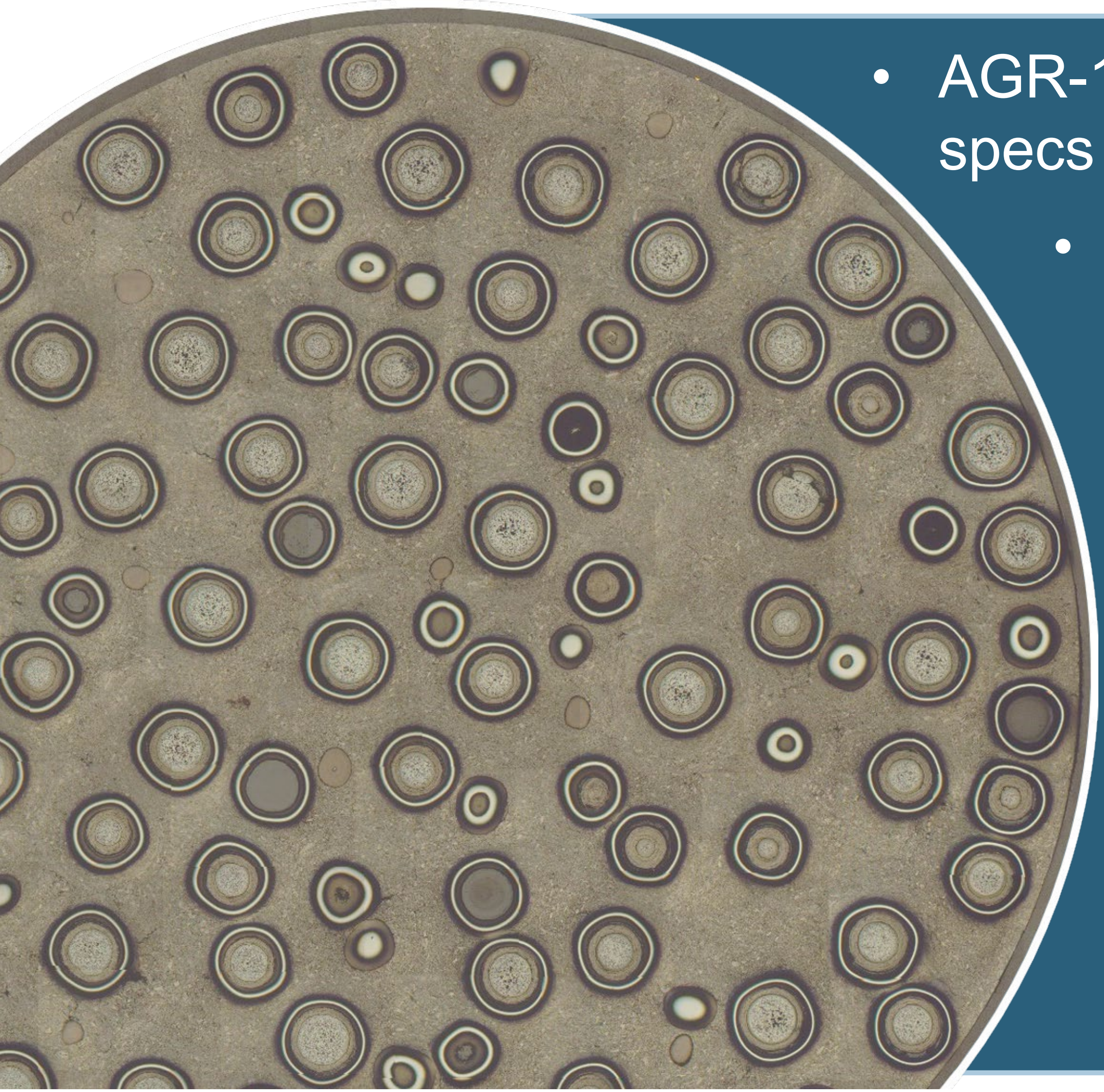


Particle Failure Statistics

- Use binomial statistics to determine upper bound on failure fractions at 95% confidence based on (1) observed failures and (2) number of particles in sample
- Historic design specifications and empirical failure fractions only concerned with TRISO failure
- AGR program has been successful at quantifying discrete failure of the SiC layer of UCO fuel as well
- AGR-1 and -2 TRISO failure fractions are ~10x lower than historic MHTGR design specs at 95% confidence



Key Points



- AGR-1 and AGR-2 fuel meet critical fuel product specs
  - Irradiations have been completed; low EOL R/B for AGR-1, AGR-2 R/B good at BOL but missing data for EOL
  - Fission product release levels quantified during PIE
  - Safety testing data obtained at 1600 – 1800˚C with excellent fuel performance
  - SiC and TRISO failure fractions quantified; TRISO failure below established design specifications for allowable particle failures

Questions?

Paul Demkowicz
paul.demkowicz@inl.gov

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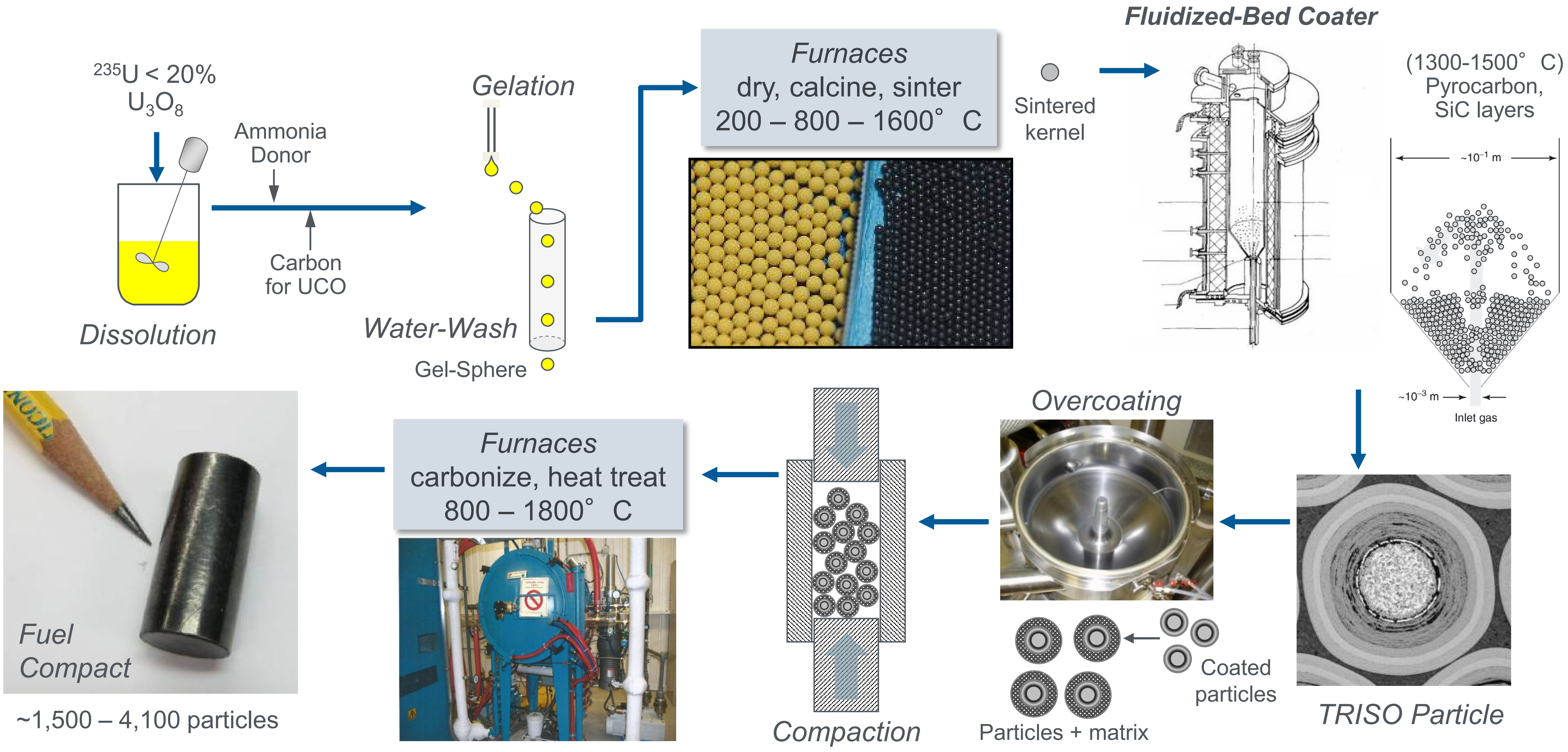
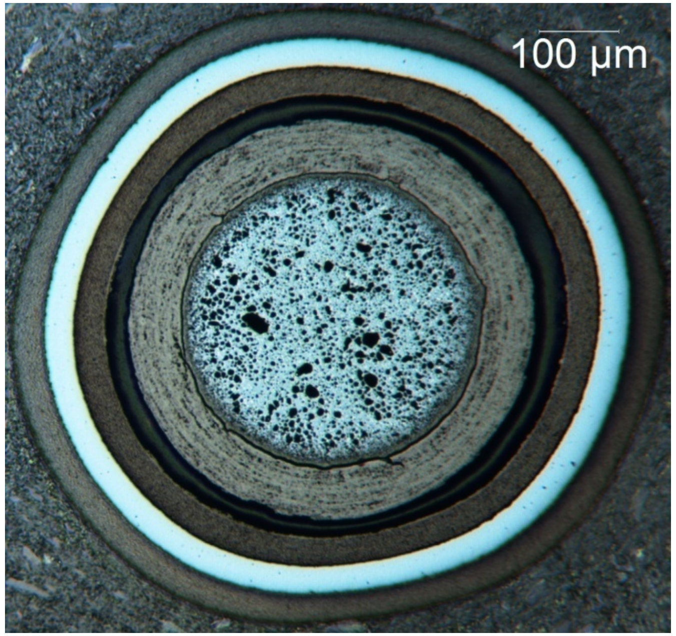
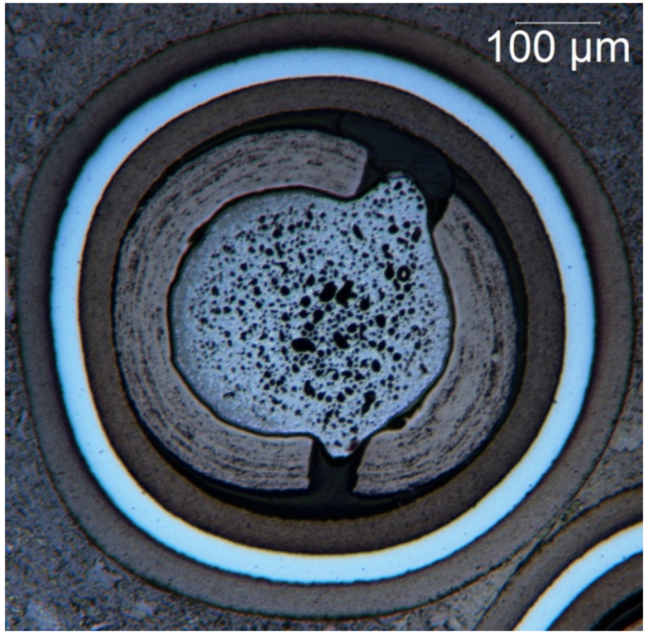
Extra Slides

