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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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KAIROS POWER LICENSING SUBCOMMITTEE

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OPEN MEETING

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MONDAY

OCTOBER 17, 2022

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The Subcommittee met via Video Teleconference, at 2:00 p.m. EDT, David Petti, Chairman, presiding.

COMMITTEE MEMBERS:

DAVID PETTI, Chair

RONALD G. BALLINGER, Member

CHARLES H. BROWN, JR., Member

VESNA DIMITRIJEVIC, Member

GREGORY HALNON, Member

JOSE MARCH-LEUBA, Member

JOY L. REMPE, Member

MATTHEW SUNSERI, Member

ACRS CONSULTANTS:

DENNIS BLEY

STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

WEIDONG WANG

ALSO PRESENT:

BENJAMIN BEASLEY, NRR
MATT DENMAN, Kairos Power
TIMOTHY DRZEWIECKI, Kairos Power
DARRELL GARDNER, Kairos Power
RUSSELL GARDNER, Kairos Power
MICAH HACKETT, Kairos Power
RACHEL HAIGH, Kairos Power
BRANDON HAUGH, Kairos Power
MICHELLE HAYES, NRR
ISHAK JOHNSON, Kairos Power
RYAN LATTA, Kairos Power
GABRIEL MERIC, Kairos Power
SCOTT MOORE, ACRS
DREW PEEBLES, Kairos Power
NADER SATVAT, Kairos Power
NICOLE SCHLICHTING, Kairos Power
JEFF SCHMIDT, NRR
JIM TOMKINS, Kairos Power
CHRIS VAN WERT, NRR
GARETH WHATCOTT, Kairos Power

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P R O C E E D I N G S

2:00 p.m.

CHAIR PETTI: Good afternoon, everyone.

The meeting will now come to order

This is a meeting of the Kairos Power Licensing Subcommittee of the Advisory Committee on Reactor Safeguards.

I'm David Petti, Chairman of today's Subcommittee meeting.

ACRS members in attendance are Charles Brown, Greg Halnon, Jose March-Leuba, and Ron Ballinger. Dennis Bley and Steve Schultz, our Consultants, are also online.

Weidong Wang, of the ACRS staff, is the Designated Federal Official.

And I forgot Joy Rempe is also online.

During today's meeting, the Subcommittee will review the staff's Safety Evaluation on the Topical Report entitled "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor," Revision 2.

The Subcommittee will have presentations by and hold discussions with the NRC staff, Kairos Power representatives, and other interested persons regarding this matter.

The product presentations by the Applicant and the NRC staff may be closed in order to discuss information that is proprietary to the Licensee and its contractors, pursuant to 5 USC 552b(c)(4). Attendance at the meeting that deals with such information will be limited to the NRC staff and its consultants, Kairos Power, and those individuals and organizations who have entered into an appropriate confidentiality agreement with them. Consequently, we need to confirm that we have only eligible observers and participants in the closed part of the meeting.

The rules for participation in all ACRS meetings, including today's, were announced in The Federal Register on June 13th, 2019. The ACRS section of the U.S. NRC public website provides our Charter, Bylaws, agendas, Letter Reports, and full transcripts of all full and Subcommittee meetings, including slides presented there. The meeting notice and agenda for this meeting were posted there.

We have received no written statements or requests to make an oral statement from the public.

The Subcommittee will gather information, analyze relevant issues and facts, and formulate proposed positions and actions, as appropriate, for deliberation by the full Committee.

The rules for participation in today's meeting have been announced as part of the notice of this meeting previously published in The Federal Register.

A transcript of the meeting is being kept and will be made available, as stated in The Federal Register notice.

Due to the COVID pandemic, today's meeting is being held over Microsoft Teams for ACRS, NRC staff, and the Licensee attendees.

There's also a telephone bridge line allowing participation of the public over the phone.

When addressing the Subcommittee, the participants should first identify themselves and speak with sufficient clarity and volume, so that they may be readily heard. When not speaking, we request that participants mute your computer microphone or phone by pressing *6.

We'll now proceed with the meeting, and I'd like to start by calling upon NRR management. Michelle Hayes will now make an opening statement.

MS. HAYES: Thank you, Dr. Petti.

I'm Michelle Hayes, Chief of Technical Branch 1 in the Division of Advanced Reactors and Non-Power Production and Utilization Facilities in the

Office of Nuclear Reactor Regulation.

We're happy to be meeting with you today. As you know, the Hermes Test Reactor Construction Permit Review is underway. The Topical Report we're discussing today, and two others that we're going to bring to you early next year, are referenced in this Hermes application. So, these will need to be finished before we complete the Construction Permit Review.

We met with you on the Kairos Fuel Performance Topical Report a year ago. The Fuel Performance Report described a methodology for modeling TRISO failed fuel fraction and fission product released from the TRISO particles. Today, we are discussing the Fuel Qualification Topical Report.

Kairos relies on the previously-approved EPRI Topical Report for qualification of the TRISO fuel particles. The Kairos Fuel Qualification Report gives details on the qualification of the pebble form of the fuel which will be used in their fluoride salt-cooled reactors.

The Kairos Report provides a method for qualification that considers mechanical and structural performance, as well as chemical, thermal, and irradiation effects.

After Kairos gives an overview of the Fuel Qualification Report, NRC staff will give you an overview of our report, our review and our Safety Evaluation.

We will be glad to hear your insights and comments. Are there any questions before we get started?

Then I will turn it back over to Dr. Petti or Kairos.

CHAIR PETTI: I just noticed that Vesna Dimitrijevic has joined. So the court reporter can report her as present.

Jim, it's all yours.

MR. TOMKINS: Okay. Thank you, Dr. Petti.

My name is Jim Tomkins, and I'm Manager of Fuel Licensing at Kairos Power.

Today, we're going to present our methodology for qualifying our fuel for the Kairos Power Reactors. Ryan Latta, who is our Principal Engineer for Fuel Qualification, will be doing the bulk of the presentation today.

We have individuals at various Kairos locations, and I'm going to start with KP Headquarters in Alameda, California. I just introduced myself.

Go ahead, Ryan.

MR. LATTA: Yes, my name is Ryan Latta. I'm a Principal Engineer for Fuel Qualification, and I'll be giving most of the main technical talk today.

MR. JOHNSON: I'm Ishak Johnson. I'm a Safety Analysis Engineer.

MR. MERIC: Gabriel Meric, Engineering Fueling Materials.

MR. SATVAT: Hello. This is Nader Satvat, Senior Manager of Core Design.

MR. DRZEWIECKI: I'm Tim Drzewiecki. I'm a Senior Engineer, Safety Analysis.

MR. TOMKINS: Okay. Thank you.

In Charlotte, North Carolina, could folks introduce themselves?

MR. D. GARDNER: Darrel Gardner, Senior Director of Licensing.

MR. PEEBLES: And we've got Drew Peebles. I'm a Licensing Manager for Safety.

MS. SCHLICHTING: Nicole Schlichting, Senior Licensing Engineer.

MS. HAIGH: Rachel Haigh, Licensing Engineer.

MR. PEEBLES: And that's it in Charlotte, Jim.

MR. TOMKINS: Okay. And how about KP

Southwest?

MR. DENMAN: This is Matthew Denman. I'm the responsible Engineer for Mechanistic Source Term.

MR. TOMKINS: Okay. Did I miss anyone? Is anybody calling in by phone? I think so.

MR. WHATCOTT: Jim, I'm online. This is Gareth Whatcott, Lead Engineer for Fuel Handling and Storage.

MR. TOMKINS: Okay.

MR. HAGAMAN: Jordan Hagaman, Director of Reliability Engineering and Quality Assurance at Kairos Power.

MR. R. GARDNER: And Russell Gardner, Senior Engineer of Fuel Performance.

MR. TOMKINS: Anyone else? How about Micah?

Well, somebody should send Micah a Slack, by the way. But is there anyone else who's on the line for Kairos?

Okay. Rachel, do you want to go ahead and bring up the slides?

While she's doing that, I just wanted to touch again on proprietary and non-proprietary materials. The slides are non-proprietary, but it's conceivable that in the course of answering a question we might have to reveal some proprietary information. So, if we do that, we will kind of capture the question and cover that during the closed session.

And with that, I'll turn it over to Ryan.

Next slide.

Actually, I'm turning it over to myself. Sorry about that.

So, the applicability of this Topical Report, as I've said before, it presents the methodology for qualifying fuel for use in KP-FHRs. Qualification is subject to the conditions in the Topical Report.

I want to make a point that this Topical Report is a methodology for qualification. It is not the qualification. That's going to have to be demonstrated over the coming months and year or so. And that qualification will be documented in Safety Analysis Report documents as part of licensing applications.

The Topical is applicable to a test or power KP-FHR, provided that the conditions are met, but some of the conditions apply to one or the other.

Next slide.

So, qualification. So, qualified fuel means fuel for which there's a reasonable assurance that the fuel, if it's fabricated in accordance with its specification, will perform consistently with the Safety Analysis. So, that's kind of a working-level definition we've been using.

And now, I'll turn it over to Ryan, who is going to talk a little bit about our design and our fuel, and then, he'll go through the qualification methodology.

CHAIR PETTI: So, Jim, this is Dave. Just a question.

So, this report outlines all of the tests, analytical approaches, whatever you want to call it, that when taken together, collectively constitute fuel qualification from a scope perspective?

MR. TOMKINS: Yes.

CHAIR PETTI: Okay. Thank you.

MR. LATTA: Okay. Can you advance one slide?

MR. TOMKINS: Rachel, next slide. Next slide.

MR. LATTA: Yes, one more slide. Thank you.

So, this is Ryan Latta speaking now.

So, as a point of reference for the FHR, which is the application of the fuel, we have this slide. And so, we have two reactors here. There is Hermes Test Reactor, which is a non-power test reactor, and there's, farther down road, future KP-X, which is a commercial electric power reactor.

The kind of characteristics of the reactor are given here. Flibe coolant, graphite reflector. All of them use the same fuel on the design, which is a pebble fuel containing TRISO fuel particles.

The power of the Hermes, 35 megawatts, thermal; KP-X, 10 times greater in power. Both are low pressure systems, have low pressure systems below 200 kPa. Inlets, 550 C, and outlets, 620 to 650 C.

And on the right is a schematic of the reactor. You can see the vessel outlined. There's a white space between the inner cavity where the pebbles are contained, which is the core, and the graphite reflectors outside of that, and then, the vessel wall.

And so, the pebbles are contained within that inner cavity. They're in a packed-bed formation with Flibe coolant flowing from top to bottom and from bottom to top in the reactor. And the pebbles also enter in the bottom at the fuel chute, and then, they exit the reactor at the defueling chute at the top of the reactor.

And so, the pebbles are buoyant in the

Flibe coolant and the bed itself is in a packed configuration, and the pebbles move very slowly over time through the core, and then, are recirculated and inspected, and then reintroduced into the bottom of the core until they reach their limits, specifically, for burnup.

MR. TOMKINS: Any questions on that>?

Okay. So, next slide.

MR. LATTA: Okay. This is a little schematic of the annular fuel pebble and the TRISO fuel particle. The TRISO particle shown here is typical of what you have seen before, a UCO kernel with multiple coating layers of PyC, and then, a SiC layer.

The fuel particles are contained within the fuel pebble -- this pebble, specifically 40 millimeters in diameter, which is the size of a ping pong ball. Special to this design is that the pebble has three regions. There's an inner region that is a lower density than the rest of the matrix material.

Then, there's a fuel region that contains the TRISO particles, and then, outside the fuel region there's a shell that's free of fuel and that separates the fuel from the surface of the pebble.

Next slide, please.

MEMBER REMPE: This is Joy.

MR. LATTA: Uh-hum?

MEMBER REMPE: Can we go back to the prior slide, please?

You're right, we've seen this before. But this pebble and the way it's fueled is different than the German fuel because of this low density core region. But are there other differences? Are the pebbles packed more closely than the German fuel? And this fuel-free outer matrix shell, how does that differ from what we've seen in Germany or what's being done in China, for example?

MR. LATTA: Sure. So, I will go over the differences.

So, first off, the pebble is smaller in diameter. It's 40 millimeters versus 60 millimeters. We have this interior lower density core, and that's to allow the pebble to be net buoyant within the Flibe. That does not exist in the historic German pebble.

The fuel region contains a higher packing fraction of particles than historically have been done with German pebbles, but it's consistent with what has been done with compacts, and specifically, with AGR compacts.

The fuel-free outer shell is thinner in dimension than has historically been used in the German pebbles.

MEMBER REMPE: Thank you.

At some point, I guess I'd be interested in how you feel comfortable that this tighter packing is not going to damage the coatings of the particle.

MR. LATTA: Sure. So, in the manufacturing/development program we have, we'll be fabricating these with surrogate materials and proving through deconsolidation-leach-burn-leach after fabrication that the defect fraction of particles post-fabrication are within the specifications. So, we'll be able to demonstrate through sampling of product that we meet our specification.

MR. TOMKINS: And the particles are overcoated. So, they have a built-in, you know, separation, if you will.

MR. LATTA: Yes. So, all particles are overcoated, and then, poured into these molds to fabricate and press this region. And so, there's specifications on that as well to ensure that those things are met.

MEMBER REMPE: So, remind me what this overcoating is composed of? And do you have any irradiation data to show how it works? I mean, that was not done in the AGR tests, right?

MR. LATTA: It was done. So, overcoating is --

MEMBER REMPE: Oh, it was done? Okay.

MR. LATTA: Overcoating is a traditional method for packing and keeping particles separated from one another through many of the programs that exist, you know, internationally or domestically.

