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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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688TH MEETING

ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

OPEN MEETING

+ + + + +

WEDNESDAY

SEPTEMBER 8, 2021

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The Advisory Committee met via Video-Teleconference, at 8:30 a.m. EDT, Matthew W. Sunseri, Chairman, presiding.

COMMITTEE MEMBERS:

MATTHEW W. SUNSERI, Chairman

JOY L. REMPE, Vice Chairman

WALTER L. KIRCHNER, Member-at-large

RONALD G. BALLINGER, Member

VICKI BIER, Member

DENNIS BLEY, Member

CHARLES H. BROWN, JR. Member

VESNA B. DIMITRIJEVIC, Member

GREG HALNON, Member

JOSE MARCH-LEUBA, Member

DAVID A. PETTI, Member

ACRS CONSULTANT:

STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIAL:

WEIDONG WANG

ALSO PRESENT:

BLAISE COLLIN, Kairos Power

DARRELL GARDNER, Kairos Power

BRANDON HAUGH, Kairos Power

DUKE KENNEDY, NRR

SCOTT MOORE, Executive Director, ACRS

RICHARD RIVERA, Kairos Power

JEFFREY SCHMIDT, NRR

JAMES TOMKINS, Kairos Power

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P R O C E E D I N G S

8:31 a.m.

CHAIR SUNSERI: Good morning. The meeting will now come to order.

This is the first day of the 688th meeting of the Advisory Committee on Reactor Safeguards. I'm Matthew Sunseri, the Chair of the ACRS.

I'll now call the roll to verify a quorum and that communications are open.

Let's start with Ron Ballinger.

MEMBER BALLINGER: Here.

CHAIR SUNSERI: Vicki Bier? Vicki, are you there? Unmute.

MEMBER BIER: Sorry about that. Yes, I'm here.

CHAIR SUNSERI: Okay. Dennis Bley?

MEMBER BLEY: Here.

CHAIR SUNSERI: Charles Brown?

MEMBER BROWN: I'm here.

CHAIR SUNSERI: Vesna Dimitrijevic?

MEMBER DIMITRIJEVIC: I'm here.

CHAIR SUNSERI: Greg Halnon?

MEMBER HALNON: Here.

CHAIR SUNSERI: Walt Kirchner?

Walt is having some communication troubles today. I'm sure he'll be joining us as soon as he can.

Jose March-Leuba?

MEMBER MARCH-LEUBA: Here.

MEMBER KIRCHNER: Matt, I'm here. Sorry.

CHAIR SUNSERI: Okay, good. Great. Got you.

Dave Petti?

MEMBER PETTI: Here.

CHAIR SUNSERI: Joy Rempe?

MEMBER REMPE: Here.

CHAIR SUNSERI: And myself.

So, we have all members present and communications were loud and clear. So, we have a quorum.

The ACRS was established by the Atomic Energy Act and is governed by the Federal Advisory Committee Act. The ACRS section of the U.S. NRC public website provides information about the history of the ACRS and provides documents such as our Charter, Bylaws, Federal Register notices for meetings, Letter Reports, and transcripts of all full and subcommittee meetings, including all slides presented at the meetings. The Committee provides its advice on safety matters to the Commission through its publicly available Letter Reports.

The Federal Register notice announcing this meeting was published on August 16th, 2021, and provided the agenda and instructions for interested parties to provide written documents or requests and opportunities to address the Committee.

The Designated Federal Officer for this meeting is Mr. Weidong Wang.

During today's meeting, the Committee will consider the following:

The first topic is the Kairos Topical Report on Fuel Performance. We'll have a presentation, and then, we will have report preparation activities. And I do note that portions of the Kairos session will be closed to discuss and protect information designated as proprietary.

And then, in the afternoon, we will continue preparations for our briefing to the Commission which is scheduled for October.

The phone bridge line has been opened to allow members of the public to listen in on the presentation and Committee discussions. We have received no written comments or requests to make oral statements from members of the public regarding today's session.

There will be an opportunity for public comment, and we have set aside time in the agenda for comments from members of the public attending or listening to our meeting. Written comments may be forwarded to Mr. Weidong Wang, the Designated Federal Officer.

A transcript of the open portions of the meeting is being kept. So, it is requested that speakers identify themselves and speak with sufficient clarity and volume, so that they can be readily heard. Additionally, participants should mute themselves when not speaking.

So, I just wanted to open by saying it's been a while since we've gotten together. July was our last Committee meeting. We did have a subcommittee in September. So, I do appreciate everyone getting back together here.

And I want to acknowledge everybody's patience for us and the early hour of this meeting. We had intended that this meeting would be an in-person meeting. When we scheduled it as such, pandemic trends were looking beneficial to support in-person meetings, which we were greatly anticipating and looking forward to. However, in light of the public health trends, we could not in good conscience schedule travel amongst the escalating rates of the virus transmission. So, we decided to postpone in-person meetings, not indefinitely, but we'll talk more about this during our P&P session. But it's not likely to get back together until December, even if that is supported by the public health trends.

Anyway, that's all I wanted to say. So, at this point in time, I will ask Member Petti if he is ready to start the Kairos sessions, and turn it over to Dave.

MEMBER PETTI: Thank you, Mr. Chairman.

Let's see, would the senior staff like to say something before we pass it over to Kairos?

MR. KENNEDY: Yes. Good morning.

This is Duke Kennedy. I'm the Acting Chief of the Advanced Reactor Licensing Branch. So, I will give some opening remarks.

So, good morning, Mr. Chairman and Distinguished Members of the ACRS. It's my pleasure to be here today to provide introductory remarks on behalf of the Division of Advanced Reactors and Non-Power Production and Utilization Facilities in the Office of Nuclear Reactor Regulation.

With me today is Mr. Jeffrey Schmidt of the Advanced Reactor Technical Branch, who is the lead technical reviewer and will provide the staff presentation, and Mr. Richard Rivera, providing project management support, and other members of DANU.

The staff is looking forward to discussions with and feedback from the ACRS members today on the Draft Safety Evaluation of the Kairos Power Topical Report titled, "KP-FHR Fuel Performance Methodology." Staff briefed the Kairos Power Licensing Subcommittee on this report on July 6th, 2021, as was mentioned.

And as you will hear, this Topical Report is important for Kairos' safety case and is related to other Topical Reports, such as the Mechanistic Source Term and Fuel Qualification Reports.

We note that this meeting is the third time staff and Kairos Power have had the opportunity to brief the ACRS on Kairos Power Topical Reports, and the staff appreciated the helpful comments from the ACRS on Topical Reports covering reactor coolant, scaling methodology, and licensing modernization, project implementation, and the draft of the report that's the subject of today's meeting.

The staff looks forward to continuing to work with the Chairman and the rest of the ACRS members and staff as we complete the reviews of more

Kairos Power Topical Reports and review license applications for facilities that will use the Kairos Power design.

We expect to receive a construction permit application for the Kairos Power's Hermes Test Reactor later this year.

I'd like to highlight that the working relationship between NRC staff and Kairos Power was excellent. Similar to previous reviews of Kairos Power Topical Reports, the staff has used public meetings as an efficient means for addressing technical issues without the need for extensive interactions via requests for additional information.

Finally, I'd like to thank the technical staff from the Advanced Reactor Technical Branch and DANU for their efforts to produce a high-quality Draft Safety Evaluation and the staff from the Office of Research for their valuable support.

That concludes my opening remarks, and I guess we'll turn it over to Kairos Power.

MR. TOMKINS: Okay. My name is James Tomkins. I'm Kairos Power licensing and focused mainly on Fuel Topical Reports and Chapter 4 of the PSAR.

So, we have Blaise Collin, who is one of our fuel performance experts, who will present an overview of the Topical Report.

So, Blaise, I think you're on?

MR. COLLIN: Yes, I am on.

Good morning, everybody.

MR. TOMKINS: So, with that said, I will turn it over to Blaise. He's going to present a high-level overview of the Fuel Performance Topical, because we did cover it in pretty substantial detail at the last meeting. And this is a public meeting.

So, Weidong, if you can set up Blaise, so that he can share his screen?

And, Blaise, go ahead and share your screen and take it away.

MR. WANG: Blaise is already as a presenter. So, he can share the screen.

MR. TOMKINS: Okay.

MEMBER PETTI: We don't see anything yet, Blaise.

MR. COLLIN: Good morning, everybody, again.

Sorry for the technical blip. The team has asked, when it actually starts, that I share my screen. I am not presenter anymore at the moment. So, we ask the ACRS if they could make me one again.

CHAIR SUNSERI: My screen shows you as a presenter. This is Matt.

MR. COLLIN: Okay. Now it seems to be working again. I'm not sure what you're seeing. Are you seeing my presentation?

MEMBER PETTI: There we go. We can see it.

MR. COLLIN: All right. Okay, here we go.

All right. Sorry for the technical difficulties.

Good morning, Mr. Chairman, and good morning, Members of the ACRS Committee. Good morning to the staff and the public listening in.

This will be an overview of our Fuel Performance Methodology Topical Report. We already had an extensive discussion about this Topical Report with the ACRS Subcommittee in early July. This will be a high-level public presentation in which we, obviously, do not disclose any of our proprietary material.

So, the Topical Report for October from Kairos Power contains the following introduction. Basically, it covers how we modeled the behavior of TRISO fuel under our KP-FHR conditions, and also discusses how we intend to perform verification and validation, including answers on the quantification of the fuel performance code which is named KP-BISON. It's the Kairos Powers commercial version of the BISON code developed at INL. And there's a consequence section in the Topical Report that describes exactly how we intend to perform fuel performance analysis with KP-BISON.