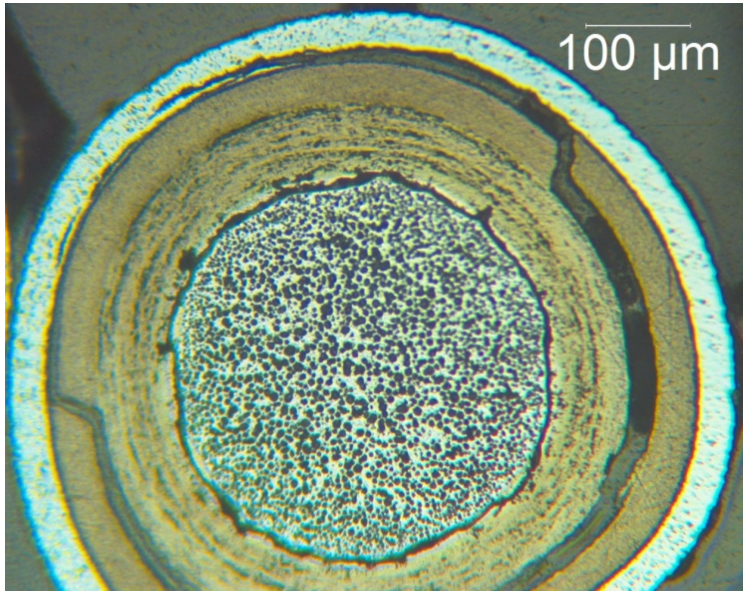
TRISO Fuel Fabrication



Irradiated Particle Morphologies







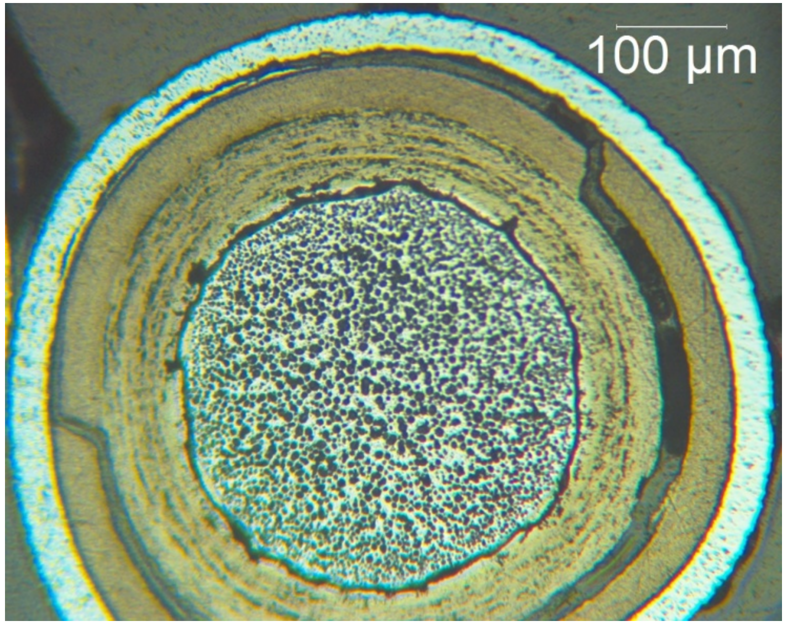
- Kernel swelling and pore formation
- Buffer densification and volume reduction
- Separation of buffer and IPyC layers
- No noticeable effects of CO(g) in particle
    - ⇨ UCO fuel is controlling P_{O2}

- Buffer fracture relatively common
- Dependent on irradiation temperature and fast neutron fluence
- When buffer separated from IPyC, buffer fracture appeared to have no detrimental effect on dense coating layers

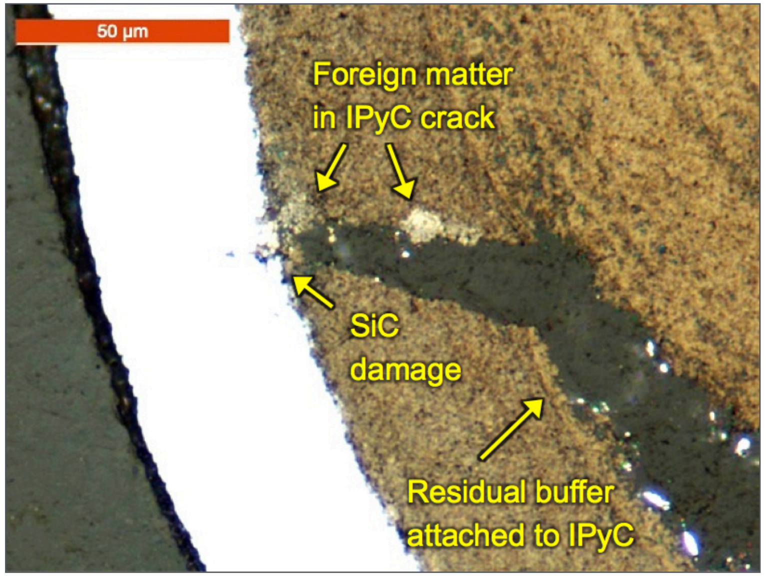
- Buffer densification in conjunction with strong buffer-IPyC bonding can lead to IPyC cracking

AGR UCO Particle SiC Failure

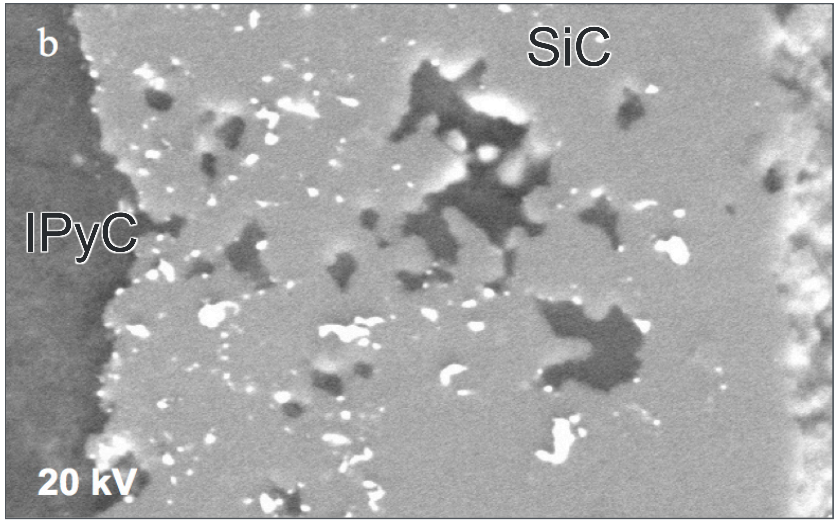
IPyC cracking and SiC separation during irradiation; no SiC failure