So, you roll the particles in the matrix material. All the matrix material, the three zones, is the same material. It just has, you know, either has a lower density from having more -- fabricated with more porosity or it's fabricated with TRISO particles embedded in it.

MEMBER REMPE: Is the packing fraction tighter than what was done in AGR-1 compacts?

MR. LATTA: No, it's within that range.

MEMBER REMPE: Okay. Thank you.

CHAIR PETTI: So, Ryan, since this was brought up -- I was going to bring it up later --

MR. LATTA: Okay.

CHAIR PETTI: -- deconsolidation-leach-burn-leach is not a perfect QC technique. And the concern in pressing is (a) you're right, breaking particles, but (b) partial cracks in layers that would pass through the QC, and the cracked particles, under irradiation, the cracks potentially growing. This is just one of the concerns I have with the qualification approach. As we get into it a little bit more maybe later in the presentation, or even in the closed session, we can talk some additional details.

MR. LATTA: Okay. Thank you.

MR. TOMKINS: Okay. Next slide.

MR. LATTA: Okay. I was just going to go through these parts more individually, as I've already done a little bit just before.

So, the kernel is a UCO kernel. It's a mixture of UO2 and uranium carbide phases. So, this is where the uranium is and where the fission occurs, and the fission products are generated. Outside of the UCO kernel is a porous carbon buffer layer. This layer kind of serves as the plenum for fission product gases generated in the kernel and, also, mechanically separates the kernel from the structural PyC and SiC layers.

On top of that is the IPyC layer. So, this is the first real structural layer and barrier, fission product barrier of the fuel particle.

You can go to the next slide.

MR. TOMKINS: Rachel, next.

MR. LATTA: So, after the IPyC is the SiC layer. So, this is a silicon carbide layer that is the primary structural layer and fission product barrier to prevent fission product release.

The next layer on top of that is the OPyC layer. This is kind of the final and secondary layer of barrier for fission product retention structural barrier or structural component of the particle.

And then, finally, as we had just described, in fabrication, you overcoat the particles, and then, they're pressed into the fuel region to obtain your nominal packing fraction.

MR. TOMKINS: Okay. Next.

MR. LATTA: And now, talking about the features of the pebble design itself.

So, first off, going from interior to exterior, on the interior is the low carbon core, low density carbon core. And so, the objective of this core is that is reduces the overall density of the pebble, so that it is net buoyant in the Flibe coolant.

Then, outside of that region is a shell of fuel-containing matrix material. And so, the advantage of this is that the fuel is moved to the outside of the pebble, and this lowers the fuel temperature for a given power rating versus if the fuel was uniformly distributed throughout the whole pebble. So, this helps you obtain higher power density, lower temperatures in an FHR.

And then, finally, there's the fuel-free outer shell. And so, this is a region of the same matrix material that separates the fuel region from the Flibe or exterior environments and protects the fuel from mechanical damage.

MEMBER BALLINGER: This is Ron Ballinger.

I have a question relating to the low carbon density core. How much margin do you have, or does it really matter, where if you get a change in density pebble-to-pebble, it alters the migration rate through the core? Is that an issue?

MR. LATTA: You're worried about migration of fission products through the core?

MEMBER BALLINGER: No, no. Migration of -- excuse me -- movement of the pebble, of the fuel pebble itself through the core.

MR. LATTA: Oh, yes. Okay. So, we do expect the pebble to densify with accumulated fluence. There's also a distribution of allowable densities from the fuel specification, and the density of the pebble is set relative to the Flibe density, such that it would be able to maintain positive buoyancy even with the extreme bounding conditions of what the density could become with irradiation.

MEMBER BALLINGER: So, I guess when you measure the burnup of pebbles that exit the core against what you might expect it to be, you would notice if there was something funny going on?

MR. LATTA: We would also be performing an inspection. So, there would be a visual inspection of the pebbles, and we would be able to examine the diameter of the pebble through that process.

MEMBER BALLINGER: No, no. I guess what I was saying was you anticipate by analysis, or whatever, that the pebble that exits the core has a certain burnup, and then, you measure it and you discover that the burnup is actually X plus or minus. Is that an indicator that the pebble has migrated through the core at a different rate than expected?

MR. LATTA: It could potentially be. If the burnup was significantly larger than expectation or significantly lower, then that could be an indication that the pebble had traversed either slowly --

MR. TOMKINS: By the way, these pebbles

move kind of en masse. I mean, there isn't that much room in there. So, you're not going to have one pebble that speeds ahead of the others. We've done visuals of this process.

MEMBER BALLINGER: Okay. All right. Okay. Because I recall an experiment that Andy Kadak did a very long time ago where he mixed the colors of the pebbles and looked at the migration rate through the core, and the density did make a difference in that case -- yellow and red and green pebbles, believe it or not.

MR. HACKETT: And we do expect a distribution in the migration pathway for the pebbles anyway, and we're accounting for that. And that's the reason why we do the pebble inspection, to ensure that the pebbles are extracted within the expected burnup range that we have, the limits that we have for burnup.

MR. TOMKINS: By the way, that was Micah Hackett, who is our Director of Fuel and Materials.

MEMBER BALLINGER: Thank you.

MR. TOMKINS: Okay. Next slide.

MR. LATTA: So, one more slide, please. All right.

So, this is an outline of the sections of the methodology. I'll go through each one of these points more in-depth through the next series of slides.

To start out with, they're just talking about historical experience and ties to AGR and the EPRI TRISO Topical Report, and discuss an internal PIRT we perform for the fuel pebble and TRISO particle, and discuss more on manufacturing after that, the specification and QC to control quality through inspection.

Next, I'll talk about the fuel qualification envelope and operating range for the fuel, and what we do to be within that or external to that.

Next slide, please.

MEMBER REMPE: This is Joy.

And actually, I think it fits better on that prior slide. I had a couple of questions that are, I think, at a higher level.

Again, it's related to whether you decide you want to do an irradiation test, and if the operation is going to be within the bounds of the qualification envelope.

Say Hermes doesn't need to have additional irradiations, but you think the larger one might because of something or other. And I guess I'm curious on the something or other, because don't you need validated codes to determine that, and will you have the codes validated for the larger plant? Or even for Hermes to decide that you don't need it, are the codes validated? So, I'm wondering if it's a roundabout argument to decide I don't need irradiation data.

And then, the second question I had is, where would the irradiation -- I mean, I saw in the text it talks about the facility and it seems like it's going to be of the whole pebble, not compacts, and then, where would you do such a test? Because, as I understand it, the High Flux Reactor is going to go down in 2024 and they're having troubles with it. And are you planning to go to Russia? Where would you do such a test?

MR. TOMKINS: I don't know about Russia, but --

So, the first question on the qualification envelope, for the commercial reactor, the particle power and the burnup are beyond the limits we're holding ourselves to. So, we would, presumably, have to do irradiation to address that.

MEMBER REMPE: And you're confident

because of what? What reason you won't have to do it for Hermes, irrespective of Dave's concern? I'm just wondering, did you need to have a validated computer code to know you don't need to have it for Hermes?

MR. TOMKINS: Yes, but at the time we make that judgment about whether we were within the fuel envelope or not, we will have validated codes to determine that.

MEMBER REMPE: Okay.

MR. TOMKINS: Or validated --

MEMBER REMPE: And the codes are? What are the codes that are validated?

MR. TOMKINS: Well, we probably need Brandon. Maybe you can help with that.

MR. LATTA: KP-BISON is our fuel performance code. And so, part of this validation are AGR-1 and AGR-2.

MEMBER REMPE: Okay. Part of it is, but, then, I read the Topical Report, and I believe it's even in our letter, that you plan to come back. Not all the properties are well-defined for fully validation. So, you are planning to get all the data required to have that code validated before you go too far in your licensing application? Or is it going to be, I mean, it's a Construction Permit, so you go ahead and build it, but you can't load the fuel. So, you'll have to have data by that time to have the validated code? I'm just kind of thinking about this --

MR. HAUGH: I'm going to step in here. This is Brandon Haugh, the Senior Director of Modeling Simulation at Kairos. Thanks, Joy.

It depends on how you define validation, right? So, we're defining validation within the scopes of the predictability of the code to predict the performance of our envelope, which is the AGR envelope. We believe we have all the data to do that.

MEMBER REMPE: And is the staff onboard with that assumption?

MR. HAUGH: They'll get a chance to review that validation and concur, and that work is ongoing. And they should get a chance to see that.

MEMBER REMPE: And so, we'll see the validation, the fully validated Topical Report for TRISO with KP-BISON before? Because I was just was kind of going, well, nothing is going -- we've discussed this before in our reviews of these Topical Reports, the kind of preliminary reviews for the methodology, but it's not totally -- or the approach to the methodology. It's not a validated methodology, even though you have an approved --

MR. HAUGH: Sure.

MEMBER REMPE: -- a staff evaluation that concurred. And so, again, I just want to make sure everybody understands that.

And then, what's the answer to the question about the facility where you're going to be doing these irradiations of the pebble?

MR. TOMKINS: That might be a closed session.

MEMBER REMPE: Oh, okay. That sounds good. Thank you. Don't let me forget.

MR. TOMKINS: Yes. Nicole, can you kind of note that, so we pick that up during the closed session?

MS. SCHLICHTING: Sure.

CHAIR PETTI: This is Dave. I just want the court reporter to note that Matt Sunseri, Member Sunseri, has also joined. Thank you.

MR. TOMKINS: All right. Next slide.

MR. LATTA: Yes. So, we're going to definitely go through the methodology, talking about the fuel pebble laboratory testing. These are tests to demonstrate that the pebble meets functional requirements. In addition to that, there's fuel irradiation testing that we'll go into, and then, some connections with fuel performance modeling, and then, finally, the fuel surveillance program for the reactor.

And next slide. Advance one more, please.

Okay. This slide just talks to the long history of experience with TRISO fuel and matrix materials and fuel forms that have been demonstrated in the U.S. and through international experience. The TRISO fuel form was first introduced for gas reactors in the 1960s.

A lot of attention in this case was given to the German pebble reactor designs and use of pebble fuel, and then, in addition to that, more recently, China has gone down this road of licensing and starting to operate two high temperature gas reactors.

And then, within the U.S., there was the General Atomics experiences with a couple of prototype reactors and carbides fuel and prismatic core.

And so, there's quite a long history of many nations being able to set up fuel fabrication and demonstration through irradiation testing, operation of prototypes or demonstration reactors, the capability of this technology, fuel technology, to work within a gas reactor.

And then, this kind of all culminates within the U.S. through the AGR program, which built on this extensive experience to develop a domestic UCO TRISO coated fuel particle. And a large part of what Kairos is proposing here leverages this DOE program and the EPRI Topical Report on TRISO particles as a foundational case for our fuel qualification.

Next slide, please.

MEMBER REMPE: This is Joy.

MR. LATTA: Yes?

MEMBER REMPE: Just on that, in the Topical Report, I think there's a typo about the years the THTR operated. So, you might want to fix that if you're updating it at some point.

MR. LATTA: Okay. Thank you. We'll take that down.

All right. This slide, it's a lot of numbers, but the point of this slide is to talk to the extensive amount of testing the DOE has been doing with the AGR program.

And then, the bottom set of slides is a comparison to German irradiation test data that was also performed in test reactors. Whereas, the AGR particles were tested as compacts, the German fuel was tested in a pebble form. Historically speaking, the performance of German fuel had been considered kind of the gold standard for excellent experience with TRISO fuels, and then, the AGR program over the last many years has been able to really demonstrate an equivalence with that through the domestic testing program.

So, this slide talks to the kind of testing that was performed and the low failure fractions that were demonstrated in the AGR program and how that was then incorporated into the EPRI Topical that was reviewed by the NRC and issued an SER.

Then, next slide, please.

And then, to go on with that kind of data we see in the literature and what has been done recently with the AGR, there's also furnace safety testing data with AGR compacts tested at a range of temperatures of 1600 to 1800 C for hundreds of hours, tens of thousands of particles tested between AGR-1 and AGR-2, showing fairly low failure rates and high reliability of the TRISO particles.

In addition, historically, German fuel has been tested under very similar conditions with UO2 TRISO particles but in pebble fuel form and, also, has historically demonstrated excellent performance, especially up to the 1600 C range.

Okay. Okay. So, switching gears towards the PIRT, Kairos Power conducted a PIRT on the two main parts of the fuel, which are the pebble and the fuel particle, and then, broke it down by subcomponents, the regions within the pebble, the layers and parts of the fuel particle. The application for this was our reactor and its thermal and radiation conditions. The scenarios were fabrication operations and accident conditions, and the PIRT was performed to identify high priority phenomenon that are related to the figure of merit, which was fission product transport and release.

And so, there was an internal PIRT performed in Kairos, and then, an external PIRT performed with subject matter experts. And these are kind of now the main results of the PIRTs. There's a graph on the right which shows kind of the number of high-ranked phenomenon we observed for TRISO or pebbles. There was almost 200 phenomenon identified over the course of this PIRT.

For TRISO, there's a lot of high-level knowledge related to this now. So, the highest ranks were Rank 2, where it's high importance, and medium knowledge level. And then, for the fuel pebble, we saw much more diverse rankings, and these were mostly related to the novel fuel design, manufacturing, and performance of the annular fuel pebble.

Also to say that this PIRT really built on this 2004 TRISO PIRT that was originally out there kind as a foundation for starting this effort.

CHAIR PETTI: Ryan, just a point. If you look at the date of that PIRT, 2004, that really predates AGR.

MR. LATTA: Yes.

CHAIR PETTI: I think it was about a year and a half in. And so, there were lots of things on the table. I was in that PIRT. And if you reflect back and look at everything from AGM back on that PIRT, you probably would re-rank them significantly differently. There were all sorts of issues that were out there because of a lack of data that I think today you would probably take some of them and rate them lower in terms of their importance, given where TRISO particles are today than they were in 2004.