So, as many of you know, this is just a slide presenting an overview of TRISO fuel behavior when put under neutron flux. A TRISO particle is made out of, in our case, a UCO kernel, which is uranium oxycarbide fuel. That kernel is surrounded by a carbon buffer and three outer coating layers, a silicon carbide layer sandwiched between two pyrocarbon layers.

So, all these layers, all these constituents have various behaviors. When under flux, the kernel tends to swell outward. The buffer and the PyC layers tend to shrink early during irradiation and reverse to swelling when neutron fluence accumulates. And the SiC layer, which is sandwiched here between the two PyC layers, tends to have pretty much elastic behavior.

So, the whole purpose of, I mean, one of the purposes of our fuel performance calculation is, obviously, to ensure the integrity of the fuel when put under the KP-FHR irradiation conditions, and therefore, we need to calculate the elemental changes of all these coating layers and calculate the associated stresses to these dimensional changes.

Again, something that is pretty well known by the TRISO community, historically, and more recently with the development of the Advanced Gas Reactor Program by their department of energy, the fuel failure mechanisms have been identified for TRISO fuel, in general, and UCO fuel, in particular. These are listed on the slide.

There is a potential pressure vessel failure of TRISO particles that results from increasing internal pressure inside the particle, that pressure coming from fission gas. And in the case of UO2 fuel, it can also come from the formation of carbon monoxide.

As I mentioned earlier, the PyC layers tend to shrink early during irradiation, and that could, in particular, lead to the cracking of IPyC layer. That cracking can itself lead to a failure of the silicon carbide layer by, basically, adding additional stress on the silicon carbide layer.

Another phenomena that exists between the

IPyC and the SiC is the potential debonding between the two layers that will also put stress on the silicon carbide layer, potentially, again, leading to its failure.

There are other phenomena that are specific to UO2, like kernel migrations, where the kernel would migrate towards the SiC layer because of accumulation of carbon monoxide on one side of the layer, the particle pushing the kernel in the other direction. And once the kernel contacts the coating layers, the outer coating layers, it could fail the silicon (audio interference).

(Audio interference) attacked by fission products that are, obviously, generated in the kernel or by, in the case of UO2, it could be chemically attacked by carbon monoxide, and that also could lead to its failure when the thickness of the silicon carbide layer gets too thin.

At very high temperature, the silicon carbide layer might or would also decompose between its constituent silicon, on the one side, and carbon, on the other side. That only occurs at temperatures above about 2,000 degrees Celsius, so far out of reach of KP-FHR temperatures.

And finally, a more recent failure

mechanism that was observed by post-irradiation examination of FHR fuel is a fracture of the buffer that could lead to cracking of the IPyC in case the IPyC doesn't debond from the buffer during irradiation. And as we've seen cracking of the IPyC layer could itself lead to failure of the silicon carbide layer.

So, these are about half a dozen failure mechanisms that are well identified for TRISO fuel and models for the relevant failure mechanisms relevant to UCO fuel, which is the Kairos Power fuel, and relevant to the irradiation conditions of KP-FHR. So, these relevant failure mechanisms were developed and implemented in BISON and, by extension, in KP-BISON, with the purpose being to predict potential failure of the coating layers, including the SiC layer, and potential subsequent release of fission products from the particle into the fluoride coolant of the KP-FHR.

MEMBER MARCH-LEUBA: This is Jose March-Leuba.

This is a good exposition of the degradation mechanisms of the kernel. Do you also consider fabrication problems when it came out defective from the factory? How are those considered?

MR. COLLIN: Correct. So, we do have a

fuel specification, and they're similar to the actual specification of the AGR program. By fabrication, you can have manufacturing defects. These defects have specifications. So, for instance, you could fabricate particles with defective layers. So, you know by fabrication that some of your particles might have a defective SiC layer or defective PyC layers or a missing buffer.

So, you have like a set of defects that were identified by previous TRISO fuel fabricators, including the AGR program. And all these defects have upper allowed limits. So, when we run our calculations for (audio interference) release of fission products, we take into account that, purely by fabrication, some of these particles are potentially already defective. So, it's sort of independent of additional calculations made by KP-BISON.

KP-BISON would, basically, tell you if you put intact particles into flux, are they going to keep their integrity or are some of these coating layers failed? But, in addition to these calculations, we have already a small fraction of already-existing or already defective particles, and that is accounted for when we do calculations of release of fission products.

MEMBER MARCH-LEUBA: And that fraction is calculated based on sampling? I mean, it's on quality control? Previous experience? Testing?

MR. COLLIN: So, at this moment, because we do not have, well, Kairos has not produced TRISO particles yet. So, at this moment, we are using this specification. And so, we have, for each potential defect, there is an upper limit on the allowable fraction of defects. And we're using these upper bounding values for our calculations in the short term. So, it's short-term calculations.

In the future, once the fuel is fabricated, it will be characterized and all these defects will be measured as part of the characterization process. So, we will, potentially, we will be able to replace the upper values from the fuel specification by actual measured values from actual fabrication. And obviously, we expect these values to be, these measured values to be smaller than with the specification, and it's the point of the specification to reject every lot whose measured characteristics would be above specification.

MEMBER MARCH-LEUBA: Okay. Thank you very much.

MR. COLLIN: Sure.

MEMBER REMPE: This is Joy.

During our Subcommittee open meeting, we talked about the fact that Kairos will still need to get data to show or support any statements that say the coolant is a separate and independent fission product release barrier. Because we don't have, or Kairos doesn't have, data to try and characterize whether there's any chemical attack by the coolant on the various layers of the particle.

How will Kairos try and estimate a mechanistic source term when they have so much uncertainty in the timing and magnitude of the fission products released? Because there could be some chemical attack by the coolant on the various layers of the particles.

MR. COLLIN: So, at this moment and at this time, I guess we are assuming that there will actually be no interaction between the coolant and the TRISO particles. So, like in our design, in our fuel design, obviously, we do have -- in the pebble form, there's a layer, there's an outer shell that keeps the fuel itself or the TRISO particles separate from the fluoride, from the coolant.

And so, we are going to conduct tests -- so, these tests are actually already ongoing -- to basically study the interaction between the fluoride and the graphite and the pebble; check for potential infiltration of the fluoride into the pebble. It is my understanding at this point that we do not have infiltration of the fluoride into the pebble, so that the fluoride is not reaching the TRISO particles.

MEMBER REMPE: So, discuss those tests a little bit more here on the record. Are they high temperature or at temperature and at characteristic fluids conditions?

MR. COLLIN: So, I would have to let our test expert discuss these. I don't know the details.

MEMBER PETTI: Blaise, can I ask you a question?

I understand that a white paper on mechanistic source term has come in. And I don't know that my colleagues know that, but I do. We will be reviewing that. Will there be more information in that Topical Report on this sort of topic?

MEMBER REMPE: And, in particular, will there be experimental data to support it? Because, yes, I am aware that that paper has come in. And I'm just kind of wondering because, if you don't have data to support it, I'm just thinking, then, you must have to take into account a lot of uncertainties with respect to timing and magnitude.

MR. TOMKINS: Yes, Joy, this is Jim Tomkins.

I think the question you're asking is really more related to the Fuel Qualification Topical Report, which you will be seeing at some point in the near future.

MEMBER REMPE: This Topical Report, in tests -- it is not saying that it's proprietary -- indicates that you believe that the coolant is a separate and independent barrier, right?

MR. TOMKINS: Yes, it is.

MEMBER REMPE: So, I think it's a legitimate question, if you believe that it's a separate and independent barrier, and then, the fact that you're mentioning release of fission products here, to ask. Again, this is a big uncertainty if you don't have data to support the timing and magnitude of the release.

And I know the staff has addressed this by not making a finding at this time. But, again, when we have a lot of uncertainties, and we start having the staff review things with a lot of gaps in data, then there will be re-reviews as you're planning -- this is like the first step in a multi-stage review, correct?

MR. TOMKINS: Correct.

MEMBER REMPE: So, I just am curious on what the plan is.

MR. TOMKINS: And we have data in the fuel qualification that indicates that infiltration at the pressures we're at, it does not occur.

MEMBER REMPE: Okay. So, do you have data that also is considering radiation, temperature, pressure, all of these phenomena together? And it's characteristic of your anticipated burnup that you expect for the fuel?

MR. TOMKINS: That I don't know. I don't know what --

MR. GARDNER: So, this is Darrell Gardner. I apologize for jumping in.

I think we're getting off-topic. The questions being asked really are specific to another Topical Report that hasn't been presented and is still under review by the staff. So, I think we acknowledge the comment, but we're not prepared to have the conversation about fuel qualification and the testing, and all that, today at this meeting.

MEMBER REMPE: Okay, I'll wait. And I want to discuss this same issue with the staff.

Thank you.

MR. COLLIN: So, if I can just add something to close the discussion in a way. Obviously, development of any type of fuel performance code, you have to go with some assumptions about what you should model and what you can, basically, ignore because of insignificant impact.

In the case you mention, the assumption is that the fluoride will not have any deleterious effect on the TRISO particles, which, as we mentioned, is something that is under test. Obviously, if the findings contradict the assumption, we'll obviously have to account for that potential interaction and find a way to develop the appropriate model to include and implement in KP-BISON. But, at this point, we don't have any reason to believe that this will be the case.

As you mentioned, this is a multi-step process. We're, basically, at step one of this development of our fuel performance code. We do have a lot of verification and validation still to be done, and, of course, in the future, potential implementation of new models, depending on findings on our fuel qualification tests.

So, I guess I'll go ahead and discuss our fuel performance code KP-BISON. So, Kairos Power, which is on the left side of this slide, we decided to go with UCO TRISO fuel in the fluoride salt-cooled, High-Temperature Reactor.