SiC failure during irradiation



SiC degradation and failure after 300 h at 1700° C



- Buffer densification in conjunction with strong buffer-IPyC bonding can lead to IPyC cracking and separation from SiC layer
- Allows localized attack of SiC layer by fission products (especially Pd)
- Pd attack can eventually result in loss of FP retention by SiC layer
- Degradation is worse at higher temperatures

Acronyms

- AGR – Advanced Gas Reactor
- ATR – Advanced Test Reactor
- BOL – beginning of life
- BWXT – BWX Technologies, Inc.
- DTF – designed to fail
- EFPD – effective full power days
- EOL – end of life
- FIMA – fissions per initial metal atom
- FP – fission product
- INL – Idaho National Laboratory
- IPyC – inner pyrolytic carbon
- MHTGR – modular high temperature gas-cooled reactor
- ORNL – Oak Ridge National Laboratory
- PIE – post-irradiation examination
- P_{O2} – oxygen partial pressure
- R/B – release rate to birth rate ratio
- UCO – uranium oxycarbide

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Response to Requests for Additional Information Related to NRC Review of Topical Report EPRI-AR-1(NP)

Advisory Committee on Reactor Safeguards
Meeting of the Subcommittee on Metallurgy & Reactor Fuels
May 6, 2020

Paul Demkowicz, Ph.D.
Idaho National Laboratory
AGR Program Technical Director

RAI Response Overview

- NRC submitted four RAIs concerning technical content of the topical report
- RAIs reflected a careful reading of the report and good grasp of key issues impacting the conclusions
- Applicant provided NRC staff with responses to RAIs
  - Additional information and technical discussion
  - Revisions to the topical report
- Revisions include minor changes to the conclusions and the supporting discussions in Section 8

RAI #1

RAI: Are there important operating conditions beyond burnup and temperature?

Response:

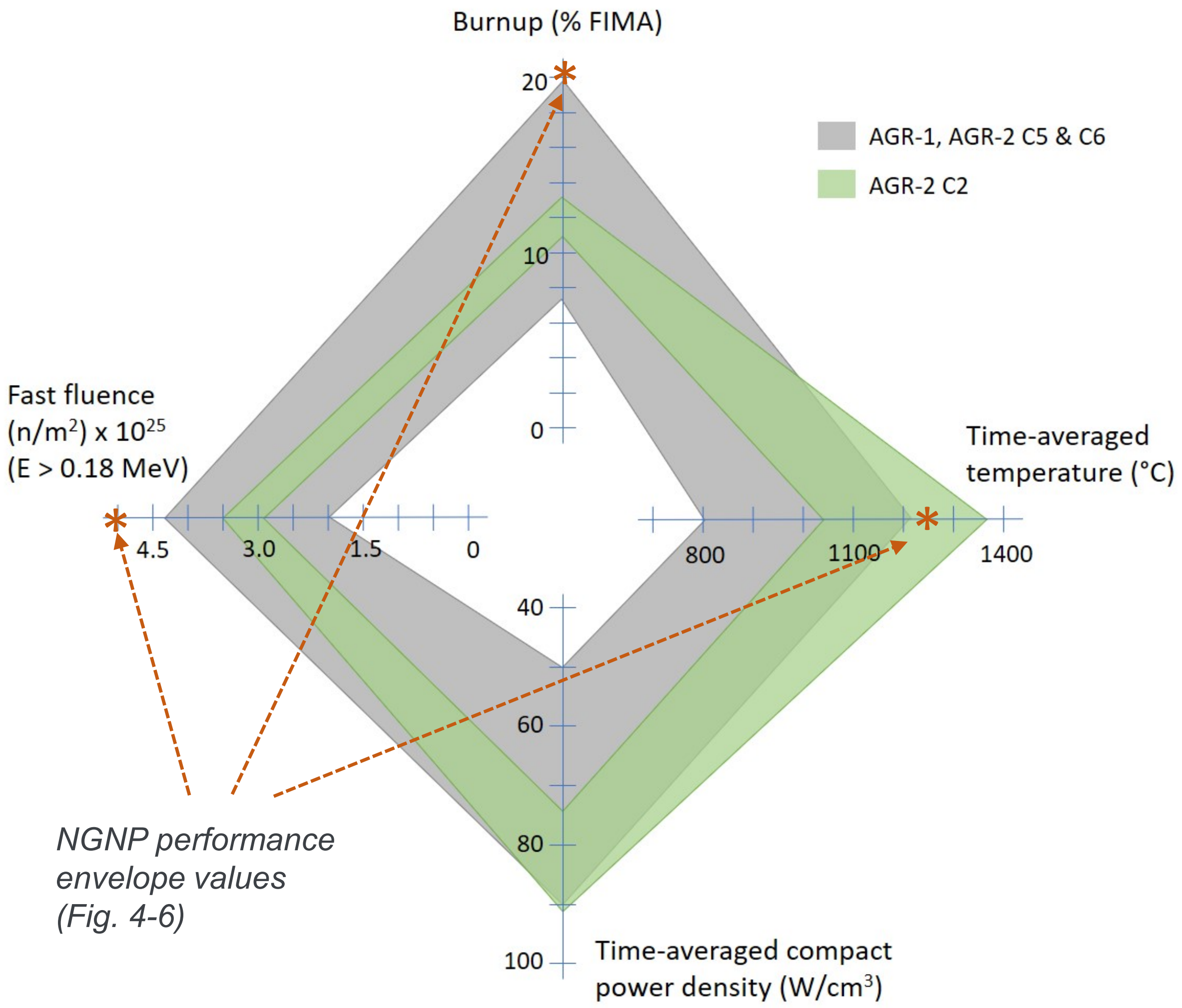
- Yes; irradiation conditions of *fast neutron fluence* and *power density* also considered important for fuel performance
- Ranges for burnup, temperature, fast fluence, and power density for AGR-1 and AGR-2 were added to topical report in tabular and graphical form
- Supporting discussion related to Conclusion 1 was revised

AGR-1 and AGR-2 Irradiation Conditions

- Data combined into two sets
  - AGR-1 and AGR-2 Capsules 5 and 6
  - AGR-2 Capsule 2 (higher temperature)

Property	AGR-1 + AGR2 C5&6		AGR-2 C2	
	Max	Min	Max	Min
Burnup (%FIMA)	19.6	7.3	13.2	10.8
Fast fluence (n/m^2 x 10^{25})	4.30	1.94	3.47	2.88
Time-average temperature (°C)	1210	800	1360	1034
Time-avg compact power density (W/cm^3)	90	50	92	74
Time-avg particle power (mW/particle)	66[a]/86[b]	37[a]/48[b]	88	71

a. AGR-1 values
b. AGR-2 C5 and C6 values



RAI #2

RAI: Are there important fuel properties beyond those included in Table 5-5, or key coating process parameters?

Specific items mentioned:

- Kernel-to-buffer volume ratio
- SiC microstructure
- UCO kernel stoichiometry
- Uninterrupted coating process

RAI #2.1: Kernel-to-Buffer Volume Ratio

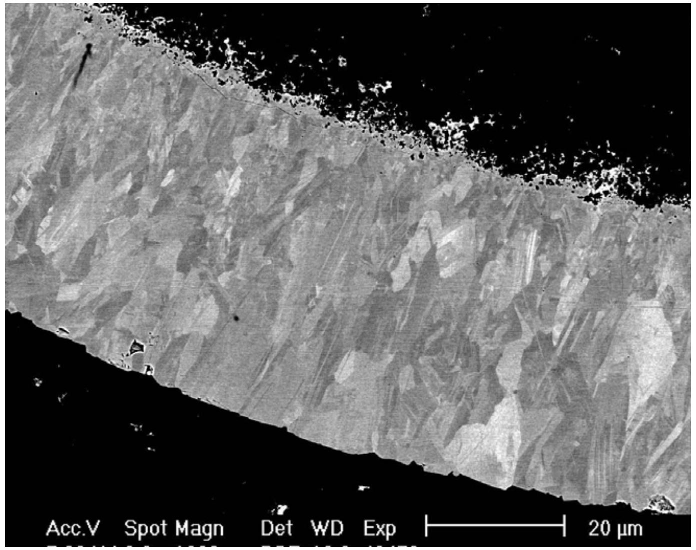
- SiC stress metric discussed in Section 4 of topical report