MR. LATTA: Yes, and largely, what we did, we took like the phenomenon, and then, we gave everything brand-new ratings and rankings based on present knowledge.

CHAIR PETTI: Ah, okay.

MR. LATTA: And, you know, we have a different application --

CHAIR PETTI: Right.

MR. LATTA: -- a different scenario. You know, the pebble and some other things are different. So, things were re-rated and ranked to reflect that difference.

CHAIR PETTI: Ah, good. Thanks.

MR. LATTA: Thank you.

MEMBER REMPE: So, this is Joy.

And when I was reading the Topical Report, I thought there was just a single PIRT. And my question had been, are they internal and expert people? It never identifies who participated.

I think what you just said in your presentation was that you had an internal PIRT, and then, you had an external one? But you must have combined the results somehow? Could you elaborate a little bit more about who you hired to bring in and their years of experience? And if you had a single internal one, who all -- I mean, did you just take everyone in your fuels branch, or how did you do this?

MR. LATTA: Yes. So, the internal PIRT was performed by the subject matter experts at Kairos, and then, later, we included a set of experienced subject matter experts that were external, whether academic or related to the National Laboratories, to get their input. And this was combined into a report, and then, that report was seen by the NRC.

MR. TOMKINS: We can probably give the name.

MR. LATTA: Can we give the name?

MR. TOMKINS: Yes.

MR. LATTA: Okay. Okay. So, I can go with a list of names. The PIRT process was facilitated by Chris Lamm.

MR. D. GARDNER: Hey, Ron? Hey, Ron, this is Darrell Gardner.

I think we need to, if we're going to be mentioning names, we need to be doing that in closed session.

MR. LATTA: Okay. We could save that for the closed session.

MEMBER REMPE: That would be great. And then, I guess if there is a report that actually has the PIRT report, and you did share it with the NRC, could we ask you share it with us?

MR. D. GARDNER: The PIRT was not submitted on the docket.

MEMBER REMPE: Okay. So, we're not

allowed to see it?

But, yes, please share the names, then, in a closed session.

MR. LATTA: Okay.

So, next slide, please.

Okay. And so, the objective of the PIRT is to understand where you have high importance and medium or low knowledge level, and there you know the phenomena that you really need to investigate as far as your fuel qualification program.

So, through that process, this slide just talks to the main things that were found in the PIRT that need to be addressed. And so, there were, obviously, manufacturing/development-related issues with the pebble, since this was conducted a few years ago now, and the objective was that we would have manufacturing/development, obviously, and be able to leverage German and AGR program experience in that process.

And then, for fuel qualification, specifically, things related to the pebble and its performance to meet functional requirements, there was a series of mechanical and material compatibility-related phenomenon we would like to investigate. And so, a fuel pebble laboratory testing program was created to address those issues.

MR. BLEY: This is Dennis Bley.

Either you -- or it's really a question for staff, or maybe Weidong can follow up -- if PIRT was not submitted on the record, did the staff do an audit and is there an audit report on the PIRT?

Weidong, you can follow up with the staff later on that. We don't need to talk about it here.

MR. WANG: Okay. Will do.

MR. LATTA: Okay. Move on to the next slide, please.

Okay. So, this slide talks to the specification, manufacturing, and quality control.

So, the TRISO particle specification used in our reactor is equivalent to the AGR in AGR-5/6/7 specifications. It largely draws from this and we're trying to replicate the fuel that was generated and used for AGR-2 as a way to leverage the irradiation test data and the AGR-2 program and review of the EPRI TRISO Topical. The TRISO specification draws on and is similar to historic ACGR fuel pebbles with special features, as we have discussed, for FHRs.

And then, discussing manufacturing, kernels are fabricated through a sol-gel process to create microspheres. Particles are coated through a continuous CVD process, and then, pebbles are formed from a mixture of graphite powders and binders and with incorporated TRISO fuel particles impressed in the shape and heat-treated. So, these are kind of traditional methods and forms of manufacturing that have been used in the past, but apply to our specific application.

And then, beyond that, is the inspection of product to demonstrate that the product meets compliance to the specification we previously mentioned.

Next slide, please.

CHAIR PETTI: Ryan?

MR. LATTA: Yes?

CHAIR PETTI: A question. Why don't you go back?

MR. LATTA: Sure.

CHAIR PETTI: The AGR-2 and 5/6/7 particles were enriched at a little over 14 for AGR-2 and I think a little over 15 for 5/6/7. Is that the enrichment levels you are going to go with or are you going to go up to the LEU limit?

MR. LATTA: Yes. No, we go up to the LEU limit, and that's about the only real difference between --

CHAIR PETTI: Right. And then, you're going to try to get to complete burnup, if you will? And that's what puts you out of, sort of in this -- AGR-1 went to those limits, but it was a small kernel. These are bigger kernels than AGR-2, and that's where you feel you may need testing for the --

MR. LATTA: Yes, yes. And so, we had recognized that.

CHAIR PETTI: Yes.

MR. LATTA: And that is explained within the Topical for the reasoning. And AGR-5/6/7 was the larger particle, but it never reached to the 19-plus --

CHAIR PETTI: Right, yes.

MR. LATTA: So, we're sticking with AGR-2 now, which was also previously reviewed, as you know.

CHAIR PETTI: Yes. Okay.

MR. LATTA: Okay. Next slide, please.

Okay. This just talks of quality control. There's a list of components of the particle and pebble, and it kind of just lists the different kinds of inspections that will be performed. There's a significant amount of characterization and inspections that are performed through the fabrication process to demonstrate the product meets the specifications.

That's a very important part of fabrication, to demonstrate and prove that the product meets the spec.

Okay. Okay. So, it addresses the qualification envelope. So, for fuel operated in the reactor, there are really four key parameters related to fuel performance that we identified: power, burnup, temperature, and fluence.

And so, operating under steady-state conditions, there's an operating envelope, and then, an envelope for temperature under transient conditions. And so, in the Topical, what we proposed in there has been that the qualification envelop is really the AGR-2 irradiation conditions, as defined by the TRISO Topical Report. As long as you're able to demonstrate that you're operating within that envelope, the fuel is qualified for these irradiation conditions. If your reactor needs to operate outside of those conditions, then you would need to collect additional irradiation test data.

If you can advance to the next slide, please?

And so, this is a table of the qualification envelope and example conditions for the Hermes non-power, and then, the KP-X Power Reactors. On the right -- or excuse me -- on the left are the four parameters we have just discussed, and then, temperatures, and also, temperatures below that for postulated events. The first are for normal operations. And so, the proposed qualification envelope for normal operation matched conditions that were observed in the AGR-2 irradiation.

And then, you need to go to the next column which are examples of Hermes conditions. As you can see, the temperatures, burnup power, and fluences are less, and sometimes significantly less, than the operating envelope.

And then, as you go to the right, you see KP-X in the final column, the conditions are higher, and some of them exceed -- specifically, power and burnup and fluence is a little bit higher than the operating envelope.

So, you can see there's a difference between Hermes, which should be able to operate within the operating envelope of AGR-2, while KP-X would be outside of this operating envelope and require irradiation testing.

Okay. So, moving on to a different part of fuel qualification. This is the laboratory test program. So, no irradiation involved in this case. And so, the objective is to demonstrate that annular fuel pebbles meet the functional requirements, and this is through a series of mechanical-related tests and material compatibility tests in a laboratory environment.

Okay.

MEMBER REMPE: So, this is one where I'm curious, I guess, along with what Ron was talking about. I just really am wondering what the basis is to know that radiation won't affect molten salt infiltration with cracking. I know you're going to be looking for cracking, but the depth of cracks, as the pebbles are going in circulation. I just am wondering if there's a good, strong basis for saying we don't need to do testing to assess the combined effects.

MR. LATTA: Sure. So, you would less expect cracks to open up with irradiation, more to close with irradiation indensification. The fluences are fairly low, especially for Hermes, going in. Infiltration is more related to the width of the pore, or I guess in that case it could be a crack, the crack width. But you would need to also infiltrate a significant amount of Flibe coolant to lose buoyancy.

MR. TOMKINS: Right. And the Chinese casting showed that you didn't have infiltration up to, I think it was 600 kilopascals. And we're operating at 200. So, we've got that background as well.

MR. LATTA: Yes.

CHAIR PETTI: So, can I just ask, in terms of the testing, particularly on the compatibility and the infiltration, will you use sort of a tech spec limit of impurities? You know, in a lot of these systems I know that the chemical compatibility of graphite with air and steam is strongly dependent on impurities that are present in the graphite. And so, I could imagine that the impurities might have an effect.

MR. LATTA: Yes, I think for material compatibility, if you think back to MSRE, where the fuel was dissolved into the Flibe, and you had a whole series of fission products and other transition metals and materials from the structurals, you still didn't see degradation of graphite or graphitic materials in Flibe, and that, thermodynamically, and the way we plan to run this reactor with fairly clean salt, that we would not expect to see much interaction at all between graphite and Flibe.

CHAIR PETTI: Since we're here on compatibility -- and you can decide to answer in the closed session -- I am concerned about some of the stuff that will be corroded out of the steel by the salt. And, in essence, you've set up a chemical pump, right? There's an equilibrium concentration at the hot end and an equilibrium concentration at the cold end, and you'll get some Delta T mass transfer, and in between the hot and the cold is this large pebble bed with a huge amount of surface area. And what I'm worried about is the iron-chrome-nickel in the salt getting into the pebble and attacking the silicon carbide.

Iron, chrome, and nickel, as you probably are aware, must be as far away from this fuel as possible. In a gas reactor, the closest of that is the Kobel, and it's in a solid state, very far away from the fuel.

If you've read some of the AGR-2 papers, you'll find that a thermocouple wire -- a thin, tiny thermocouple wire -- attacked silicon carbide, and that was a nickel wire.

You can go and read the literature, that there is strong chemical interactions between iron, chrome, and nickel and silicon carbide. And you're going to operate for, you know, thousands of hours with a certain concentration in the salt that could be picked up by the pebbles and could attack the silicon carbide.

It would seem to me, since you mentioned you were going to make some surrogate pebbles, that you could test this in a Flibe loop -- you wouldn't have to have a uranium-containing pebble -- and see what sort of interactions you would actually get.

MR. LATTA: Yes. So, I completely understand this concern. And there's a number of barriers between Flibe, you know, Flibe on the exterior that might contain transition metals and Flibe getting into the silicon carbide layer.

First off, there would have to be infiltration of the Flibe into the fuel region, which is separated by the fuel-free region in the pebble. So, your pressure would have to get fairly high. Operating pressures are below 200 kPa, and as far as we know, infiltration should begin above 600 kPa. So, there's a pressure that would have to drive Flibe into that region.

Secondly, if the Flibe got into the fuel region, you would still have OPyC protecting the silicon carbide, and then, if that barrier were not there, you would still have to have an exchange of Flibe-containing transition metals to feed a reaction. So, there's a number of barriers that are in place to prevent this kind of a reaction.

MR. TOMKINS: Also, we're inspecting pebbles every 50 days or so. We could see --

CHAIR PETTI: Well, you're not going to be able to see the silicon carbide.

MR. LATTA: But you might be able to -- there's a potential opportunity to determine if Flibe could be getting into the pebbles that are inspected.

CHAIR PETTI: Yes, we had all these same arguments in AGR, and I'll just tell you that the program thought that thermocouples 3 millimeters away -- there was graphite between the thermocouple and the compact, and there was overcoat between the compact and the powder coats, and the nickel got there. Okay?

So, I understand all these technical arguments for barriers, but chemistry is funky stuff.

MR. LATTA: Yes.

CHAIR PETTI: And the chemical potential, those transition metals want that silicon carbide, and they seem to make it there.

MR. LATTA: Yes. We're also at a lower temperature, which also --

CHAIR PETTI: I understand that. Yes, we don't know the kinetics. You know, it hasn't been studied systematically or anything. But --

MR. LATTA: Sure. Okay.

MEMBER REMPE: So, to follow up on your response about the Chinese data, talk to me more about the Chinese data and what they obtained. You're just talking about their pebble bed reactor, which used helium as the coolant, right?

MR. LATTA: No. We're talking about five infiltration tests. There's an ASTM standard for molten salt infiltration testing and the structural graphite and carbon matrix material. And so, as part of this laboratory test program, we have a setup to perform an experiment according to this ASTM standard.

And Oak Ridge researchers have been trying to also perform these tests with, I believe, Flibe and Flinak on a series of structural graphites and carbon matrix materials. And they've been able to demonstrate at what pressures you reach a threshold for infiltration of salts into the porosity of these graphites.

MEMBER REMPE: Okay. So, this was just part of their molten salt program, not the program that was discussed earlier on slide 14?

MR. LATTA: No. And Oak Ridge has also been doing this kind of work. They have a setup in Oak Ridge to perform these kinds of tests. And now, we have a setup here to do this as well.

MEMBER REMPE: Okay. Thank you.

MR. LATTA: Yes. Thank you.

Next slide, please.

Okay. So, this slide just talks to the type of mechanical and anthropology testing that's been performed. The objective is to demonstrate that pebbles do not fracture from static or dynamic loads in the reactor, and that wear is accept over the pebble's lifetime.

And so, there is compression testing, crush tests to demonstrate the load at which a pebble would fail. There's impact testing. So, cyclic impact tests to demonstrate when a pebble might fracture or chip. And then, tribology testing that measures the wear rate in different environments and under different loads and the coefficient of friction.

Okay.

MEMBER REMPE: Again, wouldn't you expect that pebble fracture would occur much more easily after it had been irradiated?

MR. LATTA: The data actually shows the strength increases with irradiation and with the temperature.