On the other hand, INL, Idaho National Laboratory, with its own funding early on, and then, with support from the MOOSE program, has been working on the development of a high fuel performance code called BISON. And it was our understanding at Kairos Power that there were like a lot of benefits to use BISON as our fuel performance code.

So, we developed this collaboration with INL to implement UCO TRISO models in BISON and, like I mentioned earlier, get our own commercial version of the code that's being called KP-BISON to run our fuel performance calculations. So, a few more words about KP-BISON. As mentioned, it was chosen by Kairos Power for its fuel performance code.

BISON sits on the MOOSE framework that also has a lot of other "animals" under its framework. There's like computation of benefits from using BISON because of the link to MOOSE. We also leverage extensive developments made by INL and NEAMS, not only for TRISO fuel, but for fuel performance in general. The code is pretty robust.

So, what we worked on with INL, it's a conversion between Kairos and INL. So, we, basically, wrote the BISON code to like almost, I would call that state of the art in terms of TRISO fuel modeling. So, it's quite a bit of the plan where we imported existing TRISO models into BISON. A lot of that work has been done through an FOA award. So, it's a collaboration; this FOA is a collaboration between Kairos Power and a couple of National Labs on various modeling and simulation aspects, including one on fuel performance that we are working on with INL.

And obviously, one of the important benefits of the using BISON as our fuel performance tool is the ongoing support from the BISON team at INL. There's a group of half a dozen INL engineers that are really on top of things and really helping develop this TRISO modeling in BISON to, again, like a state-of-the-art status.

So, how does this all work? Well, it's a modeling code. So, there's not many surprises here. On the one hand, we have the geometry show characteristics of the TRISO fuel, as we mentioned earlier when discussing fuel properties. Because of fabrication, all the fuel properties will have distributions. All the properties are computed around no known values, but they have tails extending on both sides of their nominal values.

We have our KP-FHR with its own irradiation conditions, and KP-BISON takes these as inputs, and together with some of the material properties implemented in the code -- material properties being, for instance, some of, I know we mentioned like a swelling of the kernel, shrinkage of the PyC layers. So, these are material properties that are ones which have correlations that are implemented in the code.

So, the geometry, the irradiation conditions, they feel into some of these material properties, and with all these input parameters, KP-BISON calculates intermediate results, such as the fuel temperature or temperature in the kernel or in the coating layers, the pressure coming from the fission gas, the displacements of the coating layers, and the stress or stresses that are induced by these displacements.

And all these intermediate results serve the purpose of calculating the two figures of merit of KP-BISON which are the probability of failure of the outer coating layers and the release of fission products that can be directly from intact particles or that could be enhanced by failure of some of the coating layers. So, that's the overall philosophy of these KP-BISON calculations.

As I mentioned earlier, the fuel properties or the fuel that is used by Kairos is similar to the fuel developed by the AGR program. Specifically, it is similar to, there's the same or very close specification, so similar to the AGR-2 UCO fuel and the AGR-5/6/7 fuel.

The AGR-2 UCO fuel is discussed in a Pre-Topical Report. That's compilation of results from AGR-1 and AGR-2 PIE that was issued, presented to the staff, obviously, and issued in 2020.

The AGR-5/6/7 is the latest portion of the AGR irradiation program. The fuel is now out of the reactor and awaiting PIE. And obviously, a lot of information from the AGR-5/6/7 PIE will become available in the upcoming years.

So, it's just important to note that we are relying on the fuel that proved to be robust and showed very good performance during the AGR irradiation tests.

So, that's two properties are, obviously, one big part of the KP-BISON input parameters. The other inputs are the material properties and the physical model. So, these two tables summarize, on the one hand, the material properties that are included in KP-BISON for all the constituents of the TRISO particle. So, there's the swelling of the kernel. We have elastic properties. We have properties that depend on the irradiation level, so, basically, on a fast neutron fluence. Obviously, thermal properties, and for the purpose of fission product release, we also have diffusion coefficients for a handful of isotopes and for each of the TRISO constituents as well.

And obviously, to capture the physical behavior of the fuel, we rely on a few physical models. Some of these are very basic, like heat equation, something you would find in any fuel performance code.

We're looking at things like fission gas release and the pressure that fission gas will create inside a particle, but we also have things that are more particular to TRISO fuel like penetration of palladium into the silicon carbide layers, meaning the migration of palladium from the kernel into the SiC and corrosion of that layer that could lead to its failure.

For short-lived fission gas, we're looking at something called release-rate-over-birth-rate ratio, which is just basically a measure of the release of these short-lived fission gases over their production rate.

And finally, as I mentioned, we're doing fission product release calculations, and we model fission product transport through these kernel or TRISO constituents using fission diffusions.

So, all this makes, all these models and properties implemented in KP-BISON -- so, the existing database, if you will, is pretty well-suited to studying and modeling behavior of UCO TRISO fuel in the KP-FHR. So, we feel that we have a good tool to now perform our fuel performance calculations in the KP-FHR.

So, that slide shows our V&V, so verification and validation, plan. We really rely heavily on these two existing benchmarks. One is from the IAEA. It's a benchmark that was already executed by some of, at the time, some of the participating countries.

And our purpose is to go through, again, all of these benchmark cases that cover normal operation or operational transients and, also, some of the expected behavior under accident conditions. It mixes verification and validation cases. And like I said, it's been already run by a lot of different codes. So, it's a very good starting point to make sure that all the TRISO models have been currently implemented in BISON.

A more recent benchmark from the Generation IV International Forum focuses on a couple of, again, more recent experiments; namely, AGR-1, AGR-2, and the European Commission test, HFR-EU1bs. We will also use this benchmark to verify and validate KP-BISON.

And in addition to the AGR tests, including in this benchmark, we also intend to extend our ow V&V to what we refer to as INL benchmark. Basically, it means that we want to use even more AGR data to test KP-BISON, specifically, under conditions that are more relevant to or KP-FHR irradiation conditions.

So, basically, we want to basically select data that are closer to the KP-FHR envelope. We also want to use the AGR data to look at separate effects, looking at things like swelling of the buffer -- swelling of the kernel, I'm sorry, or shrinkage of the buffer; looking at cracking of the IPyC. Yes, so we will use select data from the AGR PIE to look at separate effects and check that KP-BISON is able to reproduce the PIE data.

And actually, we'll rely on other existing data published from German tests or, more recently, tests on the HTR-PM Chinese reactor. So, basically, like the irradiation tests they did on their fuel prior to, obviously, inserting in the HTR-PM core.

So, a lot of different things that cover -- we're trying to basically cover and use most of the existing data on TRISO fuel. It's still a small, TRISO is still a small world when compared to light-water reactor fuel, but we're trying to be exhaustive in the data that we can use to perform the V&V of KP-BISON.

MEMBER REMPE: So, this is Joy.

I was just wondering about when you plan to do a peer review. Because isn't that required for -- I assume this would be considered a newly developed method, and the staff is going to require peer reviews as part of a PRA of a newly developed method. And is that in your plan? Because I didn't recall seeing that in your Topical Report.

MR. COLLIN: I'm not sure I understand what you mean by "new."

MEMBER REMPE: Well, although BISON has

been around for a while, you're adding new models to it. And so, for your code, I believe, if you're going to be using something that supports a PRA, which I believe you're going to use the licensee modernization process with your design, right? And so, the staff usually requires newly developed methods to have a peer review. And where will that be in your code development process, before or after you do the V&V?

MR. COLLIN: I might let some of my licensing colleagues answer that question. We have not -- well, at least as far as I know, I have not gotten into that type of discussion with the rest of the Kairos team yet. Now we're early in our V&V. So, right now, we're mostly focused on doing that V&V. But Darrell or Jim, maybe you have an answer.

MR. TOMKINS: Blaise, maybe Brandon can.

Brandon, can you address that?

MR. HAUGH: Sure, I can do that.

Hi. This is Brandon Haugh, the Director of Modeling Simulation at Kairos Power. Hopefully, you can hear me okay.

So, Joy, to answer your question, I'll do it in two parts.

So, we will go through a commercial grade dedication activity for BISON and KP-BISON when we get to that point. So, that will be at the end or near the end of our verification and validation process. So, that will meet our quality assurance requirements to make sure that the code performs as it's supposed to.

When it comes to the peer review, I would leave that to the PRA model, when we get to the application of the licensing modernization project. It wouldn't necessarily be BISON itself. It would be an application within the PRA, whether that's Level 1, 2, or 3, and how it's used, determining frequency and consequences.

So, we haven't committed to the application of the licensing modernization project for the Hermes Test Reactor. That's what we're focused on now.

While this report, methodology, could be applied to both, our nearer-term horizon is the non-power test reactor. So, we'll be applying it in a more deterministic fashion.

MEMBER REMPE: So, if you're just going to focus for the near term on Hermes, do you really need NRC approval? I mean, that's going to be built on the Oak Ridge site, right?

MR. HAUGH: No, it --

MEMBER REMPE: So, it's not a powered reactor. So, why worry about all these safety evaluations?

MR. HAUGH: Well, the reactor is not on a DOE site. It's outside of that. So, we are licensing that with the NRC. While it is a non-power reactor, we still need appropriate methods to ensure that we meet the top-level regulatory requirements. And fuel performance, since it's a fission product barrier, is one of those.

MEMBER REMPE: Okay. Well, we'll just have to see how this goes. Thank you.

MR. HAUGH: Uh-hum.

MR. COLLIN: All right. So, back to the presentation. So, yes, this slide shows like a high-level -- it's a high-level flow chart of fuel performance analysis and methodology. As mentioned earlier, what we're trying to do, basically, is from our irradiation input parameters, which are fission rate density, fast fission fluence, and the temperature of the coolant, these are inputs to the code.