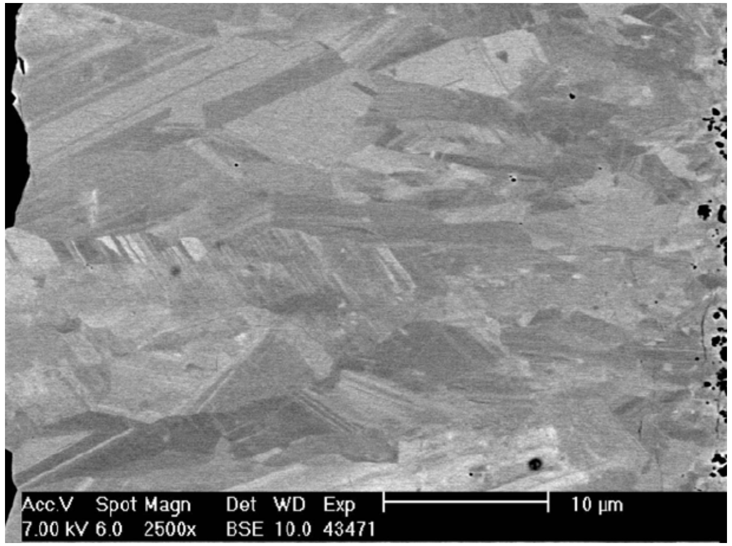
$$\sigma \propto \frac{B \cdot V_k}{V_b} \cdot \frac{r_{SiC}}{t_{SiC}} \qquad \text{Eq. 4.1}$$

- Ranges of σ were calculated for AGR-1 and AGR-2 particles at peak burnup to demonstrate the variation in these two irradiations
- Quantitative data on the SiC stress metric were added to the topical report

RAI #2.2: SiC microstructure

- AGR-1 and AGR-2 fuel specifications utilized a visual standard for SiC microstructure to avoid excessively large grain sizes and unfavorable orientations (e.g., highly columnar grains)
- Visual standard is added to the topical report





Reference micrographs of SiC with grains too large
(AGR-1 Fuel Product Specification, EDF-4380 Rev. 8, 2006)

RAI #2.3: UCO Kernel Stoichiometry

- Response included discussion of thermochemical analysis of kernel chemistry as a function of starting composition and burnup
- There is a wide range of oxide/carbide ratios that will adequately work to (1) limit CO(g) formation and (2) immobilize lanthanide fission products at peak burnups of ~20% FIMA
- The AGR fuel (30% UC_x) is in the middle of this range
- One would have to be significantly outside this range to fail to accomplish these goals
- Material from the response was incorporated in the fuel description in the topical report

RAI #2.4: Uninterrupted Coating

- Uninterrupted process is the *de facto* standard in modern TRISO fabrication
- Most historic data sets derive from fuel fabricated with this process
- AGR-1 and AGR-2 used this process
- Uninterrupted coating is considered a process requirement when applying the results of this topical report
- The discussion in Section 8 in support of Conclusion 2 was modified to reflect that point

RAI #3

RAI: Clarify the acceptable ranges for fuel in order to apply the topical report conclusions. Address differences between specifications and ranges of measured values on actual particles in Table 5-5.

Response:

- Revised data in Table 5-5
  - Provided confidence intervals for means and tolerance limits for the range of property values
  - The additional information demonstrates the range of values for the particles that were irradiated in these experiments
- Included additional discussion in topical report on interpretation of Table 5-5 values and how these would be applied to compare a fuel particle population to the AGR-1 and AGR-2 fuel

Table 5-5 (Revised): AGR-1 and AGR-2 Particle Properties

Particle Property	95% Confidence Interval Extrema	95%/98% Tolerance Limit Extrema
Buffer thickness (μm)	96.5 – 105.0	75.2 – 124.7
IPyC thickness (μm)	38.6 – 41.1	32.4 – 47.6
SiC thickness (μm)	34.8 – 36.2	30.6 – 41.2
OPyC thickness (μm)	39.1 – 44.3	33.6 – 51.6
Buffer density (g/cm^3)	1.04 – 1.11 [a, b]	NA
IPyC density (g/cm^3)	1.84 - 1.92 [b]	1.808 – 1.958 [b]
SiC density (g/cm^3)	3.196 – 3.209	3.191 – 3.217
OPyC density (g/cm^3)	1.878 – 1.923	1.850 – 1.949
IPyC anisotropy (BAF_{True}) [c]	1.024 [d]	1.036 [d]
OPyC anisotropy (BAF_{True}) [c]	1.018 [d]	1.030 [d]
Aspect Ratio	1.057 [d, e] 1.039 [d, f]	1.102 [d, e] 1.068 [d, f]

Footnotes explained topical report

RAI #4

RAI: Clarify any limitations on the fission product release data

Response:

- Revised text of Conclusion 3 to state that fission product release data “can be used to *<u>support</u>* licensing of reactors” (not intended to imply that the data are wholly sufficient for this purpose)
- Short-lived fission products: Clarified that Conclusion 3 only applies to fission products specifically referenced in the report

Questions?

Paul Demkowicz
paul.demkowicz@inl.gov

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Extra Slides

RAI #1: Additional Important Irradiation Condition Parameters

- Conclusion 1 of the TR states that “testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions.” Discussions under the conclusion reference a compact-averaged burnup of 7.3-19.6% fissions per initial metal atom (FIMA) and time averaged maximum temperatures of 1069-1360˚C. Are there other relevant performance parameters that bound the data set, such as those referenced in Figure 4-6 (packing fraction, fluence, power density)? Based on the discussion in the report, it appears some of these parameters could influence particle performance, but these values are not provided as bounds for the “range of normal operating and off-normal accident conditions”. Provide context for what constitutes a “range of normal operating and off-normal accident conditions” (e.g. reference a table), or provide a justification for why burnup and time averaged temperature are sufficient.

RAI #2: Additional Fuel Parameters

- Conclusion 2 of the TR states "UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance." While Table 5-5 provides a list of physical parameters for fuel specifications, it does not appear to directly cover all of the parameters that govern the specifications that constitute the parameter envelope applicable to the tested AGR fuel. Some elements in particular that the report highlights as important but that are not directly referred to in Table 5-5 include kernel-to-buffer ratio for the fuel particle (and potentially its associated size), columnar grain structure of the SiC, and carbon content of the UCO. It is not clear to the staff how these limits are applicable to the conclusions in the report. Provide a justification for how these parameters are implicitly captured in Table 5-5, supplement the report to include these parameters as limits for TR applicability, or provide justification for why these elements are not important.
- Further, the report references the importance of an uninterrupted coating process in the manufacture of the fuel. Do the parameters in Table 5-5 adequately restrict fuel particle specifications such that this process does not need to be explicitly required? If not, provide a justification, consider restricting the applicability of the TR to fuel manufactured using a similar process, or add a proxy measurable parameter to Table 5-5 that does provide assurance that an uninterrupted coating process has been followed.

Relationship Between Kernel and Buffer Volumes

- Relationship is actually more complex than just kernel and buffer volumes, and involves several other terms, including ***peak burnup***
- SiC stress proportionality given in Eq. 4-1:

$$\sigma \propto \frac{B \cdot V_k}{V_b} \cdot \frac{r_{SiC}}{t_{SiC}}$$

B = Peak burnup (% FIMA)
V_k = Kernel volume (mm^3)
V_b = Buffer volume (mm^3)
r_{SiC} = SiC radius (mm)
t_{SiC} = SiC thickness (mm)