MEMBER REMPE: So, what about brittleness?

MR. LATTA: The load is increased -- the allowable load increases with temperature and irradiation. The load results in fracture. They're fairly comparable. You know, you see about 2 to 3 millimeters of displacement before fractures. It's generally been observed in these pebbles, whether irradiated or not.

MEMBER REMPE: Okay.

MR. LATTA: They're porous. So, they kind of crush a little bit before they fracture.

MEMBER REMPE: Okay.

MR. LATTA: Okay. And then, going on, there's Flibe infiltration and buoyancy testing. So, this is where you put a pebble, as we previously explained, you put a pebble in a bath of Flibe under pressure at temperature and you measure its weight change before and after the test to investigate when and under what condition or pressure you would see Flibe infiltrate into the pebble. As I said, these tests have been previously performed by Chinese researchers and at Oak Ridge.

The test is really a mechanical test, but there's also a Flibe compatibility portion of that test, where you might run the test for thousands of hours to demonstrate interaction between the carbon matrix material and the Flibe salt.

The other compatibility test is with air, and in this case, we're looking at oxidation rate of the matrix material under a range of temperatures from 400 to about 700 C. And you're measuring mass loss with time to create an equation to demonstrate that, first of all, the pebble under normal conditions should not interface with oxygen. It should be largely in an inert environment. But, under safety conditions, you could be concerned with oxidation with overt air into the system.

CHAIR PETTI: Ryan, you probably know, but there has been data developed under, I think, university grants at DOE looking at oxidation of matrix material with air. So, it would be a nice comparison.

MR. LATTA: Yes, thank you. And that's all we're trying to do, is demonstrate equivalence of our materials with existing data or use a model.

CHAIR PETTI: All right.

MR. LATTA: Okay. And then in the topical we have defined acceptance criteria for each of these tests related to specific parameters. These are kind of the non-proprietary definitions of the acceptance criterias. So for mechanical testing of compression and impacts it's really about demonstrating that the loads within your reactor system are allowable compared to the data you've collected. For tribology it's about wear rate to demonstrate that the outer fuel- free zone of the pebble is adequate to prevent mechanical interaction of TRISO particles out -- with something outside of the pebble.

Next slide, please? Going down the list there's the buoyancy testing, so about density and whether there's Flibe infiltration or not and then material compatibility related to interaction of Flibe or air with the pebble and demonstrating that there's -- what damage might occur or that you're preventing damage under normal operation.

Next slide, please? Okay. So this slide talks to irradiation testing. So when we looked at the fuel operating envelope we discussed if you were inside AGR-2 irradiation conditions would be acceptable, but if you were outside of that you would need to perform an irradiation test. So this part of the methodology defines what that irradiation test would be. It would be irradiation of fuel pebbles or fuel pebble design with -- in a non-KP-FHR facility, very similar to the AGR irradiation test with fission product measurement and PIE to determine particular failure fractions. And then we defined an acceptance criteria for the particle failure fraction that would result in what we consider high-quality fuel for use in FHRs.

Okay. This slide talks to fuel performance and the models that interface with either analysis or data we've collected. KP-BISON, as you know, is our main fuel performance model for analyzing normal operation and transience, so this is connected to the AGR validation. We performed an irradiation test that -- we would also be validating this model to that irradiation test. Additional model interfaces are the modeling of the pebble bed. This informs wear behavior and loads in the bed. And then the final is finite element modeling of a pebble where we could examine temperatures or mechanical behavior of the pebble.

Okay. Fuel surveillance program. So with the rest of the program completed and your -- get your operating license and you're operating your reactor there would be a fuel surveillance program to confirm fuel performance in Hermes. And so the three components of this program are fissure product monitoring first to cover gas and Flibe coolant.

Then there's the PHHS, which is the pebble handling and storage system. There will be an inspection system that checks for burnup and examines the physical condition of the pebble. And this happens as the pebble -- the pebble goes through the core multiple times, up to on -- well, up to an average around six times through the core. So each time it goes through it would go through this PHHS inspection process.

And then finally there would be post-irradiation examination of pebbles from Hermes and then the initial commercial reactor. And key things would be examining our -- the TRISO particle failure fractions, the amount of wear on the pebble surface and whether we're seeing any amount of molten salt infiltration into the pebbles after they have reached their equilibrium burnup end conditions.

CHAIR PETTI: Ryan, go back for a minute.

MR. LATTA: Yes?

CHAIR PETTI: You guys may have done some modeling on this, but the sorptivity of the cesium and strontium in the graphitic matrix is very strong and the Flibe coolant may not see significant changes in those two isotopes' concentrations if something were happening where the silicon carbide was degrading and you didn't know it. It would be interesting; and you can model all this, because I think you guys have to tools, to see what a step increase in release of cesium would mean in terms of transport through the pebble and the coolant and can you see a significant increase in the concentration of the coolant?

I've not looked at the chemistry, but it is something to -- worth noting as you're thinking about setting up limits and the like.

MR. LATTA: Thank you for that comment.

CHAIR PETTI: So let me here -- before you go to summary, let me talk about my other concern.

I think you and I have different definitions of fuel qualification. Your definition is necessary for sure, but I don't think it's sufficient. The irradiation proof testing is at the heart of every TRISO program worldwide.

The Germans did it for pebbles called HFR K5 and K6. Well after pebbles were being irradiated in AVR they did these tests at Petten.

The Japanese took their compacts, tested them in a reactor in Japan. Wasn't a really strong reactor, so they came out to Oak Ridge and tested at the HFIR.

The Chinese irradiation-proof tested the pebbles they made in Russia for their 10 megawatt test reactor at Beijing and then subsequently irradiated tested -- proof tested pebbles off the production line for the pebble bed that's in commercial operation.

And of course the U.S., that's what AGR-5/6/7 in the DOE Program is about.

And the reason for the proof testing is because specs aren't perfect and you never know everything. And that's why you do these things. And there's tons of history across fuel development programs beyond TRISO where people made, quote, small changes and it had a deleterious effect on the fuel.

I would say that this pebble is unique. I know that the topical report says it's like a German pebble. I find it very different in a lot of different ways. The free zones, the high packing fraction, and the pressure that you'd have to press a pebble is much, much higher than when you press a compact.

And that plus the fact that the QC may not catch everything in my mind suggests that there needs to be irradiation testing, not that it has to be completed before you're operating Hermes, but that if you were sure that the burnup and fluence stayed ahead of what was in Hermes, you'd at least have some indication that this process of making pebbles out of production scale you didn't bring something in that you didn't foresee in the manufacture and that wasn't captured by the QC.

MR. TOMKINS: Could we respond to that, David? That was a good comment.

CHAIR PETTI: Sure.

MR. HACKETT: David, this is Micah Hackett. I'll take a part of that at least. We recognize that if we were to press spherical pebbles in the same way in which for example the German program pressed them, yes, very high pressures would be needed to press those pebbles. So we have developed an alternate method of being able to press pebbles. And we're going to be using a hot press process instead of a cold process.

What that means is we use far less force and being able to press our spherical compacts. So that should, we believe, that greatly diminishes the amount of energy needed to press that pebble and also should prevent damage to the TRISO particles.

CHAIR PETTI: So you're going to -- the resin will activate in the pressing?

MR. HACKETT: Correct.

CHAIR PETTI: Is it hot pressing or is it warm pressing? Do you know the different --

MR. HACKETT: Yes.

CHAIR PETTI: I mean I don't want to get into proprietary, but --

MR. HACKETT: Yes, maybe let's talk about it more in the proprietary session.

CHAIR PETTI: Okay. Yes. Yes.

MEMBER BALLINGER: Yes, this is Ron Ballinger. I thought about this also, but I'm struggling whether I would consider the differences that might -- that we see a potential safety risk or a commercial risk. And so I haven't decided whether I think that's true, but isn't that the question that we're talking about here? If it's simply a commercial risk, well, some days chicken, some days feathers. But if it's a safety risk, that's a whole different ball game. And I guess I would certainly defer to Dave's judgment there because he has all the experience.

MR. TOMKINS: So, Dave, I think you said that if we were to do an irradiation program, it might not be needed for Hermes, but it would be needed for APX, the power reactor. Is that what you said?

CHAIR PETTI: No, I said that you didn't have to have the irradiation complete to get the operating license, that you just had to have the irradiation stay ahead of where you were in the reactor itself.

MR. TOMKINS: All right. Because the test reactor is obviously a test reactor, right, or you know, it's to test things. And certainly that can be a foundation for what we do in the commercial reactor, which is coming to come behind it.

CHAIR PETTI: Right.

MR. LATTA: Additionally versus a gas reactor we have the FliBe coolant as a containment outside of the fuel itself.

MR. TOMKINS: Right, which is a significant difference. The other thing is our margin to any kind of limits is very large. I mean we are way far away from the 1,600 for transient and from the 1,360. So --

CHAIR PETTI: Yes, I'm not at all worried about a performance issue. I'm worried about particles failing in PIE that were unanticipated because of something done in fabrication that was missed.

So I mean, if you go back through and you read the EPRI Topical Report, they'll talk about what happened in the new production reactor program. And

I can tell you that the vendor swore up and down it was not their fuel that caused the massive failures in those irradiations until they happened at both Idaho and Oak Ridge. And then it was oh, it wasn't those guys doing the irradiation. It was us who made the fuel. And they still couldn't figure out what they did until PIE was performed. And it was subtle. They had made changes and were convinced that it wouldn't make any difference.

This is the same argument as saying an accident-tolerant fuel where I'm going to change either the fuel pellet or the cladding in some minor way and I don't have to irradiation test it and yet they are being irradiation tested. I mean that's just sort of like the first commandment of fuel behavior, people.

MR. BLEY: Well, this is Dennis Bley. And, Dave, I certainly don't have your expertise in the fuels area, but it's not just the golden rule of fuels. All across technology there are so many cases of places where we designed a new system specifically to solve a problem in an existing one and yet when we put it into service it probably did solve that problem, but new ones were introduced. And the idea that you don't need testing because you haven't thought of what's going to go wrong is just not comforting.

MR. TOMKINS: Well, it's not that we're not doing testing, because there's been a lot of testing of the particles and there's separate testing of a pebble. But you're right, as an integrated entity we're not doing irradiation testing.

CHAIR PETTI: Right. I mean I completely agree with much of the documentation about the positives that the two technologies bring, but when you bring two technologies together, besides bringing the positives, you can potentially bring some negatives. And just thinking in that failure space is what I think Dennis and I are both talking about.

MR. TOMKINS: Okay. Next slide. I think the last couple are mine. So I'm just going to click through these. We kind of covered these, but there's 50 years of operating and testing experience on these particles certainly.

We did a PERT and we implemented actions to address the PERT. The manufacturing and inspection of the fuel will be to a spec that ensures that it's equivalent to what was tested in AGR-2. We're also going to meet the conditions in the TRISO Topical Report. I think there's five conditions and limitations in that report, so we will have to make sure that our fuel meets those conditions. We're going to operate well within a defined set of fuel qualification limits during both normal and licensing basis events.

Next slide? We will do irradiation testing if the TRISO particle is going to operate outside of AG-2, which might be needed for the commercial reactor. We have a surveillance program that confirms that the pebble form is not adversely impacting fuel particles. We can talk a little bit about this in the closed session, but we're going to take a camera shot of these pebbles that come through. And so if the wear is through and particles are exposed, we would know that. And then we have the ability to examine pebbles as they -- oh, I just mentioned that. And we're also going to do PIE on both the test reactor and on the commercial reactor. Of course that's obviously after the fact.

Next slide?

CHAIR PETTI: So, Jim, just a question: Are you also planning on potentially taking a pebble out before it reached its full burnup, if you will, and do PIE? So you'd have them at 25 percent, 50 percent, and 75 percent?

MR. TOMKINS: Hadn't really thought about that, but you wouldn't get the burnup of course.

CHAIR PETTI: Right, but you'd get sort of a characterization, if you will, one-every-so-often-sort of thing.

MR. TOMKINS: That isn't currently part of our plans, but --

CHAIR PETTI: Yes.

MR. TOMKINS: So conditions. Joy, did you have a question?

MEMBER REMPE: Yes, it's something I forgot to ask earlier. If this is a good time to have a detracting question, on slide 31 on the material compatibility, it has Flibe -- the acceptance criteria is Flibe interaction with the pebble does not result in damage to the fuel region of the pebble. How do you define damage? Does that mean if you see any Flibe ingress into the fueled region? So it goes past the unfueled region into that region, you'll stop and say we got to stop here, folks, we've got a problem? Or does it have -- is there something more significant than ingress? And if it's just ingress or infiltration, then why don't you say Flibe infiltration into the fueled region of the pebble?

MR. LATTA: We're looking for -- what

you're looking for would be like degradation, so microstructural changes that could impact either heat transfer or the mechanics of the pebble and break down from expected -- what we expect of the material. So it would be --

MEMBER REMPE: It's going to be a harder thing if you -- I mean one, you ought to be specific and say okay, I want to do testing to see if it adversely affects heat transfer in the fueled region --

MR. LATTA: Yes.

MEMBER REMPE: -- or material properties.

MR. LATTA: Sure.

MEMBER REMPE: Or an easier criterion to have is the acceptance criteria is that you don't have Flibe ingress into the fueled region.

MR. LATTA: Yes.

MEMBER REMPE: I mean, you can do that if you want to, but then okay, how much degradation in the heat transfer? I mean, this is a very vague criterion in my opinion and so I think you ought to be more specific. And the easiest way to deal with that would just say ingress into the pebbled fuel region.