Our code performs thermal analyses, so looking at the temperatures of all the coating layers and of the kernel, performs a stress analysis and calculates the stress in the coating layers. And the stresses inform about potential failure of the coating layers. And the temperatures inform the diffusivities, so the values of the diffusion coefficients in the various layers, and that leads to calculation of the fission product really. So, we say there's like more to each of these boxes, but for a public presentation, that's the high-level methodology for KP-BISON analysis.

So, I already mentioned the fact that, during quantification, all of the fuel properties will be distributed around a nominal value and extend on both sides of these nominal values, for the average values during quantification.

So, basically, each property will have statistical variations because of this process. And we know from experience that particles that are in the tails of these distributions are usually more likely to fail. That is, for instance, when the thickness of your silicon carbon layer gets too thin, it might not be able to sustain the internal pressure from the fission gas, if it's too thin. So, it's more likely to fail.

So, we have to account for these statistical variations when assessing the probability of failure of the fuel. So, this table here shows just a summary of all of the fuel properties that will have a distribution around these new values. And as mentioned in these bullets, part of the methodology is to treat the fuel statistically, so it captures (audio interference) the rise of failure probability.

And this is done in KP-BISON by using Monte Carlo modeling, where we, basically, sample through these distributions for -- each particle is sampled through the distribution of its fuel properties. So we can, for each particle, more accurately determine if it fails or if it stays intact during irradiation.

That's sort of, again, a high-level summary of that Monte Carlo calculation scheme where we sample the fuel properties. We let KP-BISON do its -- like with the sampled particles, look at the potential, you know, the particular performance of that particle under KP-FHR irradiation conditions. Basically, does it fail or does it stay intact?

We sample many, many particles to get something representative of the KP-FHR core and, also, representative of the distributions of these fuel properties. And when the loop is over, we just compute the statistics of all these sampled calculations and come up with the overall failure probability for that sample and, again, the potential or subsequent fission product release.

So, we have, obviously, discussed this scheme in greater details with the Subcommittee in July. Again, this is a high-level flow chart for this public meeting.

As I mentioned, part of V&V is uncertainty quantification. In general, when talking about fuel performance modeling, and, in particular, for UCO, uncertainty can be found in these four inputs to the code:

Your operating conditions. So, that would be in our case the fission rate density, the neutron flux, the temperature of coolant. All of these can have uncertainties that for KP-BISON would come from -- these are inputs that come from neutronation and thermal-hydraulic codes. So, these codes have their own uncertainties, and we, obviously, have to account for the fact that all these inputs to KP-BISON come with their own uncertainties.

Uncertainties can also be found on the material properties. So, I think kernel swelling, shrinkage of the carbon layers. So, all these material properties are known within a degree of uncertainty. And since they impact the potential or the interior of the coating layer, we also have to account for their potential uncertainty when running KP-BISON.

Some of the physical models that we use are also subject to uncertainty. They would, for instance, include diffusivities that are used to model fission product transport. So, again, we have to understand what the impact of the uncertainties on these physical models, what impact they have on the results calculated by KP-BISON.

And finally, as already mentioned, we do have uncertainties on the fuel properties that come from these statistical variations during the quantification process.

So, that's a lot of different parameters. I think at some point we tallied up to about 60 different input parameters to KP-BISON. We already know from previous codes or evolution of programs that some of these input parameters have a large impact on fuel performance. And since some of them have a negligible impact, it's our goal to run some sensitivity studies to particularly assess the relative impact of all these input parameters to the code.

And again, we find these two FOMs throughout the presentation. We are concerned about the probability of failure of the fuel and the potential release of fission products that would be enhanced by failure of some of the coating layers.

So, we give a methodology for uncertainty quantification. This methodology is proprietary. So, we will not discuss it in detail during the open session of this meeting. It's already been discussed in early July with the Subcommittee.

We feel that methodology provides us with a conservative way of calculating of failure of the fuel and release of fission products. So, the methodology includes the calculation of one-sided 95/95 tolerance limits on these two figures of merit. And we think that these tolerance limits, the way they are calculated and the way the methodology for uncertainty quantification has been developed, we feel that these are conservative tolerance limits that will, then, show that we do have like a conservative way of calculating the performance of the fuel in our KP-FHR cores.

And I think that's the end of it.

MEMBER PETTI: Members, any questions?

MEMBER HALNON: This is Greg Halnon.

A quick question on the uncertainty calculations. Since the plant is not really physically built or designed yet, from my understanding, how did you ensure that the operating conditions that you chose were bounding in the fact that, since there's an input to the model for uncertainties -- I guess what I'm trying to get to is, how did you define the operating conditions, such that you bounded all the necessary fuel parameters that may result from operating transients and other things that may happen, based on human interactions?

MR. COLLIN: So, I will, unfortunately, to answer this question during this public session. The treatment of operating conditions is a large, like important part of our methodology.

MEMBER HALNON: Okay. Well, we can talk --

MR. COLLIN: Yes, we can discuss; I can answer that question once we hit the closed session, if you --

MEMBER HALNON: Sure. Yes.

MR. TOMKINS: And I might add, I mean, Greg, we haven't made a final determination of the operating condition uncertainties because it does depend on the instruments we use in the plant and things like that. So, that isn't done yet.

MEMBER HALNON: Okay. Well, that may be the answer to the question.

MR. TOMKINS: Yes, yes.

MEMBER HALNON: We can talk in more detail later on.

MR. COLLIN: Yes, we do have -- they're still TBD. Again, they do not depend on -- they're, you know, outside of -- well, I guess what I'm trying to say is like these are things that are not controlled by KP-BISON. These are inputs to the code. The code will take whatever is given to it. But, right now, we have the way around to, again, make sure that we run conservative evaluation of this uncertainty. But, yes, we can discuss it in more detail.

MEMBER HALNON: Okay. Yes, let's discuss the relationship between the inputs and how you chose the operating conditions to provide those inputs. I think that's my question. So, we'll talk more.

MR. COLLIN: Sure.

MEMBER PETTI: Okay. If there's no more questions, does staff have their presentation?

MR. SCHMIDT: Yes, I do.

MEMBER PETTI: Thanks, Jeff.

MR. SCHMIDT: I'll log in here.

Can people see this?

MEMBER PETTI: Yes.

MR. SCHMIDT: All right. Great.

Good morning, everyone. My name is Jeff Schmidt, and I'm a Senior Reactor Systems Engineer in the Advanced Reactor Technical Branch II, the Division of Advanced Reactors and Non-Power Production and Utilization Facilities, or better known as DANU. We're going to be discussing the KP-FHR Fuel Performance Methodology Revision 3.

Kairos requested approval of the Fuel Performance Methodology Revision 3. The Topical Report is applicable to the Kairos UCO TRISO fuel for the FHR non-power reactor, which has been identified as Hermes earlier, and the power reactor. So, this is kind of a dual-use Topical Report. I think that's already been addressed.

The TR itself identifies several open items to be addressed in subsequent revisions. We've talked about that already. That is a staged review. So, there are some known. Kairos identified open items, and some staff identified open items in the limitation section of the SE.

The staff review focused on the

calculational framework, which is composed of UCO TRISO fuel failure mechanisms, which Blaise went into in some detail; uncertainty parameters and associated methodology; determination of the upper tolerance limits for the figures of merits of in-service failed fuel fractions and fission product release. TRISO being one of the important barriers to fission product release, these outputs from the fuel performance analysis fell into the mechanistic source term methodology, which is a separate Topical Report.

The regulatory basis, Kairos wants flexibility so far in the licensing path. So, you'll see that 10 CFR 50.34(a) and (b) are also listed, and the corresponding regulations for design certification, combined license application, and standard design approvals.

As mentioned, the TRISO particle is the primary fission product barrier. So, 10 CFR 100.11, "Determination of exclusion area, low population zone and population center distance," is an important regulatory basis.

And then, Kairos has a PDC 10, "Reactor Design," which has been approved by staff, which, basically, limits the release of TRISO, well, of fission products during normal operations and AOOs.

Portions of the Topical Report not addressed by the Safety Evaluation, and there's a number here. So, the PIRT in Section 2.3; Section 2.4, "Fission Product Transport," and all the subsections of 2.4; Section 3, "Fuel Modeling, Material Properties, and Physical Models"; Section 4.1.1, "Verification and Validation"; Section 5, "KP-BISON Code, and all subsections; Topical Report (audio interference), "Defeating Coefficients for Key Fission Product Modeling KP-BISON"; Section 6.4.2, "TRISO and Pebble Models, including potential pebble behavior and material uncertainties that could affect TRISO particle failure fractions," and Section 6.3, "Fission Product Release," as it pertains to fuel-pebble mechanical and chemical interactions with a salt environment and possible wear, which (audio interference) could be outside the scope of this Topical Report.

And I know there was a question on the salt environment, and those type of questions are being addressed by the Kairos Fuel Qualification Topical Report.

So, the staff made no findings in these areas, primarily because of verification and validation and quantitative uncertainty analysis was not provided in Revision 3.

As was mentioned --

MEMBER MARCH-LEUBA: Jeff?

MR. SCHMIDT: Yes?

MEMBER MARCH-LEUBA: Yes, this is Jose.

MR. SCHMIDT: Okay.

MEMBER MARCH-LEUBA: This petition from the staff, they are going to provide that in Revision 4 in the near future? Or is it going to be a supplement? Or both?

MR. SCHMIDT: Yes, I don't know. Maybe Kairos can speak to that. I mean, my conceptual idea was a Revision 4, but --

MEMBER MARCH-LEUBA: Yes, that's what I was thinking because, if we issue Revision 3 as an approved Topical Report, and it doesn't get superseded by a Revision 4, then there are holes in this approach.