Table 4-2. Particle design attributes contributing to tensile stress in SiC

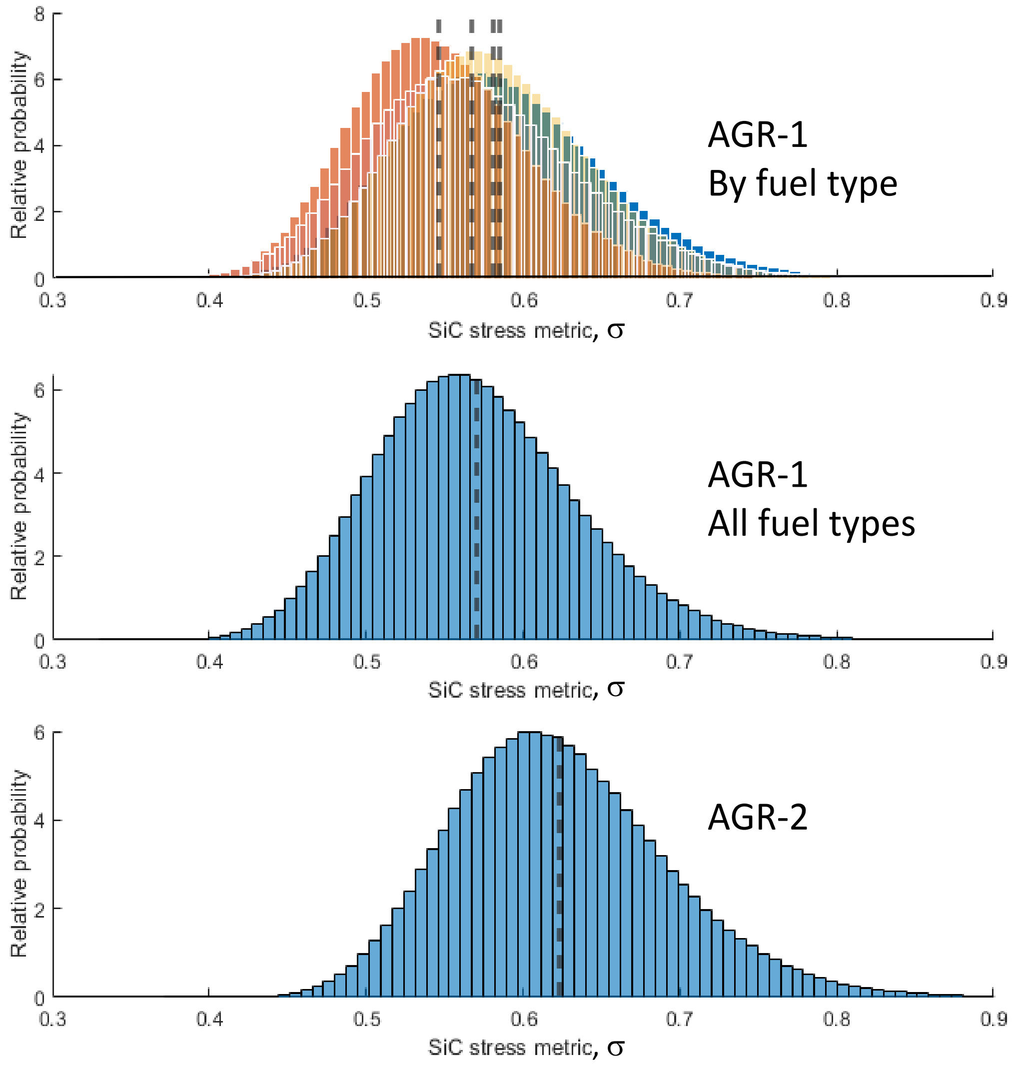
Parameter	German	JAERI HTTR	JAERI Advanced	U.S. LEU Fissile	U.S. Fertile	U.S. NPR	AGR
	Particle Design Parameters						
Kernel Composition	UO_2	UO_2	UO_2	UCO	UCO	UCO	UCO
Kernel Diameter (µm)	500	600	550	350	500	200	425
Buffer Thickness (µm)	95	60	100	100	65	100	100
IPyC Thickness (µm)	40	30	35	35	40	50	40
SiC Thickness (µm)	35	30	35	35	35	35	35
OPyC Thickness (µm)	40	45	40	40	40	40	40
Enrichment (%)	10.6	6	10	19.9	0.7	93	14.0
Burnup (% FIMA)	10	3.6	10	26	6	80	17
	Calculated Values						
Particle Diameter (µm)	920	930	970	770	860	650	855
Kernel volume (mm^3)	0.065	0.113	0.087	0.022	0.065	0.004	0.040
Buffer volume (mm^3)	0.107	0.082	0.134	0.065	0.065	0.029	0.088
Simple tensile stress metric	0.676	0.643	0.763	0.799	0.608	0.816	0.785
Normalized to German value	1.00	0.95	1.13	1.18	0.90	1.21	1.16

Relationship Between Kernel and Buffer Volumes (cont'd)

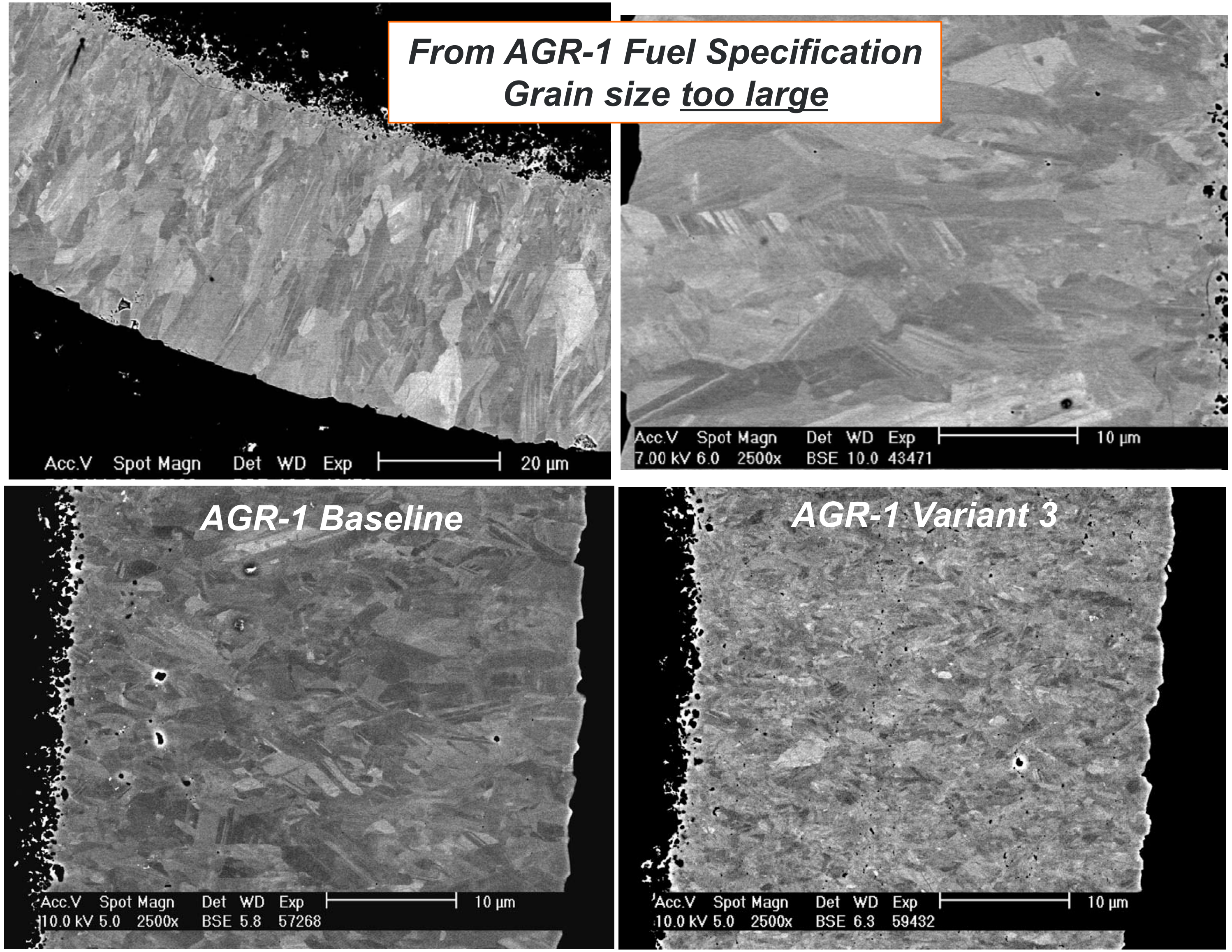
- Monte Carlo simulation used to explore the effect of randomly varying particle geometries on σ for AGR-1 and AGR-2 fuel
- One million random variates calculated for each particle dimension, for each fuel type
- Peak burnup used for each fuel type
- Results demonstrate the approximate range of values for the SiC tensile stress metric for AGR-1 and AGR-2 fuel at peak burnup

Test	SiC Stress Metric, σ			
	Mean	Distribution quantiles		
		1%	50%	99%
AGR-1	0.570	0.440	0.566	0.742
AGR-2	0.623	0.485	0.618	0.810

Histograms of σ



SiC Microstructure Comparison



SiC grain size of AGR-1 and AGR-2 fuel particles (Data presented in Table 5-3)