MR. LATTA: Yes. Well, then the expectations that really see -- is not to observe anything occurring because these materials have been shown to be highly compatible and they're thermodynamically compatible. And there's been a lot of experience in the other tests and in the MSRE to show that graphite is compatible with Flibe. So we're just really kind of trying to confirm that when we use our materials that we see this same history of compatibility between the materials.

MEMBER REMPE: So again, I lobby for you ought to just say ingress to confirm what you've seen elsewhere unless you want to try and go further. And if you want to go try --

MR. LATTA: Yes.

MEMBER REMPE: -- and go further, then please be specific so we know what it is.

MR. LATTA: Sure.

MR. TOMKINS: Okay. So I'm just going to close with the limitations. So we have some limitations we've put on ourselves. And we also have one that was in the NRC's SER.

The first limitation is that this methodology only applies if the design is described in Section 112 and you have Flibe that's maintained.

We have to demonstrate that the operating conditions and the safety analysis conditions are within the qualification limits that we've specified in table 3-11 of the report.

If we're going to extend that envelope, then we have to do an irradiation program. We also have to meet the limitations and conditions in the EPRI TRISO Topical Report, which I previously mentioned that.

There's a couple of conditions that we have to meet for the power reactor, and that is we've got to provide additional justification on the applicability of this methodology during rapid transience and additional justification that Flibe does not inversely impact irradiated fuel pebble buoyancy.

And then this methodology only applies to a design with a safety-related positive flux rate trip. And then the NRC has added SER limitations to justify the applicability of this methodology to a test reactor for rapid transients. That's it.

CHAIR PETTI: Members, questions?

Okay. Then I guess who from the staff is going to be presenting?

MR. VAN WERT: That will be me. This is Chris Van Wert.

CHAIR PETTI: Hi, Chris.

MR. VAN WERT: Hey, how are you doing?

CHAIR PETTI: Okay.

MR. VAN WERT: So do we jump into it now? I didn't --

CHAIR PETTI: Well, I was just going to -- I'm sitting -- how many slides do you have?

MR. VAN WERT: It is -- one second -- I believe it's about 10 or 11, somewhere around there.

CHAIR PETTI: Well, why don't we take a 10-minute break then and we'll come back at half past the hour?

MR. VAN WERT: Sounds good.

CHAIR PETTI: Thanks.

MR. VAN WERT: Thank you. So, okay, 3:30 your time? Okay.

MEMBER REMPE: And the slides from the staff are now open slides, is that true? They were given to us --

MR. VAN WERT: Correct.

MEMBER REMPE: Okay. Thank you.

MR. VAN WERT: And I will share/control them, so --

(Whereupon, the above-entitled matter went off the record at 3:20 p.m. and resumed at 3:30 p.m.)

CHAIR PETTI: Okay. We're back in.

Chris, it's yours.

MR. VAN WERT: All right. I'm going to go ahead and share the slides, so give me one second.

(Pause.)

MR. VAN WERT: All right. Is that visible to everyone okay?

CHAIR PETTI: Yes, looks good.

MR. VAN WERT: So I will also say before we start here that I will not be able to see -- while sharing it I can't see the rest of the screen from the Teams meeting, so I am asking the other NRC members to keep an eye out for any raised hands and to speak up and let me know if there's a question. Also any of the members, please feel free to just speak up during the presentation as well, but we will continue on that then. And like I said, feel free to speak up at any time.

All right. Are we ready to start then?

CHAIR PETTI: Yes, go ahead.

MR. VAN WERT: Okay. So good afternoon, everyone. My name is Chris Van Wert and I'm a senior reactor systems engineer in Technical Branch 1 of the Division of Advanced Reactors, Non-Power Production and Utilization Facilities. I will be presenting the staff's review of Kairos' topical report, Fuel Qualification Methodology for the Kairos Power

Fluoride Salt-Cooled High Temperature Reactor, Revision 2.

So Kairos requested the staff's review and approval of the topical report which provides the methodology for qualifying the Kairos fuel pebble design for either a power or non-power version of the KP-FHR. The staff's review is focused on the overall fuel qualification of the framework -- fuel qualification framework which includes but not limited to the use of existing data, unirradiated testing, irradiation testing, and surveillance.

It's important to note that the topical report is applicable to both non-power tests and power versions of the KP-FHR, as we've mentioned already, and the staff considered this in the review.

Also, this topical report does not directly present any fuel performance code updates for staff review and approval, but is instead focused on the methodology itself to support fuel qualification. That being said, the data obtained from the fuel qualification process can be used in future performance code updates, but that is not covered directly as part of this topical report or the staff's review.

Just quickly, the regulatory basis for the fuel qualification framework is -- includes 10 CFR 50.34(a) and (b), 10 CFR 50.43(e), and the corresponding regulations for design certifications, COLs, and standard design approvals in 10 CFR Part 52. The licensing basis also includes 10 CFR 100.11. Additionally Kairos Power's PDC 10 and PDC 16, which were previously approved by the staff in Topical Report KP-TR-003MP-A, are also part of the licensing basis.

So the first discussion topic I wanted to cover you just heard about in Kairos' presentation, but this is the applicability of the existing data. And the Kairos Power fuel qualification methodology builds upon the approved topical report on TRISO fuel particle qualification, EPRI-AR (NP)-1. This was a topical report submitted by EPRI in coordination with INL to provide TRISO particle testing data and qualification from the AGR-1 and 2 campaign.

This topical report serves as a fuel qualification for TRISO fuel particles as long as it's within the fuel specifications and operational conditions defined by the AGR-1 and 2 Program.

Additional existing data related to carbon matrix property data was used to inform Kairos' testing plans to support fuel qualification.

The staff reviewed the Kairos fuel particle specifications in comparison with the AGR-1/2 campaign and finds that the Kairos particle specifications are consistent with the AGR-2 TRISO test particles and therefore the data is applicable to the Kairos particle design up to the test conditions investigated as part of AGR-2.

Additionally the staff finds that the carbon matrix property data is acceptable for informing the test conditions as used in the topical report.

In Section 3.6 of the topical report Kairos presents their planned fuel pebble laboratory testing and it will be used to obtain Kairos' fuel pebble data in support of fuel qualification. And this includes mechanical tribology, buoyancy and salt infiltration, material compatibility.

The staff reviewed the pebble test to confirm that the testing conditions chosen would bound those experienced by the fuel pebbles in reactor conditions and that the testing methods either followed an established method or were appropriate for obtaining the desired data. The staff found the fuel pebble testing as presented in Section 3.6 of the topical to be acceptable for determining Kairos' fuel pebble characteristics to support fuel qualification.

Section 3.7 of the topical report addresses planned irradiation testing to support operation of TRISO particles outside of the AGR-2 operational envelope if desired. I said a little bit about that earlier that there's a certain box that the AGR program kind of gave them an area to start with. And Hermes fits within that, however the desired power reactor version goes beyond that. So the irradiation testing does include fuel pebble irradiation in a gas environment, purged gas monitoring for fission gas, and post-irradiation examinations.

The staff reviewed the description of the irradiation test plans as presented in Section 3.7 and notes that similar to the EPRI-AR (NP)-1 TRISO particle fuel qualification topical report the methodology uses sweep gas monitoring to initially determine the release rate to birth rate ratio of gaseous fission product releases from the test levels, which is then followed by PIE. The non-destructive PIEs include visual examinations, dimensional measurements and gamma-spectroscopy to identify gross external damage and burnup as well.

The Kairos power fuel qualification methodology also includes destructive PIEs of a limited number of test pebbles. This destructive examination includes using the DLBL technique to quantify fuel particle failure fraction. These DLBL results can't results can't be used -- can be used to confirm the failure fraction calculated by measuring fission gas release during the irradiation test.

Staff finds that the irradiation testing presented in Section 3.7 is closely related to the previously approved topical report EPRI-AR (NP)-1 and is acceptable for determining irradiated fuel failed particle fraction and gross double behavior which could impact behaviors of operation outside the bounds of the AGR-2 test conditions.

Section 3.8 of the topical report addresses fuel particle performance modeling and discusses how the data collected from the fuel qualification program will be used to inform and improve fuel performance models. The staff's approval of this topical report is related to the fuel qualification methodology by which Kairos' fuel pebble can be qualified. The staff further finds the data collected while implementing the fuel qualification methodology is acceptable for use in updating the Kairos fuel performance model KP-BISON, however the staff's approval of the fuel qualification topical report does not approve a priori any modifications to the fuel performance model itself beyond whatever is allowed by the staff's approval of the KP-BISON.

Section 3.9 of the topical report addresses fuel surveillance plans for the initial test and power KP-FHR cores which are used to both monitor fuel performance and to collect data for fuel performance codes. The fuel surveillance plan includes cover gas monitoring, non-destructive examinations, and destructive examinations.

Again the staff reviewed the surveillance plans as presented in Section 3.9 and finds that, one, the use of cover gas monitoring is an acceptable means for measuring in real time any unexpected gross failures of particles which could lead to an increase in fission gas inventory in the cover gas.

Two, the non-destructive visual examination methods are acceptable for determining if a pebble has wear or other damage sufficient enough to potentially impact the TRISO particles.

Three, the use of gamma-spectroscopy -- spectrometry is acceptable for determining burnup levels to determine if the pebbles can be reinserted into the core or should be instead sent to storage.

Four, the DLBL destructive examinations are acceptable for confirming the failed fuel particle fraction as seen in the sweep gas measurements.

And five, the destructive examinations are also acceptable for confirming the wear and Flibe infiltration separate effects test results.

Staff limitations. In addition to the fuel qualification methodology limitations provided -- oh, yes?

Sorry. I thought I heard someone.

So in addition to the limitations that were presented by Kairos within their topical report the staff has the following limitation as well: And that's that future license applications for non-power KP-FHRs will include justification for the applicability of this methodology during rapid reactor transient events.

This limitation was intended to cover a gap in that the topical report only directly addresses rapid reactor transient events for power reactors in the Kairos limitations. And this is because the Hermes application addresses this issue directly in its PSAR, so this limitation was not perceived initially as being necessary in this topical report. However, the staff decided to include this limitation in its approval since the topical report addresses non-power test reactors in general and not just

Hermes. The staff limitation on the approval therefore covers all of any potential non-power KP-FHRs.

CHAIR PETTI: So, Chris --

MR. VAN WERT: Yes?

CHAIR PETTI: -- let me just understand. You're basically saying that the qualification doesn't include reactivity testing? Is that correct?

MR. VAN WERT: Correct.

CHAIR PETTI: Okay. But I thought the licensee went through some very good discussions about the response of their system to reactivity events. You guys just didn't accept it because it wasn't validated, or you just didn't accept it -- I'm trying to understand how you got here.

MR. VAN WERT: So the -- you'll hear about it more later. The Hermes application actually had even more information, and the staff's review of that is going to be included there.

CHAIR PETTI: Ah.

MR. VAN WERT: So we were trying to figure out where to put it. We could either have asked for additional information to be put into the topical report and address it here or just leave it there and put the staff's review and approval within that SER for the PSAR application.

CHAIR PETTI: Okay.

MR. VAN WERT: So you will hear about it later.

CHAIR PETTI: Okay. I see Jeff Schmidt has his hand up.

MR. VAN WERT: Okay.

MR. SCHMIDT: Yes, Dr. Petti, I was just going to help Chris out here.

So I wrote the PSAR section for Hermes for the fuel and I thought it was just better to use the specific data for Hermes to address the lack of transient testing. So that's why it rolled from this topical report into the PSAR.

CHAIR PETTI: Okay. Thanks.

MEMBER REMPE: So this is Joy and I had a question or two.

MR. VAN WERT: Yes?

MEMBER REMPE: It's tracking things. For example, my question earlier about well, gee, KP-BISON hasn't been validated and there's data required for it. And I assume the staff is tracking all this very carefully, because again their presumption that it's okay to do this for the now-power application is based upon KP-BISON calculations.

Likewise, I'm curious about if your approval has considered things like buoyancy tests only go to 900 C, but the power reactor is supposed to have a normal -- it's like 1,100 C for operating. And so are you tracking and saying okay, they can use it for Hermes, but not the other reactor until they do higher temperature testing? Is there some place where the staff has all this documented carefully?

MR. VAN WERT: So I'll try to address it all; please let me know which parts I miss and I'll go back to it.

So yes, the initial -- and Jeff was the lead reviewer for the KP-BISON topical report, and he can jump in as well I'm sure. But the initial topical report in this review is associated on its -- on the data supplied by the AGR-2 Program. And within those bounds -- yes, Hermes is going to operate within those.

When you're talking about updating KP-BISON in the future as we're getting this data, that's for when we're looking at operations outside of the AGR-2 Program. So I wanted to make sure that that was clear.

Joy, was there --

MEMBER REMPE: So let me stop you real

quick here.

MR. VAN WERT: Yes, yes.

MEMBER REMPE: So you're telling me you have confidence even though KP-BISON hasn't been fully validated, it has been validated using the data from AGR testing -- that you feel comfortable that all of their assumptions are correct about the operating conditions for Hermes and there's nothing that needs more data?

MR. VAN WERT: So I am going to kick that one over to Jeff --

MR. SCHMIDT: Yes.

MR. VAN WERT: -- since he's the author for KP-BISON's --

MR. SCHMIDT: Dr. Rempe, so for -- some of this stuff I think we can talk about in the closed session. The short answer is yes for Hermes. We looked at the operating conditions and the test ranges and it's fine for Hermes. I don't know if I looked personally at the commercial design. I might have to go back and take a look at that, but for the Hermes it is.

MEMBER REMPE: Okay. Because I mean they don't have material compatibility testing done yet for Flibe and the fuel, and I would have thought that would be something that would be important for KP-BISON. And I thought there was a lot of other testing where they acknowledged they used some data that had been collected in the literature, but they wanted additional data. And I would have to go back and look at what all needed to be obtained, but I thought basically they were missing some just fundamental properties of materials.