MR. SCHMIDT: Yes. Yes. So, I guess I envisioned it as a Revision 4 which would supersede this revision in its entirety.

MEMBER MARCH-LEUBA: Correct.

MEMBER REMPE: So, Jeff, this is Joy.

MR. SCHMIDT: Hi, Joy.

MEMBER REMPE: I guess I'm not sure from

what I've heard from Kairos. So, it would be good to hear from them because it sounded like they're going to have a multi-stage review process, and you might end up with six or seven of these iterations. And to preclude -- I mean, I hope that it will all come in Rev. 4 -- but to preclude having a lot of these iterations for all these design developers, I'm wondering if the staff needs to start thinking about some guidance.

And I know I mentioned this during the Subcommittee meeting on, what's the minimum set of requirements for a first-step review? And will you limit it to two or three, or can they come in 10 times, and then, say, "Well, we have 10 SEs from the staff," or something? I just am kind of wondering how many iterations there are going to be.

MR. SCHMIDT: Do you want me to try to handle that or do you want Kairos --

MR. TOMKINS: Can I address that? This is Jim Tomkins. Can you hear me?

MEMBER REMPE: Sure. I'm interested in Kairos' response, but I'm also interested in the bigger picture for all of the design developers that are coming through here.

MR. TOMKINS: So, first off, it is a two-step process. So, it's not going to be an eight-step process. And so, we're going to close these open items, either with a revision to the Topical Report or a separate Technical Report or possibly as part of the FSAR. We're not committing to any one of those approaches at this point in time.

But we're going to get an SER that says, "Here's the open items." And we think any one of those three methods is a viable way to close the open items.

MEMBER REMPE: So, this is on the record, and, I mean, you've got a couple of these or several of these Topical Reports, and they're all kind of a multi-stage review process. And I guess maybe I've missed something, but this is the first time where I've heard you say on the record, "No, we're just going to have a two-step process," which gives me a lot or relief, frankly. So, we can, actually, put this in our letter, that this is the first step of a two-step process, is what the licensee told us on the record?

MR. TOMKINS: Yes. We might want to have Darrell --

MR. GARDNER: This is --

MR. TOMKINS: Yes.

MR. GARDNER: Yes, this is Darrell Gardner.

I would argue that that's not what we said. What we said was that we recognize that, when this SE is issued, it will have open items that we're obligated to address as part of a future licensing action, which would an FSAR or a PSAR, as the case may be, or a Design Certification or a COL. So, all those avenues are available in terms of licensing actions. And those licensing actions could not be completed, absent us addressing these open items. That's --

MEMBER REMPE: Well, I guess I'm confused. You're saying you may not even submit another Topical Report? You may just wait until the PSAR?

MR. GARDNER: I'm saying that is an acceptable licensing option. There's no regulations that require any Topical Reports be submitted at all.

MEMBER REMPE: Okay. So, there will be a lot more required in the FSAR and PSAR if that's your approach. And so, I guess we --

MR. GARDNER: (Audio interference). I get it.

MEMBER REMPE: -- maybe should think about documenting this in our letter; that, clearly, something else has to be done, but it's unclear whether it will come as a Topical Report or as the final FSAR.

MR. GARDNER: I guess the question would be of the Committee is, is there a reason that decision has to be made as part of this review?

MEMBER REMPE: No, but, again, I'm concerned, not just with Kairos and what you're planning on doing. You're right on that. But I am wondering what is going to happen here with all of the design developers and whether the staff needs to think about some guidance for this process. Because there have been --

MR. GARDNER: Sure, I understand --

MEMBER REMPE: -- some doubts in all of your Topical Reports.

MR. GARDNER: I understand that, and I'd like to just take the opportunity to go on the record. We've had an extensive dialog with both the staff, the management team, and the Commission, about our licensing approach and our licensing strategies. I would say we've had feedback that was very positive in our approach that's consistent with a way to innovate.

MEMBER REMPE: But you can understand that, again, our concern is safety, but sometimes we have design developers who come in who complain about the cost for licensing. And if it was an endless DO loop, it could really increase the cost. But, again, if you're just going to wait until the FSAR, that's another situation. I just am trying to understand the vision here.

MEMBER MARCH-LEUBA: Yes, and this is Jose.

And I understand your position from a very high level, point of view, but I cannot see how you can validate a KP-BISON code in the FSAR. There is no section of the FSAR that says, "Validation of Codes." You have to validate it before you use them. That's my opinion.

MR. GARDNER: So, this is Darrell Gardner again to say that, there are a number of open items. I mentioned three pathways that are acceptable licensing vehicles to address those open items. You could use a combination. So, typically, validation is not something you would see, but you could see that in a Technical Report, while other open items might be addressed directly in the FSAR.

MEMBER HALNON: Yes, and that's to mean that all the information in a study or uncertainty analysis would be in the text of an FSAR, but you would reference a report or some other thing that the staff had reviewed during the process. I'm assuming that's what you're meaning here. Because, from Jose's perspective, we wouldn't put chapters and pages and pages and pages of a study in there. It would be a lot of reference --

MR. TOMKINS: Right, because it would be proprietary.

MEMBER HALNON: Incorporation by reference. Right.

MR. TOMKINS: Yes.

MEMBER HALNON: But the staff would review those referenced reports as part of the approval process for the application.

MR. TOMKINS: Right.

MR. SCHMIDT: This is Jeff Schmidt. Should I move on then?

MEMBER PETTI: Yes, please do.

MR. SCHMIDT: Thank you.

So, the staff review, the staff found that the UCO TRISO particle failure mechanism is acceptable, based on the expected operating conditions, subject to Limitation and Condition 3, based on the AGR program data and the EPRI TRISO Topical Report.

Other relevant TRISO particle release

mechanisms, such as manufactured defect particles and dispersed uranium, are included in the calculational framework.

Relevant model uncertainties, such as particle manufacturing variability, model, and physical properties, and irradiation conditions, operating conditions, were adequately accounted for.

Individual uncertainties were conservatively combined to yield an upper tolerance limit for the predicted failed particle fraction and the fission product release from fully intact and in-service failed particles.

The staff SER limitations and conditions. NRC-approved fuel performance failure must be used to determine in-service particle failure fraction and fission product release. A subsequent TR, as has been talked about, may include other means to determine these figures of merit.

UCO TRISO --

MEMBER MARCH-LEUBA: Can you give me an example of these "other means"? What do you have in mind?

MR. SCHMIDT: Let's see. A subsequent document may include other means. I guess what we're really saying there is the revisions of the Topical

Report will -- so, there are options in the Topical Report which you could input, instead of using an approved fuel performance code, for example, you could use directly, say, the AGR fuel failure fractions as input. You could use experimentally-derived or experimentally-based inputs into the code.

That was one of the options listed in the Topical Report, but the details weren't provided sufficient for the staff to make any finding in that area.

MEMBER MARCH-LEUBA: Okay. Thanks. Yes, keep going.

MR. SCHMIDT: Yes. So, Jose, that was, let's say if you wanted to use the AGR fuel failure fractions, for example, as input, experimentally-based. Does that make sense?

MEMBER MARCH-LEUBA: Yes, basically, what you are saying is that TRISO is a very good fuel and you can probably bound what can possibly be a worse mechanism; you don't need to calculate it?

MR. SCHMIDT: Yes, or you can use experimental data.

MEMBER MARCH-LEUBA: Yes, but that's what I mean by "bounding." And it's probably a good approach. I'm not saying it's not.

MR. SCHMIDT: Yes.

MEMBER MARCH-LEUBA: I understand, but I would code, though.

MR. SCHMIDT: Yes, so, I mean, the staff is not agreeing or disagreeing. It's just saying that that was presented in the Topical Report, but we would need some information about it, how that was proposed to be done.

So, the UCO TRISO particle failure mechanism must be reevaluated if the operating conditions are not bounded by the UCO TRISO EPRI-AR-1A Topical Report.

The Kairos Fuel Qualification Topical Report will address expanding the EPRI TRISO operating envelope. Kairos has identified in the Fuel Qualification Topical Report that the particle power density is not bounded, at least for the KP reactor. It may be bounded the Hermes reactor that's still under review, but I think they acknowledge that there might be some additional work needed there for particle power.

Federal Limitations and Conditions 4, 5, 6, 8, 10, and 11 exist, due to information not included in the TR Revision 3, but is expected in subsequent revisions.

The methodology can be used to evaluate the figures of merit -- or cannot be used, I'm sorry -- cannot be used to evaluate the figures of merit for AOOs, design basis accidents, beyond design basis events, as a methodology for combining these with bounding quasi-steady-state operating conditions was not provided.

Some aspects of pebble performance will be addressed in another TR. And that's really referring to the Kairos Fuel Qualification Topical Report.

Staff conclusions. The fuel performance methodology of Revision 3 Topical Report provides an acceptable methodology for determining conservative UCO TRISO particle fission product release from in-service failed and intact particles, manufacturing defects, and dispersed uranium.

Staff approvals are subject to the Limitations and Conditions of the SER.

That ends my presentation. Are there any questions?

(No response.)

MEMBER PETTI: Thank you, Jeff.

Hearing no further questions.

So, I think were' done with this session, Mr. Chairman.

CHAIR SUNSERI: All right. Thank you, Dave.

We can ask for public comments at this point in time.

And because we are using this Teams approach, it's my understanding that the public can unmute their line by using *6, state their name, and make their comment.

So, let's call for that then. So, members of the public listening in, this is your opportunity for making a comment.

If you are muted, unmute your line using *6, state your name, and make your comment.

(No response.)

All right. We are not hearing any. So, I mean, we will offer the same opportunity for direct participants of the Teams line, just like we would be doing if you were in the room.

So, any members that would like to make a comment, please do so at this time.

(No response.)