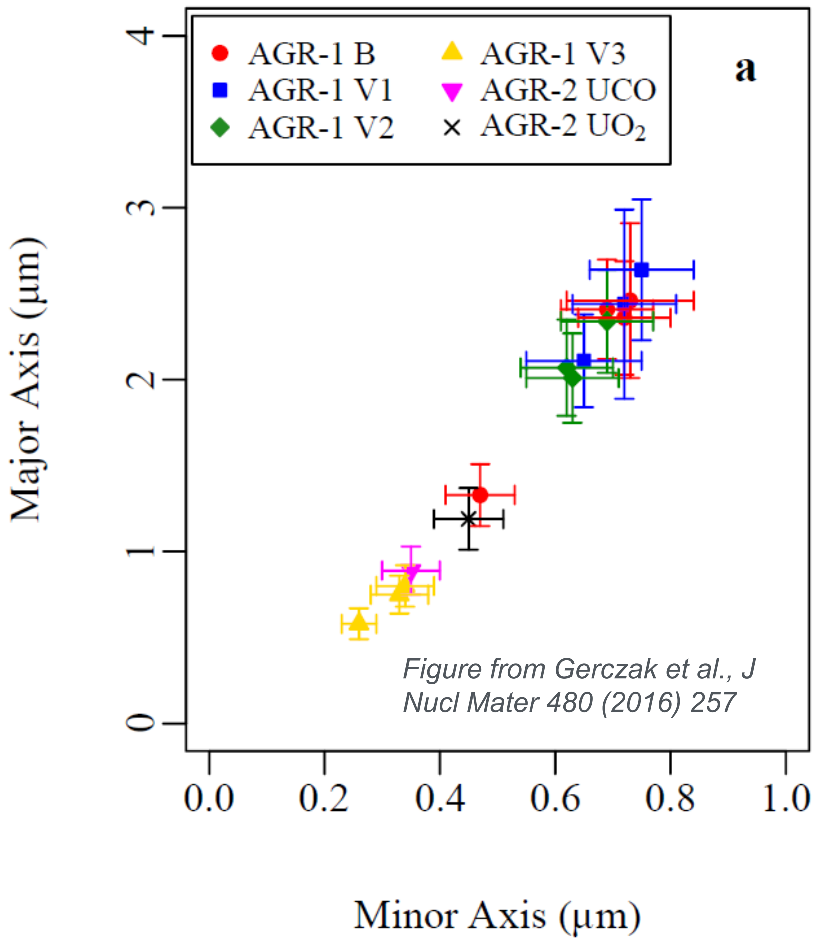
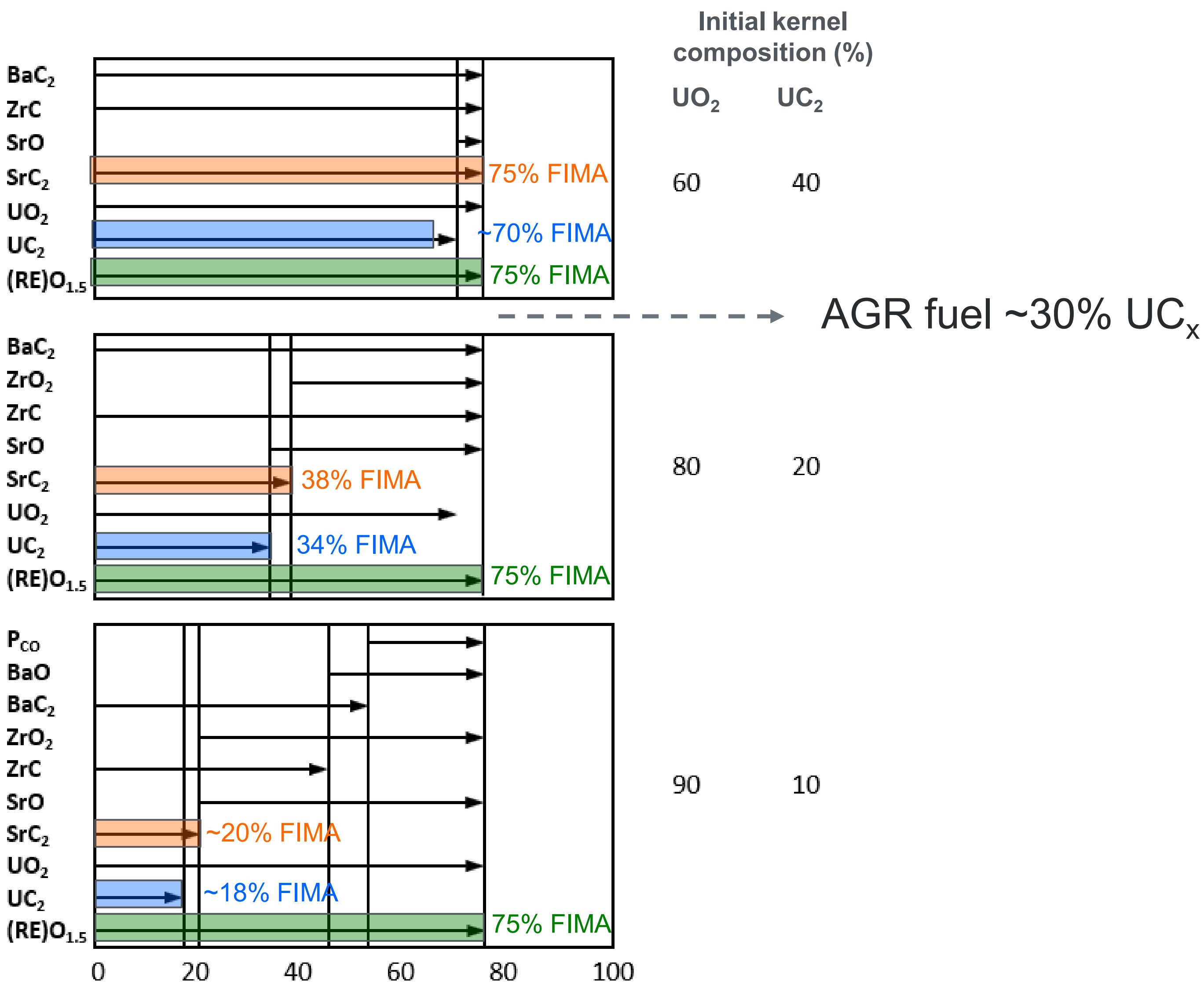


Figure from Gerczak et al., J Nucl Mater 480 (2016) 257

SiC Microstructure

- No significant performance differences were noted between the different AGR-1 and AGR-2 fuel particles during irradiation or in post-irradiation heating at 1600 – 1700˚C
  - No difference in fission product release
  - No difference in TRISO or SiC layer failure fractions
- Smaller-grained SiC exhibits increased fission product release (e.g., Ag, Eu, Sr) when heated at 1800˚C for >100 h
- This negligible difference in performance indicates that none of the AGR SiC types were approaching a limiting value in terms of grain size

UCO Kernel Stoichiometry



(Homan et al., 1977)

- Thermochemical calculations indicate oxide/carbide stability in UCO kernels as a function of starting UO_2/UC_2 content and burnup
- Calculations indicate that UC_x content as low as 10% is sufficient to maintain UC_x present in the kernel up to ~18% FIMA
- AGR-1 and AGR-2 fuel have ~30% UC_x content, indicating large margin of excess carbide for burnup ≤ 20% FIMA
- Recent thermochemical calculations suggest that as low as 5.5% UC_x is sufficient for acceptable performance of LEU TRISO up to ~16% FIMA (McMurray et al., 2017)

RAI #3: Acceptable Fuel Parameter Ranges

- The TR states that “fuel particles tested in AGR-1 and AGR-2 exhibited property variations…with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2.” Table 5-5 provides a set of characteristics for both tested fuel and specified ranges for “acceptable” fuel, both for mean values and extremes. The specification range is large[r] than the tested fuel range, sometimes substantially. Based on the provided data, there is a clear basis for use of the measured values in Table 5-5, but the basis for the specified range and especially the Maximum Allowable Fraction Beyond the Critical Limit(s) is not clear. Additionally, the table references the AGR-1 and -2 dataset separately in some cases. Provide a table with a clear requested range for each property for approval to be referenced in the conclusions. Further, provide a basis for useage of the values in this table for ranges beyond the tested ranges, paying particular attention to Maximum Allowable Fraction Beyond the Critical Limit(s), where the allowed particles may be substantially “worse” than those tested.

RAI #3 Background and Response Summary

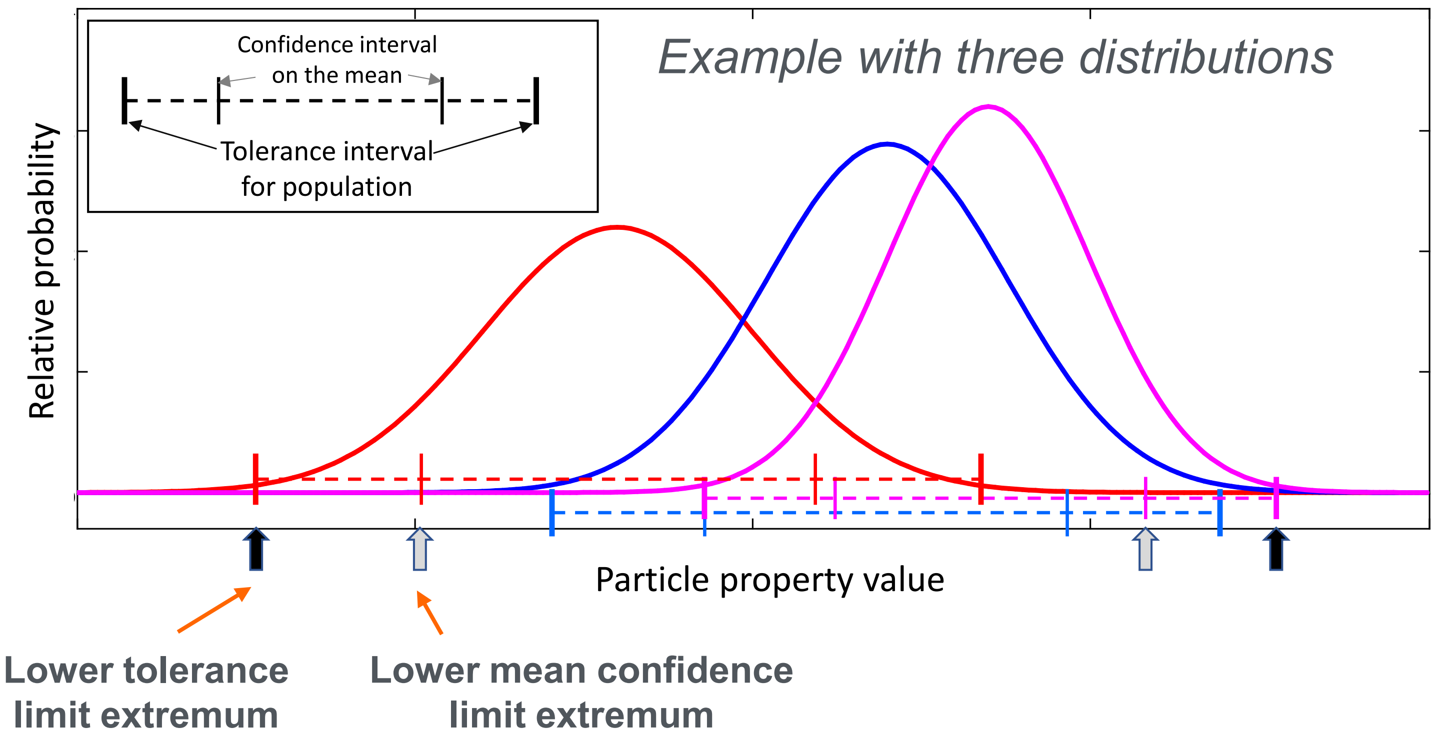
- Table 5-5 includes *specifications* and *measured ranges* for
  - Mean
  - 1% critical limits
- Separate AGR-1 and AGR-2 values provided *when specifications differed*
- Staff have requested greater clarity on the ranges of values that apply to the conclusions in this topical report
- Response to this RAI includes:
  - Revised set of property ranges, combining AGR-1 and AGR-2 fuel types
  - Discussion on the applicability of these data to other fuel populations