MR. SCHMIDT: Yes.

MEMBER REMPE: And I'm a little surprised that they are --

MR. SCHMIDT: So let me clarify my statement, I guess. The ranges of data, ranges of like temperatures I was responding to, there has been on V&V of the BISON code.

MEMBER REMPE: Okay. So that will have to be --

MR. SCHMIDT: That's all I really need to say about that.

MEMBER REMPE: That will have to be done before one can have confidence that they don't need to have additional irradiation testing for Hermes, right?

MR. SCHMIDT: Yes, that is correct. For an operating license for Hermes our expectation is that those will be -- the codes will be V&V'ed. All the codes that --

MEMBER REMPE: They might --

MR. SCHMIDT: -- are necessary for Hermes.

MEMBER REMPE: They may have a surprise then. They'll build the reactor, get a construction permit. And then they may have a surprise because the NRC could say oh, well, you know, it's not validated and you need to get some more data here. And that could happen. Just so everybody understands that because it wasn't clear to me from the SE and from the initial responses today.

And then when you go to the up-rated electric power KP-FHR, somebody needs to do a careful look at this SC, because again they only did testing for buoyancy up to 900 C. And I was curious why they didn't go on up to 1,100 C, but I thought well, okay, if that's all you need to do for Hermes, okay, but the staff SE should maybe make a note somehow or other that they did not -- that that SE is only valid for Hermes because higher temperatures or other types -- I didn't go through and look at all of the conditions, but they didn't do -- they're not planning or proposing to do testing for the full electric power KP-FHR.

MR. VAN WERT: To be clear, what

temperature are you referring to? If you're talking about --

(Simultaneous speaking.)

MEMBER REMPE: -- testing. If I look at the anticipated electric power conditions, it's less than 1,100 C. And then if I go to the laboratory testing on slide 29, test temperatures up to 900 C and pressure up to 500 KP for buoyancy testing. So either they need to bump up their test temperature a little bit when they do it the first time or it's not going to be valid for the electric power.

MR. VAN WERT: So I don't want to say the specific number, because it's listed as proprietary, but --

MEMBER REMPE: I'm looking at their open slides, by the way. I'm not looking at anything --

MR. VAN WERT: Oh, okay. Okay. Sorry. I was looking at --

(Simultaneous speaking.)

MR. VAN WERT: Okay. So I was looking at table 3-17 from the topical report. And if you're talking about the pebble surface temperature, I don't think we're looking at the same number then.

MEMBER REMPE: Okay. So I'm looking at anticipated conditions, which again it is the peak silicon carbide. I don't have a surface temperature. So you're saying the surface temperature will be covered by the 900 C? Okay. That helps me then. Have you looked carefully --

MR. VAN WERT: And once we get --

MEMBER REMPE: -- at all of the --

MR. VAN WERT: Once we get to -- yes, we'll tell you numbers in closed.

MEMBER REMPE: Okay.

MR. VAN WERT: And I think I have a backup slide with that table if we would like to see it, but --

MEMBER REMPE: But for the open session you've carefully looked at their test conditions and it covers not only Hermes but also the electric power design?

MR. VAN WERT: Well, you mean specific to the buoyancy?

MEMBER REMPE: Well, all of the testing. There's a lot of other testing that they --

MR. VAN WERT: Okay.

MEMBER REMPE: -- have too.

MR. VAN WERT: So yes. No, the answer to that would be the equilibrium core conditions go above and beyond the AGR-2 Program. And so some of the irradiation tests are not bounded by the available --

(Simultaneous speaking.)

MEMBER REMPE: Right.

MR. VAN WERT: And that's why that was addressed -- I think it's in Section 3.7.

MEMBER REMPE: Right. Other than the irradiation tests --

MR. VAN WERT: Correct.

MEMBER REMPE: -- the laboratory tests is where I have --

MR. VAN WERT: Yes, the laboratory tests -- yes.

MEMBER REMPE: And you guys are tracking what is and isn't covered for each design was the underlying question here.

MR. VAN WERT: Correct. Correct.

MEMBER REMPE: Okay. Thank you.

MR. VAN WERT: Yes, thanks.

CHAIR PETTI: Jeff has his hand up, Chris.

MR. VAN WERT: Okay. Hey, go ahead, Jeff.

MR. SCHMIDT: Yes, I was just going to say there's other material limits, Dr. Rempe, that would stop you from going above 900 C. And we can probably discuss those more in the closed session.

MEMBER REMPE: Thank you.

MR. TOMKINS: Could I just add one point following that discussion? And that is that the -- you were talking about validation of KP-BISON. So Kairos is working on that right now. So I'm not saying it's done yet, but we're -- that's something we're actively working on.

MEMBER REMPE: Good. But I hope you have data to finish it, because that was my impression when I was looking at the SE is that yes, okay, it sounds like a good idea, but until you have data -- and, you know? So anyway.

MR. TOMKINS: Yes. Okay.

MR. VAN WERT: So were there any more questions or --

CHAIR PETTI: Chris, I want to throw the question I threw to Kairos to you guys: Why didn't you require an irradiation given the Chinese even proof irradiation test. I mean I just can't understand. Is it because it's a test reactor that somehow it has a lighter touch?

MR. VAN WERT: We kind of -- we had to look at it holistically. So we were looking at the literature data that was presented. We were looking at the gas environment irradiation tests that they do plan to do. And then also recognizing that they have a surveillance plan. So at the end of -- well, at the end of both, Hermes as well as the power reactor, but in this case of interest it's the end of Hermes they will be doing all sorts of examinations including the non-destructive and destructive PIE. And so that data will become available.

And then also their ability to look at the cover gas products as they accumulate allows them to kind of keep on top of it. So if you look at it holistically in its entirety, we felt that the reasonable assurance threshold was crossed and we felt it was a good foundation.

I am not opposed if they so desire to do additional tests, but we had to make that safety determination and that was where we came from.

CHAIR PETTI: So the key issue is that yes, the gas will tell you if you failed all the TRISO, but if you feel the silicon carbide, it's a lot harder to do that for monitoring. That's why I was intrigued initially when I read about the salt. I'm just not sure if it will have the sensitivity. I'd be interested to see what a computer model would say there.

But in the old days when the South African pebble bed came in, the folks sitting in your seats were basically telling them they had to take pebbles out periodically and look at them and examine them sort of as a fuel surveillance -- as part of the fuel surveillance program.

MR. VAN WERT: Yes, and at the operational plans for Hermes, I don't think it gets -- it doesn't stress it enough until you're towards the end of its life. So I think the surveillance plan, the test data that you collect at the end of it is going to be more telling and more -- of the full power operation later. If we took it out at 25 percent power, unless there was a -- like you were alluding to earlier, a manufacturing defect that would be gross over the vast majority of pebbles and particles, I think that's the only case where you would potentially see something. And we couldn't find a way of thinking of that happening.

Yes, we can discuss more I suppose in the closed session all together, but that -- I just wanted to give you at least that overview of the approach we took as far as looking at all the different components. And adding it together in aggregate we thought was a strong safety case.

CHAIR PETTI: I see Jeff's hand's up. Jeff?

MR. SCHMIDT: Yes, I just wanted to chime in, too. I think you asked a good question there. For me it was the destructive testing for the initial non-power test reactor personally as a reviewer. That was important to me to add to be able to use the test reactor to get data in a real-life FHR, right? The data that you might be referring to would still be say in a gas environment.

CHAIR PETTI: Yes.

MR. SCHMIDT: This getting data from a prototypical reactor is probably the most informative you could do, or you could get. So we, at least I thought that was the key in proceeding forward.

CHAIR PETTI: Yes. No, I would not recommend that they have to test it in salt. That's not an easy thing to do in a test reactor. Very difficult to prevent the salt from freezing all the time. If you have an unexpected scram in your test reactor, which happens, it's much more challenging to do a salt -- flowing salt experiment in the test reactor.

MR. SCHMIDT: So it does kind of -- I think from the staff's perspective it does kind of leverage the test reactor aspect.

CHAIR PETTI: Yes, it just doesn't come

through enough I guess in either the topical report or the SE that -- it comes across as sort of after the fact. It doesn't come through enough to me at least. Okay.

MR. SCHMIDT: Yes, there was significant -- all I can tell you is there was very significant dialog between us and Kairos regarding that item.

CHAIR PETTI: Yes. Okay.

MEMBER REMPE: In that dialog did you ask them how much fluence they intend to accumulate with Hermes? I mean, I know they're going to shut it down like in four years, right? And when we asked, they didn't really have any sort of specification for capacity factor. So do you need to have any sort of fluence -- total operating history you want to see?

MR. SCHMIDT: Yes, I mean, it's bounded by the fluence by the AGR-2 Program from a particle standpoint, if that's what you're referring to, the --

(Simultaneous speaking.)

MEMBER REMPE: I'm talking about Hermes. How much -- have you --

(Simultaneous speaking.)

MR. SCHMIDT: You mean like from a vessel fluence?

(Simultaneous speaking.)

MEMBER REMPE: -- up to power or do you want it at full power after so many days?

MR. SCHMIDT: No, I mean we're not specifying. I think the assumption in Hermes is that it's 100 percent capacity factor, which is probably unrealistic --

(Simultaneous speaking.)

MEMBER REMPE: Well, I don't think they've ever said that, because we asked them. Maybe they can speak up, but I know we asked them that when we had the overview introduction. I mean, it's only going to run for four years. And I asked about the capacity factor, and they said they hadn't come up with that.

Are you guys trying to do 100 percent capacity factor?

PARTICIPANT: That's in closed section.

PARTICIPANT: We moved that to the closed session also.

MEMBER REMPE: Sure.

CHAIR PETTI: Sure. So let me ask a different question, Chris. They've committed to doing an irradiation test in the topical for the power reactor, but if things go swimmingly well in Hermes and they're going -- like if they could come up with a way to do it in Hermes, would that be allowed? I mean, they'd obviously have to file more paperwork, but they'd go beyond AGR-2, but they'd use Hermes instead of a test reactor. Would that be something that is at least not off the table?

MR. VAN WERT: So I mean if they could run Hermes such that they could get that data, that would be in my opinion fine. I would support having that data ahead of time. But our understanding of the power levels, the fluence, the burnups, et cetera, that they can achieve within Hermes -- and keep in mind it's also with a time frame. They could achieve higher burnup by operating it longer of course, but at some point at the power levels that Hermes will operate at they're going to run out of time before they want to build the full-power version of KP-FHR.

So we're not opposed to it. I just don't think that Hermes will get them to those levels beyond AGR-2 within the time frame that they'll need. So that's why I think they're ending up in this space where they're using a non-power -- sorry, a non-Hermes test facility --

CHAIR PETTI: Sure. Yes.

MR. VAN WERT: -- to get those levels.

CHAIR PETTI: Okay. Thanks.

Other members, questions?

Okay. Well, let's open the line for public comment before we go into our closed session then.

Any members of the public, un-mute yourself, state your name and your comment for the record.

Hearing none, I guess we're concluding the open session and we will get onto the closed session for other comments from members.

And, Jim, you'll scan the list to make sure everybody on your side is supposed to be there? And I suppose Chris and Jeff will do the same on the NRC side.

MR. TOMKINS: Yes, could I ask for anybody from the Kairos team, if you're going to call in by phone, let -- send me an email saying that. Does anybody plan to call in by phone or is everybody going to use the Teams link?

Okay. I didn't hear anybody saying they're going to call in by phone. So I think we should be okay because we should -- they'll have the link.

MEMBER BALLINGER: Dave, this is Ron. We have a separate invitation. Are we just going to stay here?

CHAIR PETTI: No, no. We're going to go over to the separate -- we got to switch over to the separate invitation.

MEMBER BALLINGER: I got it. Okay.

MR. TOMKINS: So and again, everybody from Kairos, open up the closed file.

And so, Dave, what, are we going to go there right now? Do you want to --

CHAIR PETTI: Yes.

MR. TOMKINS: -- take a short break?

MEMBER BROWN: Hold on. Dave, Dave, Dave?

CHAIR PETTI: Yes, Charlie?

MEMBER BROWN: This is Charlie. Yes, did we get the closed session slides? I had looked for those and couldn't find them.

PARTICIPANT: There aren't any.

MR. WANG: I will send to you. It should be on your calendar. You're Charlie, right?

MEMBER BROWN: I got two sets of slides. They were both open.

CHAIR PETTI: Yes, there's no closed slides, Charlie. It's just for some Q & A.

MEMBER BROWN: Okay. That's all I wanted to know. Thank you.

CHAIR PETTI: Okay. So we're going to

terminate this one and see everybody in the closed session.

MR. WANG: And I will admit Jim. And then, Jim, then you help me to look at your need to know people. Okay. Thank you.

MR. TOMKINS: Will do. Thank you.

CHAIR PETTI: Thank you.

(Whereupon, the above-entitled matter went off the record at 4:04 p.m.)