All right. Dave, it looks like we don't have any comments.

So, at this point in time, we think we would move into report preparation, which we needed to at least start in a closed session, it's my understanding. Is that correct?

MEMBER PETTI: Correct.

CHAIR SUNSERI: All right. So, let's do this. Let's take a 30-minute break. We'll reconvene at 10:30 Eastern time in closed session.

(Whereupon, at 9:59 a.m., the open session was concluded.)

Kairos Power

KP-NRC-2109-001

September 2, 2021

Project No. 99902069

US Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Subject: Kairos Power LLC
Presentation Materials for Kairos Power Meeting with the Advisory Committee on Reactor Safeguards on Fuel Performance Methodology Topical Report

This letter transmits presentation materials for the September 8, 2021 meeting with the Advisory Committee for Reactor Safeguards (ACRS) full committee. At the meeting, participants will discuss the KP-FHR Fuel Performance Methodology Topical Report (KP-TR-010) that was submitted to the Nuclear Regulatory Commission staff for review and approval.

Enclosure 1 provides the non-proprietary presentation materials. Kairos Power authorizes the Nuclear Regulatory Commission to reproduce and distribute the submitted non-proprietary content, as necessary, to support the conduct of their regulatory responsibilities.

If you have any questions or need any additional information, please contact James Tomkins at tomkins@kairospower.com or (510) 808-5265, or Darrell Gardner at gardner@kairospower.com or (704)-769-1226.

Sincerely,

Peter Hastings, PE
Vice President, Regulatory Affairs and Quality

Enclosures:

1) Presentation Materials for the September 8, 2021 ACRS Meeting (Non-Proprietary)

xc (w/enclosure):

William Kennedy, Acting Chief, Advanced Reactor Licensing Branch
Stewart Magruder, Project Manager, Advanced Reactor and Licensing Branch

**Enclosure 1**

**Presentation Materials for the September 8, 2021 ACRS Meeting**

**(Non-Proprietary)**

# KP-FHR Fuel Performance Methodology Topical Report

KAIROS POWER

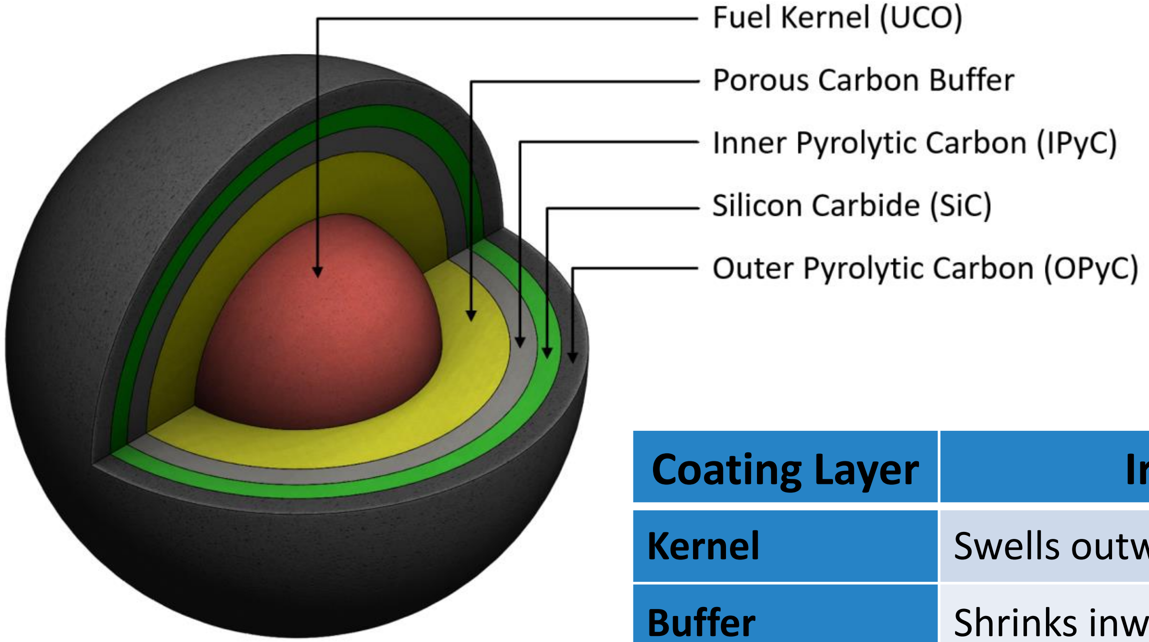
ACRS FULL COMMITTEE MEETING

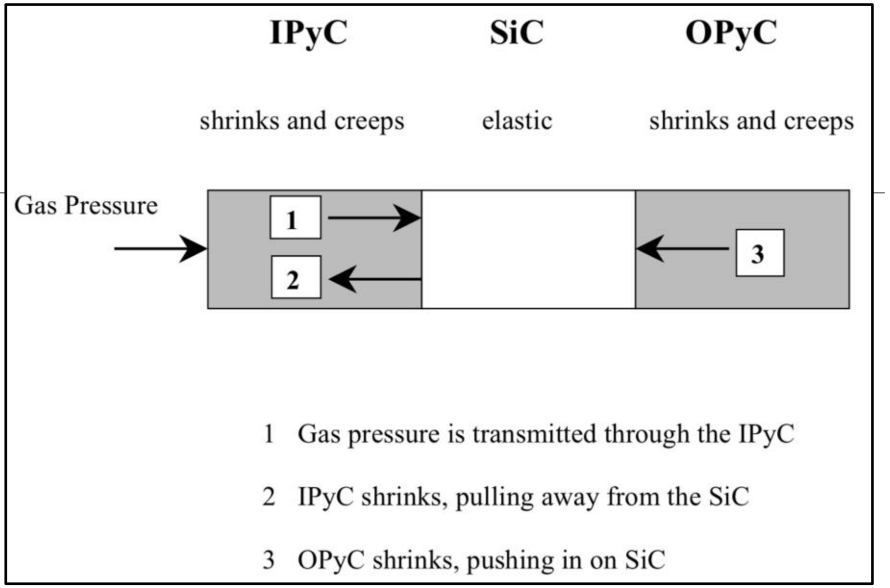
SEPTEMBER 8, 2021

# Topical Report Contents

- Introduction
- Fuel Behavior (including PIRT analysis)
- Fuel Modeling
- Verification and Validation / Uncertainty Quantification
- KP-BISON Code
- Fuel Performance Analysis Methodology

# UCO TRISO Fuel Behavior




| Coating Layer | Irradiation Behavior | Observation |
|---|---|---|
| **Kernel** | Swells outward | Pushes buffer outward |
| **Buffer** | Shrinks inward | Pulls IPyC inward if not debonded |
| **IPyC / OPyC** | Shrink early during irradiation and then start swelling later in irradiation as fast neutron fluence accumulates<br>Dimensional changes are anisotropic | Swelling starts radially at moderate fast neutron fluence levels and tangentially at higher fast neutron fluence levels |
| **SiC** | Elastic behavior | PyC shrinkage provides compressive stress<br>Fission gas pressure causes tensile stress |

# UCO TRISO Fuel Behavior – Failure Mechanisms

Key failure mechanisms identified in TRISO fuel

- Pressure vessel failure of spherical or aspherical particles resulting in the failure of all three coating layers
- Cracking of the IPyC layer leading to SiC failure
- Partial debonding of the IPyC from the SiC leading to SiC failure
- Kernel migration towards the SiC layer and its subsequent failure
- Chemical attack of the SiC layer by fission products or CO leading to its failure
- Thermal decomposition of the SiC layer at high temperatures
- Buffer fracture leading to cracking of undebonded IPyC

KP-BISON models failure mechanisms relevant to UCO fuel under KP-FHR irradiation conditions with the purpose of predicting the potential failure of the SiC layer and the release of fission products.

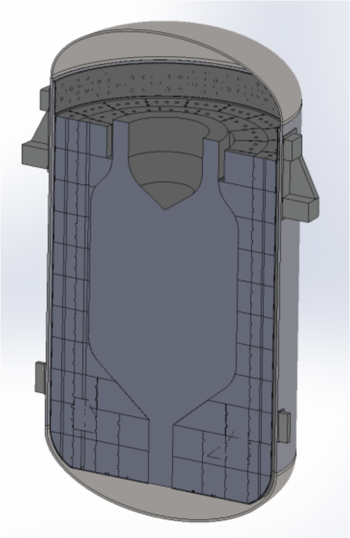
# UCO TRISO Fuel Performance Modeling – KP-BISON

Kairos Power

Idaho National Laboratory

NEAMS
NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

UCO TRISO
Model
in BISON



- Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)
- UCO TRISO Fuel

BISON

MOOSE
Multiphysics Object-Oriented Simulation Environment

**Engineering-scale nuclear fuel performance code**

- Finite-element modeling of LWR, TRISO, and metal fuels in 1D-spherical, 2D-axisymmetric, and 3D geometries
- Fully-coupled thermodynamics and species diffusion equations
- Steady and transient reactor operations

# UCO TRISO Fuel Performance Modeling – KP-BISON

KP-BISON was chosen as Fuel Performance Code by Kairos Power

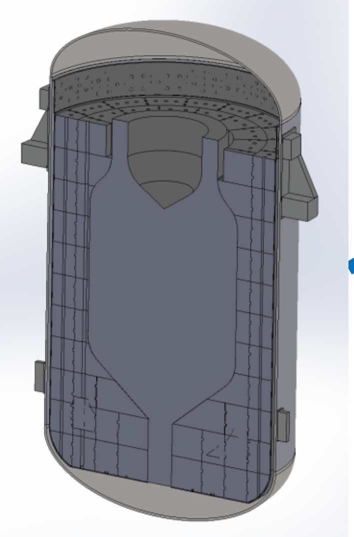
- Computational benefits from the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework
- Leverage of extensive development effort by INL (Idaho National Laboratory) and NEAMS (Nuclear Energy Advanced Modeling & Simulation Program)
- Level of development and maturity of BISON code
  - Co-development KP-INL
  - FOA award DE-NE0008854 *Modeling and Simulation Development Pathways to Accelerating KP-FHR Licensing*
- Efficient support from development and maintenance team ("BISON Team") at INL