Table 5-5. Particle layer property 95% confidence values on means and dispersion limits

Particle Property	Sample Population	Specified Range of Mean [a]	Measured Mean Confidence Extrema [b]	Maximum Allowable Fraction Beyond the Critical Limit(s) [c]	Measured Dispersion Extrema [d]
Buffer thickness (μm)	AGR-1	85 – 115	96.5 – 105.0	1% ≤ 55	1% ≤ 82.5
	AGR-2			1% ≤ 58	1% ≤ 74.9
IPyC thickness (μm)	AGR-1	36 – 44	38.6 – 41.1	1% ≤ 30 1% ≥ 56	1% ≤ 33.0 1% ≥ 47.2
	AGR-2			1% ≤ 30 1% ≥ 52	1% ≤ 33.3 1% ≥ 47.5
SiC thickness (μm)	AGR-1	32 – 38	34.4 – 36.1	1% ≤ 25	1% ≤ 32.0
	AGR-2			1% ≤ 23	1% ≤ 31.7
OPyC thickness (μm)	AGR-1, -2	36 – 44	39.1 – 44.3	1% ≤ 20	1% ≤ 34.0
Buffer density (g/cm^3)	AGR-1	0.88 – 1.18	1.08 – 1.12 [e]	Not specified	
	AGR-2	0.95 – 1.15	1.04 [f]		
IPyC density (g/cm^3)	AGR-1, -2	1.85 – 1.95	1.851 – 1.914	1% ≤ 1.80 1% ≥ 2.00	1% ≤ 1.822 1% ≥ 1.951
SiC density (g/cm^3)	AGR-1, -2	≥ 3.19	≥ 3.204	1% ≤ 3.17	1% ≤ 3.198
OPyC density (g/cm^3)	AGR-1, -2	1.85 – 1.95	1.895 – 1.914	1% ≤ 1.80 1% ≥ 2.00	1% ≤ 1.881 1% ≥ 1.935
IPyC anisotropy (BAF_{True}) [g]	AGR-1	≤ 1.035	≤ 1.023	1% ≥ 1.06	1% ≥ 1.044
	AGR-2	≤ 1.045	≤ 1.026		
OPyC anisotropy (BAF_{True}) [g]	AGR-1, -2	≤ 1.035	≤ 1.020	1% ≥ 1.06	1% ≥ 1.038
Aspect Ratio [h]	AGR-1, -2	Not specified		1% ≥ 1.14	1% ≥ 1.098

Establishing Particle Property Ranges for AGR-1 and AGR-2

- Individual particle populations from each fuel type examined to establish the range of key properties (**AGR-1 Baseline, Variant 1, Variant 2, Variant 3, and AGR-2**)
- Means: establish the 95% confidence intervals
- Tolerance: establish the tolerance intervals corresponding to 1% tails
  - 98% for two-sided tolerance limit
  - 99% for single-sided tolerance limit
  - 95%/98% interval: "98% of the particles have property values within the tolerance interval, at 95% confidence"
- Upper and lower extrema of the confidence and tolerance limits are used to determine the ranges in Table 5-5.
- Engineering Calculations and Analysis Report (ECAR) being generated to describe process in detail



Basic Application of Table 5-5

- Compare the particle property characteristics of a fuel population to the AGR-1 and AGR-2 tolerance limit extrema in Table 5-5
- If the candidate fuel population 95%/98% tolerance limits (or 95%/99% for a one-sided tolerance limit) are within the bounds of Table 5-5, the applicant could assume that the performance of its fuel population would be similar to the AGR-1 and AGR-2 fuel, given similar irradiation conditions
- If the characteristics of one or more of the particle properties exceed the tolerance limit extrema in Table 5-5, the applicant would need to address the property deviation(s) in order to justify the applicability of the AGR-1 and AGR-2 performance results

Important Considerations for Comparing Particle Populations to AGR-1 and AGR-2 Particles

- AGR spec ranges determined based on historic experience and thermomechanical fuel performance modeling; <u>represent range over which particle failure is not expected to significantly increase</u> (e.g., see Skerjanc et al. J. Nucl. Mater 469 (2016) 99)
- Range of measured properties not the only fuel that would perform acceptably
- Objective of these data is not to provide a range enveloping all "acceptable" particles, but to provide sufficient statistical data to meaningfully compare two particle populations
- "*A particle in a fuel population could reside outside of the Table 5-5 ranges, but still be within the AGR specification and be expected to perform well under the AGR irradiation conditions, based on the amassed knowledge of TRISO fuel performance over the last several decades*." – Topical Report EPRI-AR1 (NP)
- Some properties in Table 5-5 more consequential for fuel performance than others
  - Usually one side of the property distribution is more critical than the other
- Fuel quality requirements will depend on intended use of the fuel (e.g., specs for allowable defects, failures) and applicable reactor safety analyses

RAI #4: Fission Product Release Data Applicability

- TR conclusion 3 states “fission product release data and fuel failure fractions, as summarized in this report, can be used for licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5.” The phrases “as summarized in this report” and “can be used for licensing of reactors” lack specificity, though the subsequent discussion is relatively clear.
  - (a) Consider revising to more specifically reference the data presented, and narrow the scope of the request “can be used for licensing of reactors” to something more appropriate for the TR.
  - (b) Conclusion number 3 further states that the aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions can be used for licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope detailed in the topical report. The staff notes that while the topical report supports fission gas release rates for most isotopes, it does not cover short-lived isotopes which decayed away before the particles discussed in EPRI-AR-1(NP) could be characterized. Therefore, the data set does not cover all of the fission gas release data necessary for licensing. Provide justification to support the statements in conclusion number 3 or limit the conclusion to the isotopes covered by the topical report.

Acronyms

- AGR – Advanced Gas Reactor
- BAF – Bacon anisotropy factor
- FIMA – fissions per initial metal atom
- HTTR – High-Temperature Engineering Test Reactor
- IPyC – inner pyrolytic carbon
- JAERI – Japan Atomic Energy Research Institute
- LEU – low-enriched uranium
- NGNP – Next Generation Nuclear Plant
- NPR – New Production Reactor
- OPyC – outer pyrolytic carbon
- UCO – uranium oxycarbide

United States Nuclear Regulatory Commission

Protecting People and the Environment

ACRS Subcommittee

TRISO Coated Particle Fuel Performance Topical Report

May 6, 2020

Advanced Reactor Program

Purpose

- The stated goal of the TR is to provide a foundational basis for establishing fuel performance of UCO TRISO particles. The TR lays out a set of fuel performance criteria related to TRISO particles based on the AGR-1 and AGR-2 tests and irradiation