KP-FHR Fuel Qualification Methodology Topical Report

KAIROS POWER

ACRS KAIROS POWER SUBCOMMITTEE MEETING

OCTOBER 17, 2022

OPEN SESSION

Introduction

- Topical Report Applicability
  - This report presents a methodology for qualifying fuel for use in KP-FHRs
    - Qualification subject to the conditions in topical report
  - Demonstration of qualification will be documented in safety analysis report documents as part of licensing applications under Part 50 or Part 52
  - This report is applicable to a test or power KP-FHR provided that the report conditions are met

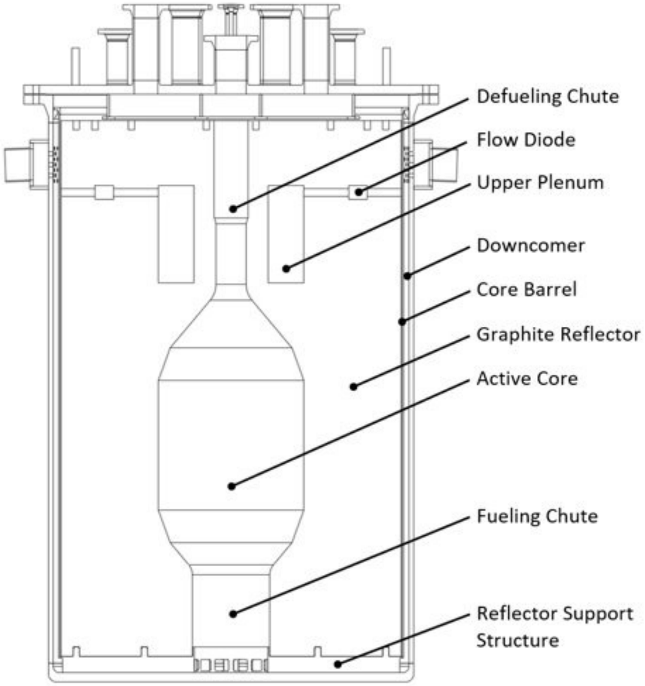
Fuel Qualification

"Qualified fuel" means fuel for which reasonable assurance exists that the fuel, fabricated in accordance with its specification, will perform as described in the safety analysis.

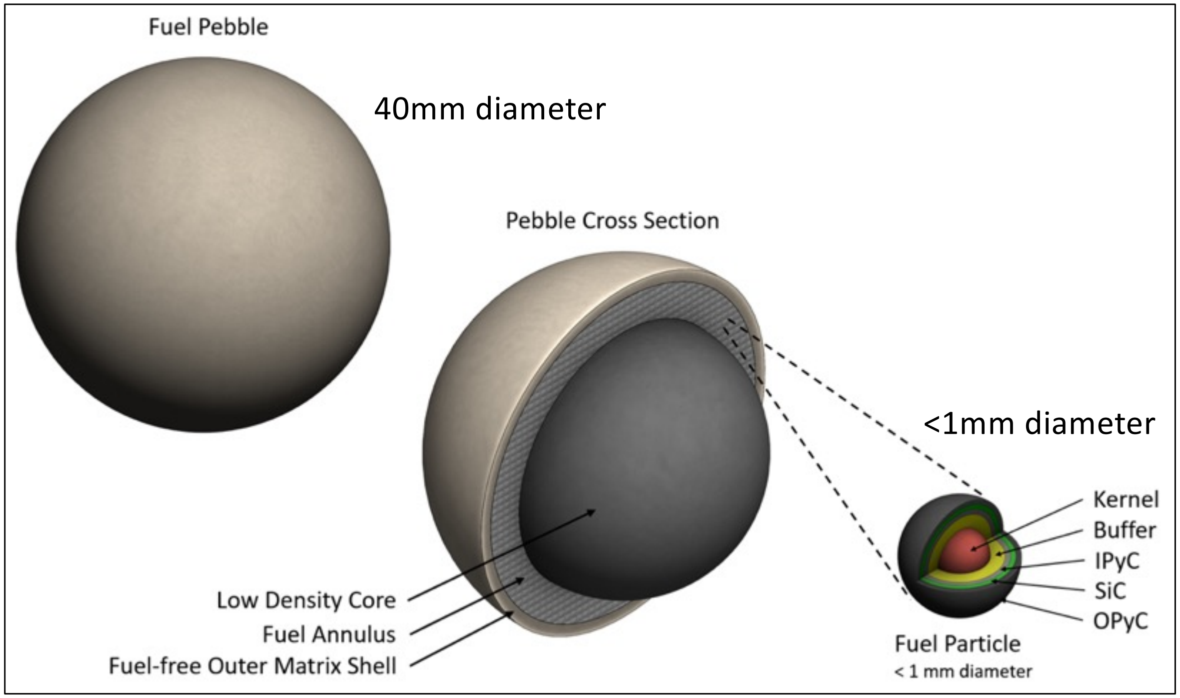
KP-FHR and Fuel Design

KP-FHR Overview

Parameter	Description / Value	
Reactor Name	Hermes	KP-X
Reactor Type	Non-Power Test Reactor	Commercial Electric Power Reactor
Reactor Vessel Size	3 m dia., 4.4 m ht.	4 m dia., 6 m ht.
Coolant / Reflector	Flibe / Graphite	Flibe / Graphite
Reactor Thermal / Electric Power	35 MWth / N/A	320 MWth / 140 MWe
Reactor Operating Pressure	<0.2 MPa	<0.2 MPa
Reactor Inlet / Outlet Temperature	550°C / 620°C	550°C / 650°C



Annular Fuel Pebble and TRISO Particle Design



Particle Design

Fuel System Component	Purpose
UCO Kernel **UO_2 + UC + UC_2**	• The kernel contains the fissile material. • The addition of a limited amount of uranium carbide suppresses CO production mitigating kernel migration, particle over-pressure, and corrosion of the SiC layer. • Oxygen remains sufficient to oxidize fission products that would otherwise diffuse through the IPyC and attack SiC in the higher mobility carbide form.
Porous Carbon Buffer Layer	• The porous carbon buffer layer provides void volume to accommodate fission product gases limiting pressure as burnup increases. • This layer mechanically de-couples the kernel from the outer coating layers and accommodates fuel kernel swelling. • This layer protects the IPyC from damage by fission product recoil.
IPyC Layer	• This coating layer is considered to be the secondary structural and fission product gas barrier after the SiC layer. • This layer introduces a compressive stress on the SiC layer that reduces SiC deformation and the risk of SiC layer failure during irradiation. • This layer serves to protect the SiC from fission product attack. • The IPyC layer protects the kernel from chlorine attack during SiC deposition in the manufacturing process.

Particle Design *(continued)*

Fuel System Component	Purpose
SiC Layer	• The SiC layer is the primary structural layer and fission product barrier. • This layer is a diffusion barrier to mobile metallic and gaseous fission products.
OPyC Layer	• This coating layer is considered to be a secondary structural and fission product gas barrier after the SiC layer. • This layer introduces a compressive stress on the SiC layer during irradiation that reduces SiC deformation and the risk of SiC layer failure. • The OPyC layer protects the SiC layer during manufacture separating the SiC layer from the carbon over-coat.
Pebble - Particle Carbon Over-Coat	• The TRISO particle overcoat with carbon matrix material prevents particle-to-particle contact during manufacture. • The overcoat also facilitates obtaining the nominal packing fraction in the pebble fuel region during manufacture.

Pebble Design *(continued)*

Fuel System Component	Purpose
Low-density Carbon Core	• Reduces the pebble density ensuring pebble has net positive buoyancy in the Flibe coolant.
Fuel Region	• The fuel region is a shell of carbon matrix material surrounding the porous carbon inner core. • Embedded with TRISO fuel particles at the nominal packing fraction. • This region locates fuel near the coolant decreasing the thermal resistance allowing particle powers to be high while keeping fuel temperatures within limits.
Fuel-Free Carbon Outer Shell	• The fuel-free carbon outer shell protects the fuel region from mechanical damage and separates the fuel particles from the coolant.

Fuel Qualification Methodology

Fuel Qualification Methodology

- U.S. and International Experience
  - Foundation of TRISO fuel particle technology
  - NRC SER on EPRI TRISO topical report
- Kairos Fuel Pebble and Particle PIRT
  - The fuel element PIRT is used to identify high priority phenomena for investigation in the fuel qualification program
- Fuel Specification, Manufacturing, and Quality Control through Inspection
  - Fuel specification equivalent to the AGR program with quality controlled through inspection
- Fuel Qualification Envelope
  - Operation is within the bounds of qualification envelope, otherwise an irradiation test is needed to expand the operational envelope

Fuel Qualification Methodology *(continued)*

- Fuel Pebble Laboratory Testing
  - Demonstrate reasonable assurance that pebble will meet functional requirements
- Fuel Irradiation Testing
  - An irradiation test of a statistically significant number of TRISO fuel particles at conditions that extends the bounds of AGR irradiation test data to support a wider operational envelope
- Fuel Performance Model
  - Physics based models in KP-BISON are a quantifiable representation of fuel knowledge used for core design and source term analysis
- Fuel Surveillance Program
  - Ongoing confirmation of fuel performance

U.S. and International Experience

Summary of U.S. and International Experience

- The use of UO_2 TRISO-coated particle fuel first occurred in the UK in the early 1960s with irradiation the Dragon Reactor.
- The German pebble-bed reactor designs (mid-1970s thru 1988) led to extensive testing and "real time" irradiation in the AVR of full commercial scale production fuel
- China and Japan have successfully developed TRISO fuel production and irradiated fuel in prototype and commercial reactors of the prismatic and pebble bed type
- In the US, General Atomics operated prototype and demonstration gas reactors using uranium/thorium carbide based coated fuel particles in prismatic cores
- The AGR program was built on this extensive experience to qualify a UCO TRISO coated fuel particle, Kairos Power leverages this DOE program

National Program	Average Particle Power (mW)	Peak Temperature (°C)	Peak Burnup (%FIMA)	Peak Fluence ($x10^{25} n/m^2$, E>0.1MeV)
German	100 - 250	800 - 1320	6.7 - 15.6	0.2 - 8.5
Chinese	150 - 250	1017 - 1067	9 - 11	3.8 - 4.9
Japanese	550	1156	6.7	2.8
U.S. Legacy	100 - 400	915 - 1350	12 - 80	2.1 - 11.5
U.S. AGR	55 - 140	800 - 1500	13.2 - 19.6	3.5 - 8.1

DOE AGR and German Irradiation Test Data

Test	Time (EFPD)	Peak Particle Power (mW)	Ave. Particle Power (mW)	Peak Burnup Compact (%FIMA)	Time-Ave. Peak Temp. Compact (°C)	Peak Fluence Compact ($x10^{21}$ n/cm^2, E > 0.1 MeV)
AGR-1	620	104	56	19.6	1197	4.7
AGR-2	559	155	73	13.2	1360	3.8
AGR-3/4	369	98	65	15.3	1418	5.8
AGR-5/6	361	247	107	15.3	1210	6.0
AGR-7	361	238	148	15.0	1405	6.1

Test	Number of Compacts	Number of Particles	SiC Failures		TRISO Failures	
			Number of Failures	95% Confidence	Number of Failures	95% Confidence
US DOE						
AGR-1	72	298,000	4	$\leq 3.1x10^{-5}$	0	$\leq 1.1x10^{-5}$
AGR-2	36	114,336	4	$\leq 8.1x10^{-5}$	≤4	$\leq 8.1x10^{-5}$
Aggregate	108	412,336	8	$\leq 3.6x10^{-5}$	≤4	$\leq 2.3x10^{-5}$
German MTR Irradiation Tests of LEU UO_2 TRISO Fuel Particles in 60mm Diameter Fuel Pebbles						
Pebbles	---	277,000	---	---	0	$\leq 1.1x10^{-5}$

The AGR irradiation tests have demonstrated performance equivalent to the German experience which has historically been considered the standard for TRISO fuel performance.

DOE AGR and German Furnace Safety Test Data

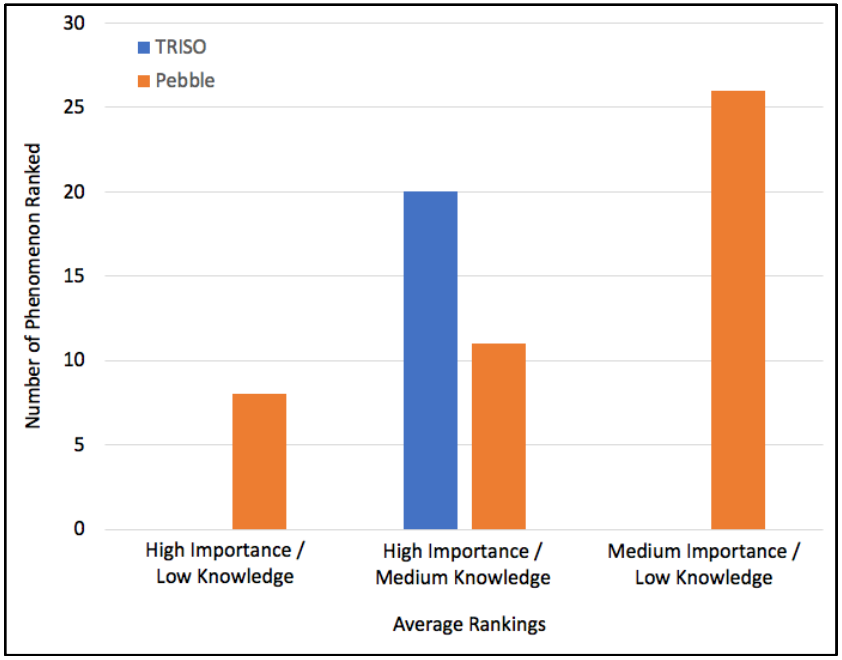
Test Temperature (°C)	Number of Compacts	Number of Particles	SiC Failures		TRISO Failures	
			Number of Failures	95% Confidence	Number of Failures	95% Confidence
AGR-1						
1600	8	33,100	3	$\leq 2.4\text{x}10^{-4}$	0	$\leq 9.1\text{x}10^{-5}$
1700	3	12,400	7	$\leq 1.1\text{x}10^{-3}$	0	$\leq 2.5\text{x}10^{-4}$
1800	4	16,500	23	$\leq 2.0\text{x}10^{-3}$	2	$\leq 3.9\text{x}10^{-4}$
AGR-2						
1600	4	12,704	0	$\leq 2.4\text{x}10^{-4}$	0	$\leq 2.4\text{x}10^{-4}$
1800	3	9,528	1	$\leq 5.0\text{x}10^{-4}$	1	$\leq 5.0\text{x}10^{-4}$
AGR-1 and AGR-2						
1600	12	45,804	3	$\leq 1.7\text{x}10^{-4}$	0	$\leq 6.6\text{x}10^{-5}$
1800	7	26,028	24	$\leq 1.3\text{x}10^{-3}$	3	$\leq 3.0\text{x}10^{-4}$
German Tests of LEU UO_2 TRISO Fuel Particles in 60mm Diameter Fuel Pebbles						
1600	19	287,480	---	---	5	$\leq 3.7\text{x}10^{-5}$

AGR and German furnace safety testing data demonstrates the high reliability of TRISO fuel particles up to 1600°C and above.