# KP-BISON – Inputs & Outputs

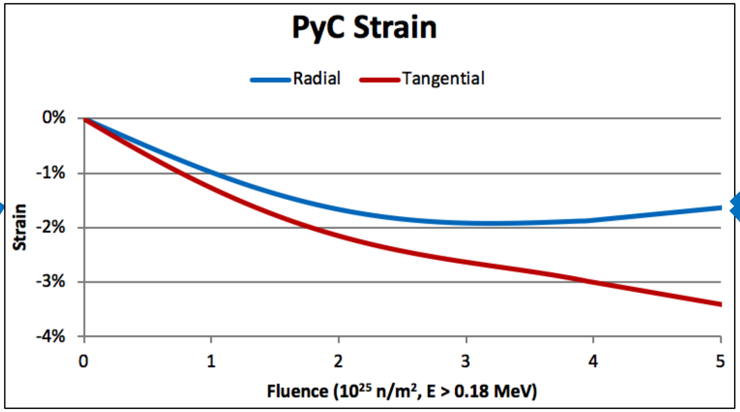
**Geometry**
- radius, thickness, etc.

**Fuel characteristics**
- composition, densities, etc.

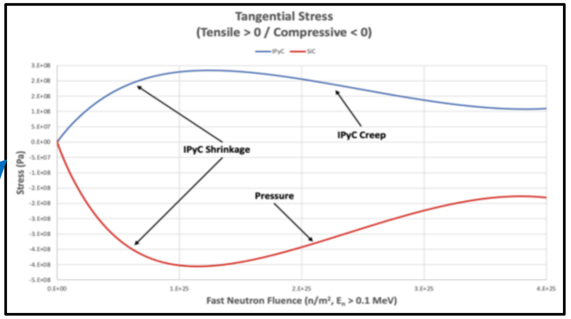
**Variation in as-fabricated properties**



**Irradiation conditions**
- Fission rate density
- Fast fluence
- Coolant temperature



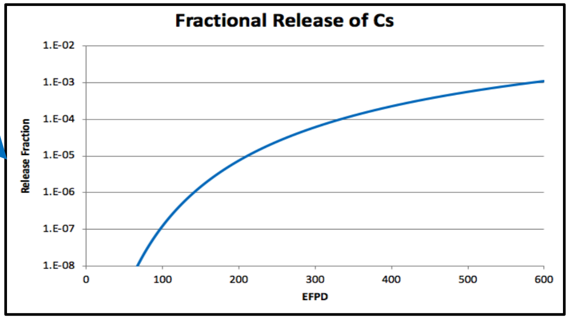

**Material properties implemented in KP-BISON**




**Fuel temperature, fission gas pressure, displacements, stress**

⇩

**Figures of Merit (FOMs)**
**Failure probability**
**Fission product release**

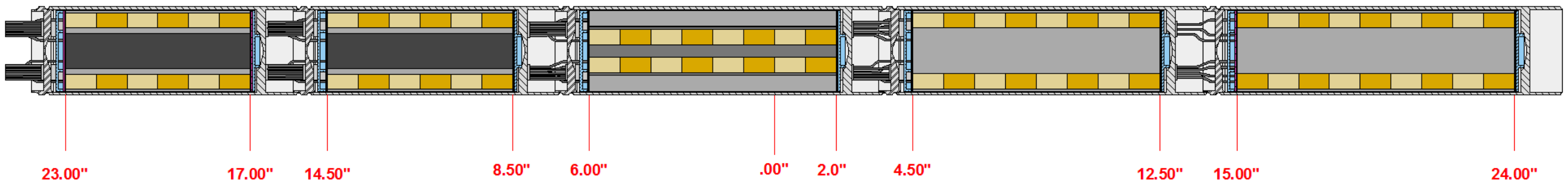


# KP-BISON – Fuel Properties

Leverage of extensive DOE effort in the development and qualification of UCO TRISO fuel (AGR Program)

KP-FHR UCO TRISO fuel is similar to AGR UCO TRISO fuels

- AGR-2 -> *UCO TRISO-Coated Particle Fuel Performance* - Topical Report EPRI-AR-1(NP)-A
- AGR-5/6/7 -> AGR Program's UCO TRISO fuel qualification and margin tests



AGR-5/6/7 Test Train – Courtesy of AGR Program

# KP-BISON – Material Properties & Physical Models

| TRISO Constituents | Material Properties |
|---|---|
| Kernel<br>Buffer<br>IPyC<br>SiC<br>OPyC | Swelling<br>Elastic modulus<br>Poisson's ratio<br>Irradiation-induced creep<br>Poisson's ratio in creep<br>Irradiation-induced dimensional changes<br>Thermal conductivity<br>Specific heat capacity<br>Thermal expansion<br>Diffusion coefficients |

Existing database of material properties and physical models suited to modeling of TRISO fuel behavior and performance

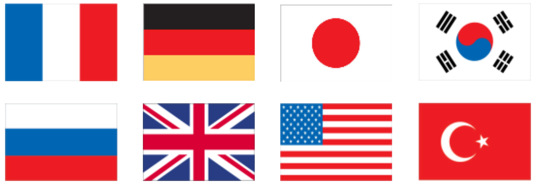
| Physical Models | Description |
|---|---|
| **Heat Equation** | Thermal state of the particle and temperature profile across the kernel and coating layers |
| **Fission yields** | Generation of fission products |
| **Fission gas release** | Generation of internal pressure |
| **Internal gas pressure** | Stress state of the particle potentially leading to its failure |
| **Palladium penetration** | Corrosion of the SiC layer potentially leading to its failure |
| **Release rate over birth rate (R/B) ratio** | Indicator of TRISO failure |
| **Fission product transport (Fickian diffusion)** | Release of fission products to the coolant |

# Verification & Validation

## INL Benchmark International Data

- Code-to-code comparison with PARFUME
  - Representative cases of KP-FHR
- AGR-1 and AGR-2 PIE and AGR-5/6/7 R/B data
  - Select data within KP-FHR envelope
  - Separate effects
- Additional PIE or R/B data
  - German, Chinese, etc.

## IAEA CRP-6 Benchmark



- Fuel Performance Models During Normal Operation And Operational Transients
  - Verification: cases 1-13
- Fission Product Release Behavior Models Under Accident Conditions
  - Verification: cases 1-5
  - Validation: cases 6-11

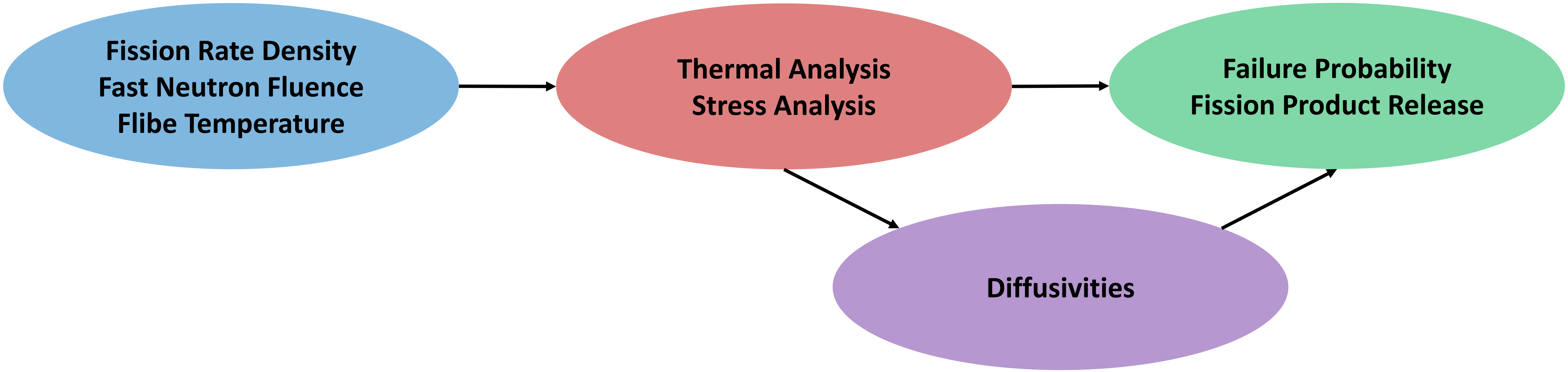
## Gen-IV Benchmark

- TRISO Fuel Performance Models Under Accident Conditions
  - Select AGR-1, AGR-2, and HFR-EU1bis safety tests
  - Includes code-to-code comparison during normal operation

# Fuel Performance Analysis Methodology

For each TRISO particle

- Irradiation input parameters
- Thermo-mechanical analysis of the TRISO coating layers
- Evaluation of the failure probability (stress) and fission product release (diffusivities)



# Statistical Treatment

- Particle-to-particle statistical variations in physical dimensions and fuel properties (layer thickness, density, etc.) that arise from the fuel fabrication process.