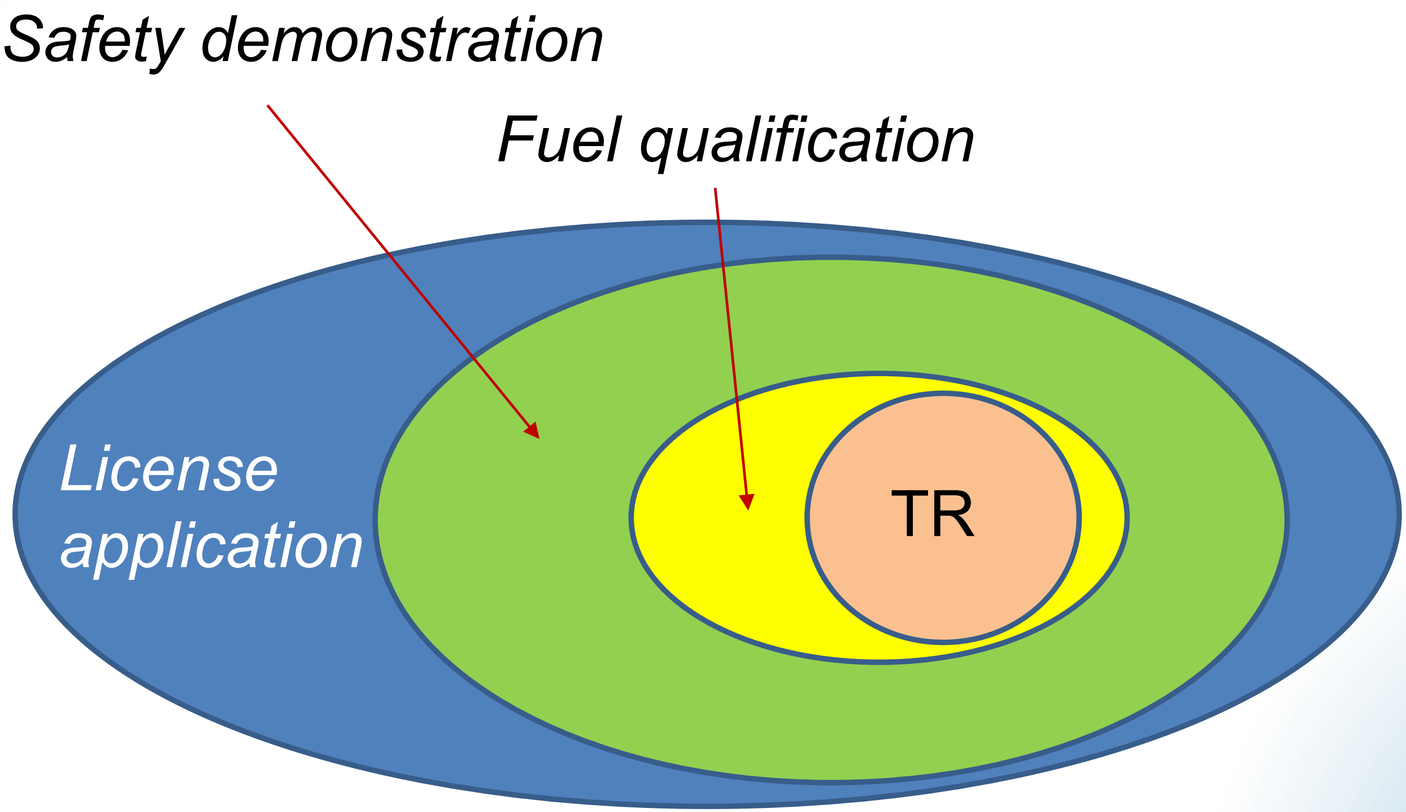
- At the request of the ACRS, the NRC staff will present the results of the staff review, including:
  - A summary of the findings in the report
  - The limitations and conditions incorporated into the SE and context behind each

Technical Review Team

- Jordan Hoellman, Project Manager (NRR/DANU/ARPB)
- Boyce Travis, reactor systems engineer and presenting on behalf of the staff (NRR/DANU/ARTB)
- Jeff Schmidt, senior reactor systems engineer (NRR/DANU/ARTB)
- Chris Van Wert, senior reactor systems engineer (NRR/DANU/ARTB)
- Antonio Barrett, reactor systems engineer (NRR/DANU/ARTB)

Background – Role of this TR

- The TR represents one stage in licensing a TRISO-fueled advanced reactor design (not to scale):



Regulatory Basis

- This is a non-traditional TR in that it is difficult to directly tie a regulatory basis to the information presented within at the present time

- Based on the expected use case for the TR, staff expects this document to be referenced to meet principal design criteria that resemble MHTGR-DC 10, “Reactor Design” and MHTGR-DC 16, “Containment Design”

- Further, the TR will likely factor into the use of a functional containment approach (as described in SECY-18-0096)

TR Conclusions Summary

1. Testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions.
2. The kernels and coatings of the UCO TRISO-coated fuel particles tested in AGR-1 and AGR-2 exhibited property variations and were fabricated under different conditions and at different scales, with remarkably similar excellent irradiation and accident safety performance results.
3. Aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions, as summarized in this report, can be used to support licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5 from AGR-1 and AGR-2.

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Review Background

- In effect, information presented in the TR would allow applicants or licensees who reference the TR to use the AGR data and associated conclusions for TRISO particle performance
  A. manufactured to the specifications in Table 5-5 and
  B. subject to the operational performance ranges detailed in the TR (Conclusion 1)

- Staff conducted an audit (report ML19310F085) and asked 5 RAIs (responses at ML20058A040 and ML20071D143)

- As a result of the review, the requested scope of the TR was narrowed somewhat (to the tested particle ranges) and additional performance parameters were identified as limits

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Notable Findings

- The TR represents a modified approach for qualifying a novel fuel design – rather than deterministic limit values, fuel performance is characterized statistically across a population of particles based on test conditions

- TR makes justification and draws conclusions for TRISO particles only, not compacts or other final fuel forms

- QA associated with the data gathered and referenced in the report part of “technology development" activities reviewed by NRC during NGNP

Notable Findings (cont.)

- NRC staff agrees that largely independent of manufacturing process, it is possible to establish a set of measurable criteria that can be used to justify predicted performance

- This predicted performance is based on demonstrated results from testing, and the test conditions represent an envelope bounding justifiable performance based on the TR

- This TR may not cover all accident scenarios - once particles reach conditions that indicate failures may occur, an applicant or licensee referencing this TR would need to justify how accident conditions were bounded by the data or provide analyses/testing to justify fuel performance in the specific scenario.

Staff Limitation 1

- **Limitation 1**: The scope of this TR applies only to the UCO TRISO particles themselves. How the final fuel form is qualified and any impacts of the fuel form on the holistic fuel performance (for instance, any uranium contamination in the compact material) is the responsibility of the vendor or designer referencing this TR.

- The scope of the report is confined to the particles themselves, and staff recognizes final fuel forms are likely to differ among designs. This limitation was written to ensure fuel qualification accounts for the entire fuel form.

Staff Limitation 2

- **Limitation 2**: This TR applies only to UCO TRISO particles that fall within the ranges discussed in Section 5.3 of the TR. If an applicant chooses to use UO2/UC2 ratios or burnup values that differ meaningfully from those used in the AGR program, the applicant must provide a justification for how the burnup and carbon content ratios conform to the performance ranges discussed in Section 5.3 of the TR.

- Table 5-5 captures the physical specifications of the particle layers that conform to the data discussed in the TR. However, some parameters – such as the carbon/oxygen ratio (which is dependent on burnup) are not captured within the table and were deemed important to ensure adequate fuel performance within the bounds set forth by the TR.

Staff Condition 1

- **Condition 1**: An applicant or licensee referencing this TR must evaluate any discrepancies between their fuel particles and the TRISO particles used in the AGR program - specifically, reviewing the ranges specified in Table 5-6 for stress values to capture any effects from different kernel sizes to ensure the data in the TR remain applicable.

- This condition was primarily written to address fuel kernel size, which is an important factor in evaluating particle stresses. Staff recognizes that there a spectrum of particle sizes that result in adequate fuel, but this value is not constrained by Table 5-5 or the TR conclusions. This condition offers flexibility but adds a suitable constraint on this parameter.

Staff Condition 2

- **Condition 2**: The performance limits in Table 6-6 and Figure 6-30 of the TR are the result of different tests with distinct samples, not all of which had the maximum bounds occur during the same test. Further, when failures may occur, the data supporting the TR provides empirical evidence of failure based on aggregate test conditions rather than mechanistic evidence of failure based on individual particle conditions. Applicants referencing this TR must ensure that they either remain within the tested bounds or justify how their proposed operating conditions remain applicable.

- This condition is primarily intended to capture proposed operation condition near the edges of the AGR testing envelope discussed in the TR – the report provides a basis for a set of operational conditions, and conditions beyond those tested bounds will require additional justification.

Staff Condition 3

- **Condition 3**: Data discussed in this TR does not consider the impacts of short-lived fission products beyond those captured in the gas phase during experiments. Any applicant or licensee referencing this TR must disposition the impacts, if any, of short-lived fission products on the safety analyses and operational dose considerations, or any other regulatory considerations resulting from short-lived fission products, in addition to the data discussed in the TR.

- This condition is relatively straightforward – the TR only provides for justification for the isotopes which data was gathered on. Isotopes that are not discussed (for instance, those that decay away before PIE) should be examined separately as required.

Conclusion / Discussion

- Based on the staff review of the TR and the information provided in the RAI responses, staff agrees with the conclusions requested in the TR, subject to the limitations and conditions identified in the SE and discussed earlier