Kairos Fuel Pebble and Particle PIRT

Fuel Particle and Pebble PIRT

- Foundation 2004 TRISO PIRT – NUREG/CR-6844
- Fuel element PIRT identifies high priority phenomena to investigate in relation to the FOM fission product transport and release
- Kairos PIRT
  - 199 Phenomenon Identified
  - TRISO fuel particles only had Rank 2 (High importance, medium knowledge level) rankings
  - Pebble fuel elements had more diverse rankings due to the novel design, manufacturing, and performance of the annular pebble



Fuel Particle and Pebble PIRT

PIRT Findings are Addressed:

- Manufacturing Development Program
  - Leverages German and AGR program experience
- Fuel Pebble Laboratory Testing Program
  - Mechanical – Tribology, Compression, Impact, Molten Salt Infiltration
  - Material Compatibility – Pebble in Flibe, Pebble in Air

Fuel Specification, Manufacturing, and Quality Control through Inspection

Fuel Specification, Manufacturing, and Quality Control

- TRISO Particle Specification Based on AGR Specification
  - Equivalent specification to AGR-2 and AGR-5/6/7 TRISO fuel particles
- Pebble Specification
  - Similar to historic HTGR fuel pebbles with features for FHRs
- Manufacturing
  - Kernels fabricated using sol-gel process to form microspheres
  - Coated particles are fabricated in a fluidized bed through a continuous chemical vapor deposition (CVD) process
  - Pebbles are formed from a mixture of matrix graphite powders, binder, and TRISO fuel particles and pressed to shape and heat treated
- Inspection
  - Products are characterized to demonstrate compliance with specifications

Fuel Specification, Manufacturing, and Quality Control

Source Material or Fabricated Component	Measured Characteristic in Inspection Program
U_3O_8	U-235 enrichment, uranium content, impurities, boron equivalent
Kernel	Diameter, density, sphericity, stoichiometry, impurities
TRISO fuel particle	Layer thickness, density, PyC anisotropy, SiC aspect ratio, surface and free uranium content
Natural and petroleum coke graphite	Density, grain size, surface area, impurities, boron equivalent
Binder material	Viscosity, molecular weight, melting point, impurities
Pebble fuel	Density, diameter, thermo-physical properties, mechanical properties, thickness of fuel free outer shell, surface defects, fraction of defective SiC layers (burn leach), uranium loading, uranium contamination in carbon matrix, ash and lithium content, boron equivalent

Fuel Qualification Envelope

Fuel Operating Envelope

- Key Parameters
  - Power
  - Burnup
  - Temperature
  - Fast Fluence
- The KP-FHR operating conditions for steady state and transients must be within the fuel qualification envelope
  - The basis of the qualification envelope are the AGR-2 irradiation conditions defined in the EPRI TRISO topical report

Fuel Operating Envelope and Qualification Limits

Parameter	Proposed Qualification Envelope	Anticipated Non-Power Test KP-FHR Conditions	Anticipated Commercial Electric Power KP-FHR Conditions
Normal Operation			
Peak SiC Layer Temperature (°C)	1360	< 900	< 1100
Burnup (%FIMA)	13.2	< 10	< 20
Peak Particle Power (mW)	155	< 155	< 350
Peak Fluence ($x10^{25} n/m^2$, E>0.1MeV)	3.8	< 2.0	< 4.0
Postulated Events			
Peak SiC Layer Temperature (°C)	1600	< 1200	< 1200
Peak Kernel Temperature (°C)	2350	< 1500	< 1500

Fuel Pebble Laboratory Testing

Laboratory Test Program

- Fuel Pebble Laboratory Test Program will demonstrate that annular fuel pebbles meet functional requirements
  - Mechanical Tests
  - Tribology
  - Buoyancy and Molten Salt Infiltration
  - Material Compatibility

Mechanical Tests and Tribology

- Demonstrate pebbles do not fracture from static and dynamic loads in the reactor and wear behavior is acceptable for a pebble’s lifetime
- Compression test
  - Compression test (crush test)
  - Pebble is loaded in compression until failure
- Impact test
  - Pebble fracture under cyclic impacts
- Tribology
  - Wear rate and coefficient of friction

Buoyancy, Molten Salt Infiltration (MSI) Tests and Material Compatibility

- Flibe Infiltration and Buoyancy
  - Demonstrate pebbles are buoyant
  - Test temperature up to 900°C and pressure up to 500 kPa
  - Measurement of weight change
- Flibe Compatibility
  - Pebble carbon matrix interaction with Flibe
- Air Compatibility
  - Oxidation rate behavior of pebble carbon matrix in Air
  - Oxidation tests in the temperature range 450-700°C
  - Measurement of mass loss with time to create an Arrhenius correlation

Laboratory Test Program Acceptance Criteria

Laboratory Test Program	Measured Parameter	Acceptance Criteria
Compression	Crush strength	The crush strength at room temperature is greater than the maximum calculated load in the core, PHSS, and during receipt and inspection.
Impact	Pebble fracture	The pebble will not fracture under cyclic impact in the core, PHSS, and during receipt and inspection.
Tribology	Wear rate	The wear determined by a conservative analysis of wear over the lifetime of a pebble does not result in damage to the TRISO particles.

Laboratory Test Program Acceptance Criteria

(continued)

Laboratory Program Test	Measured Parameter	Acceptance Criteria
Buoyancy	Density (mass and volume), coefficient of thermal expansion	Measurements of pebble density and Flibe density made over the operating range ensure that the pebble remains buoyant.
Buoyancy	Flibe infiltration	Flibe infiltration measured over operating range as well as the range of all transients to ensure the pebble remains buoyant.
Material Compatibility	Corrosion rate of the pebble carbon matrix in Flibe	Flibe interaction with the pebble does not result in damage to the fuel region of the pebble.
Material Compatibility	Corrosion rate of pebble carbon matrix in air	Air material compatibility tests analyzed over the lifetime of a pebble does not result in damage to the fuel region of the pebble.

Fuel Irradiation Testing

Irradiation Testing

- Irradiation testing expands the fuel qualification envelope
  - Testing is required for the commercial electric power reactor
- Tests would be performed in a non-KP-FHR test facility
- Online fission gas release data used to determine the TRISO fuel particle failure fraction
- Destructive PIE is used to confirm the TRISO fuel particle failure fraction
- Acceptance criteria
  - TRISO fuel particle failure fraction with a 95% one-sided upper confidence bound

Fuel Performance Model

Fuel Performance

- KP-BISON used to analyze response of the fuel during normal operation and transients
- Fuel Pebble DEM modeling
- Fuel Pebble Finite Element Modeling

Fuel Surveillance Program

Fuel Surveillance Program

- Fuel surveillance in Hermes confirms fuel performance
- Fission product monitoring
  - Cover gas
  - Flibe coolant
- PHSS pebble inspection system checks burnup and physical condition
- Post irradiation examination in Hermes (and initial KP-X)
  - TRISO particle failure fraction
  - Pebble surface wear
  - Molten salt infiltration

Summary

- Over fifty years of operating experience and testing of TRISO fuel including extensive testing of TRISO fuel particles in AGR-1 and AGR-2, including for both steady state and transient conditions.
- Successful completion of a KP-FHR fuel element PIRT and implementation of associated actions to further the understanding of the annular fuel pebble and TRISO fuel particles.
- Manufacturing and inspection of the KP-FHR fuel to a specification that ensures the fuel is equivalent in performance to the fuel tested in AGR-2, and meets the conditions in the EPRI TRISO topical report SER (Reference 13).
- Operation within a set of defined fuel qualification limits which ensure that the fuel remains within its qualification envelope during both normal operation and licensing basis events.

Summary *(continued)*

- Irradiation testing (if TRISO fuel particle will operate outside of the AGR-2 fuel performance envelope)
- Surveillance program confirms that the pebble form does not have an adverse impact on the fuel particles.
- The ability to examine fuel pebbles as they exit and re-enter the core over their expected lifetime, including the ability to remove them if necessary for disposal or PIE.

Limitations

- The design of the annular pebble, TRISO particle-based fuel and the KP-FHR design overview are as described in Section 1.1.2, including the presence of a Flibe primary coolant.
- Operating and transient conditions for the KP-FHR are demonstrated in safety analysis reports submitted with license applications under 10 CFR 50 and 10 CFR 52 to remain within the fuel qualification envelope values specified in Table 3-11, which is based on the AGR program.
- If the fuel qualification envelope is to be extended beyond the AGR-2 based limits, an irradiation test program will be conducted.
- Demonstration that the conditions and limitations of the EPRI TRISO Topical Report Safety Evaluation Report are met for the KP-FHR fuel design.
- Future license applications for commercial electric power KP-FHRs will include justification (testing or analysis based on an approved methodology) of the applicability of this methodology during rapid reactor transient events for irradiated fuel.
- Future license applications for commercial electric power KP-FHRs will include additional justification (testing or analysis based on an approved methodology) that Flibe does not adversely impact irradiated fuel pebble buoyancy.
- This methodology applies only to KP-FHRs with a safety-related positive flux rate trip.
- SER limitation to justify applicability of this methodology to a test reactor for rapid transients.

End of Presentation

Questions?

NRC Evaluation of KP-TR-011-P, “Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)”, Rev. 2

Chris Van Wert
US Nuclear Regulatory Commission

October 17, 2022

Introduction

- Kairos Power, LLC requested staff review and approval of KP-TR-011-P, Rev. 2, “Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)”
- Provides a methodology by which the Kairos fuel pebble design will be qualified for use in either a KP-FHR non-power or KP-FHR power reactor
- The staff’s review focused on the overall qualification framework including:
  - Use of existing data
  - Unirradiated testing
  - Irradiation testing
  - Surveillance

Regulatory Basis

Title 10 of the *Code of Federal Regulations* (10 CFR) Sections 50.34(a), 50.34(b), 50.43(e), and corresponding regulations for design certification applications, combined license applications and standard design approvals

10 CFR 100.11 “Determination of exclusion area, low population zone and population center distance”

Kairos PDC 10 – “Reactor design” which has been approved by the staff (KP-TR-003-NP-A)

KP-FHR PDC 16, “Containment Design” which has been approved by the staff (KP-TR-003-NP-A)

Applicability of Existing Data

- KP-TR-011, Rev. 2, builds upon the approved topical report EPRI-AR-(NP)-1
  - Kairos TRISO particle specifications comparable with the Advanced Gas Reactor campaign 2 (AGR-2) particle
  - Non-power KP-FHR reactor operating conditions are bounded by AGR-2 test conditions
  - Power reactor operating conditions exceed some AGR-2 test conditions
- Available carbon matrix property data are used to inform Kairos testing plans to support fuel qualification.

The staff reviewed the existing data use as outlined in the topical report and finds it acceptable for the stated uses.

Laboratory Pebble Testing

KP-TR-011-P discusses planned laboratory tests to obtain Kairos fuel pebble data to support fuel qualification:

- Mechanical
- Tribology
- Buoyancy and Salt Infiltration
- Material Compatibility

The staff reviewed the planned tests and found them acceptable for use in determining Kairos fuel pebble characteristics to support fuel qualification.

Irradiation Testing

Section 3.7 of the topical report details irradiation testing which will be performed to support operation outside of the AGR-2 operational envelope, if desired

- Fuel pebble irradiation in a gas environment
- Purge gas monitoring for fission gas
- Post Irradiation Examinations

The staff reviewed the irradiation testing plans from Section 3.7 of the topical report and finds them acceptable for determining irradiated failed particle fraction and gross pebble behavior which could potentially impact particle failures.

Fuel Performance Modeling

Section 3.8 of the topical report addresses fuel particle performance modeling

- The staff's approval of this topical report is related to the methodology by which the Kairos fuel pebble can be qualified
- The data collected by adherence can be used in updating or building a fuel performance model
- The staff's approval of the fuel qualification topical report does not approve a priori any modifications to the Kairos fuel performance code KP-BISON

Fuel Surveillance

Section 3.9 of the topical report addresses fuel surveillance plans for the initial test and power KP-FHR cores which are used to both monitor fuel performance and to collect data for fuel performance models

- Cover gas monitoring
- Non-destructive examinations
- Destructive examinations

The staff finds that the fuel surveillance methods are robust and can detect failed particles, pebbles at the end of life, and damaged pebbles which could lead to particle failure.

Staff Limitations

The staff's approval of KP-TR-011-P includes the following staff limitation in addition to the limitations provided by Kairos in Section 4.2 of the topical report:

> *Future license applications for non-power KP-FHRs will include justification of the applicability of this methodology during rapid reactor transient events.*

Conclusions

The staff reviewed the topical report KP-TR-011-P, Rev. 2 and concludes that the fuel qualification methodology contained within is acceptable for supporting fuel qualification of Kairos fuel pebbles in either non-power or power reactor versions of the KP-FHR.

Questions?