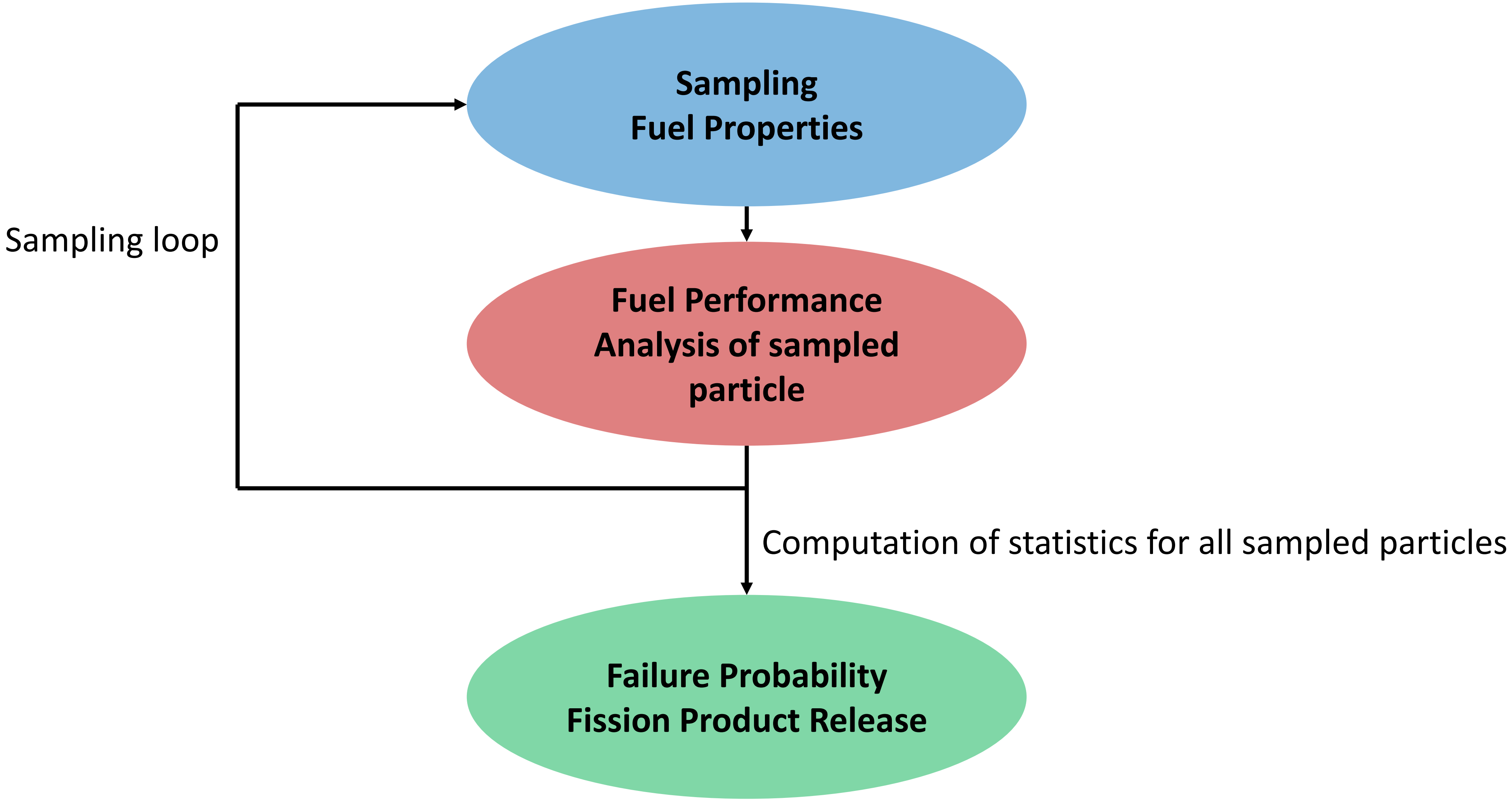
- Particles in the tails of the statistical distributions are more prone to failure.

⇒ statistical treatment of a large population of particles to compute its overall failure probability.

⇒ Monte Carlo computation scheme implemented in KP-BISON

| Property | Specified Mean Value |
|---|---|
| **Kernel diameter (μm)** | $425 \pm 10$ |
| **Buffer thickness (μm)** | $100 \pm 15$ |
| **PyC thickness (μm)** | $40 \pm 4$ |
| **SiC thickness (μm)** | $35 \pm 3$ |
| **Kernel density (g/cm$^3$)** | $\geq 10.4$ |
| **Buffer density (g/cm$^3$)** | $1.05 \pm 0.10$ |
| **PyC density (g/cm$^3$)** | $1.90 \pm 0.05$ |
| **SiC density (g/cm$^3$)** | $\geq 3.19$ |
| **C/U atomic ratio** | $0.40 \pm 0.10$ |
| **O/U atomic ratio** | $1.50 \pm 0.20$ |
| **PyC BAF** | $\leq 1.045$ |
| **SiC aspect ratio** | 1.04 |

# Monte Carlo Calculation Scheme



# Uncertainty Quantification

Uncertainty exists in:

- Operating conditions (i.e., fission rate density, neutron flux, temperature)
- Material properties that define the mechanical state of the TRISO particles and, ultimately, the integrity of the coating layers
- Physical models that determine some of the physical quantities affecting material properties and fission product transport
- Fuel properties (geometrical dimension, density, etc.) that are tailored by fuel fabrication to obtain TRISO particles that adequately perform under irradiation

⇒ sensitivity studies will be conducted to assess the quantitative impact of the variations of these input parameters to the probability of failure of the TRISO particles and subsequent release of fission products.

# Uncertainty Quantification Methodology

A proprietary methodology was developed to ensure that the probability of failure of the TRISO particles and subsequent release of fission products are calculated conservatively.

In particular, the methodology derives one-sided 95/95 tolerance limits on the two FOMs.

# NRC Staff Evaluation of the KP-FHR Fuel Performance Methodology, Revision 3

Jeff Schmidt

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Advanced Reactor Technical Branch 2
Division of Advanced Reactors and Non-Power Production and Utilization Facilities
Office of Nuclear Reactor Regulation

# Introduction

- Kairos requested approval of the KP-FHR Fuel Performance Methodology Topical Report (TR) Revision 3
- The topical report is applicable to a Kairos UCO TRISO fueled, FHR non-power or power reactor
- The TR identifies several open items to be addressed in a subsequent revision
- In addition to the Kairos identified open items, the staff identified additional items in the safety evaluation which need to be addressed in a subsequent revision(s)
- The staff's review focused on the calculational framework composed of,
  - UCO TRISO fuel failure mechanisms
  - Uncertainty parameters and associated methodology
  - Determination of the upper tolerance limits for the figures of merit (FOMs) of in-service failed fuel fraction and fission product release
- Outputs from fuel performance analysis are inputs to the mechanistic source term methodology

# Regulatory Basis

- Title 10 of the *Code of Federal Regulations* (10 CFR) Sections 50.34(a), 50.34(b) 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)

# Portions of the Topical Report Not Addressed by the Safety Evaluation

- The staff makes no finding on the following TR sections:
  - Section 2.3, "Phenomena Identification and Ranking Tables"
  - Section 2.4, "Fission Product Transport" and all the Section 2.4 subsections
  - Section 3, "Fuel Modeling - Material Properties and Physical Models," and all Section 3 subsections
  - Sections 4.1.1; "Verification;" 4.1.2, "Validation" (and all 4.1.2 subsections); and 4.1.5, "Validation, Verification and Uncertainty Quantification Results"
  - Section 5, "KP-BISON Code," and all Section 5 subsections
  - Topical report Table 3-8, "Diffusion coefficients for Key Fission Products Modeled in KP-BISON"
  - Section 6.4.2, "TRISO and pebble models", including the potential pebble behavior and material uncertainties that could affect TRISO particle failure fractions
  - Section 6.3, "Fission Product Release" as it pertains to fuel pebble mechanical and chemical interactions with the salt environment, and possible wear which are stated by the vendor to be outside the scope of this tropical

- The staff made no findings in these areas primarily because no verification, validation and quantitative uncertainty analysis was provided in Revision 3

# Staff Review

- The staff found the UCO TRISO particle failure mechanisms acceptable based on the expected operating conditions subject to Limitation and Condition 3 based on the AGR program data and the EPRI-AR-1-A topical report

- Other relevant TRISO particle release mechanisms such as manufactured defective particles and dispersed uranium are included in the calculational framework

- Relevant model uncertainties such as particle manufacturing variability, model and physical properties and irradiation conditions (operating conditions) were adequately accounted for

- The individual uncertainties were conservatively combined to yield an upper tolerance limit for the predicted failed particle fraction and the fission product release from fully intact and in-service failed particles

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# Staff SER Limitation and Conditions

- An NRC approved fuel performance code must be used to determine in-service particle failure faction and fission product release. A subsequent TR revision(s) may include other means to determine these FOMs.
- UCO TRISO particle failure mechanisms must be re-evaluated if operating conditions are not bounded by the UCO TRISO EPRI-AR-1-A TR. The Kairos Fuel Qualification TR will address expanding the EPRI TRISO operating envelope.
- Several Limitations and Conditions (4, 5, 6, 8, 10 and 11) exist due to information not included in TR Revision 3 but is expected in a subsequent revision(s).
- The methodology can not be used to evaluate the FOMs for AOOs, DBA and BDBE events as the methodology for combining these with the bounding quasi steady-state operating conditions was not provided.
- Some aspects of pebble performance will be addressed in another TR

## Staff Conclusions

- The Fuel Performance Methodology, Revision 3, TR provides an acceptable methodology for determining a conservative UCO TRISO particle fission product release from in-service failed and intact particles, manufacturing defects, and dispersed uranium
- The Staff approvals are subject to the Limitations and Conditions of the SER.

# Acronyms/Definitions

- Topical Report (TR)
- Uranium Oxycarbide (UCO)
- Tristructural isotopic (TRISO)
- Figures of Merit (FOMs)
- Kairos Power Fluoride-Salt Cooled High Temperature Reactor (KP-FHR)