Official Transcript of Proceedings

NUCLEAR REGULATORY COMMISSION

Title:	Advisory Committee on Reactor Safeguards Kairos Power Licensing Subcommittee Open Session
Docket Number:	(n/a)
Location:	teleconference
Date:	Thursday, January 12, 2023
Work Order No.:	NRC-2228 Pages 1-112

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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 SESSION
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THURSDAY
JANUARY 12, 2023
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The Subcommittee met, via Teleconference, at 9:30 a.m. EST, David A. Petti and Ronald G. Ballinger, Chairs, presiding.

COMMITTEE MEMBERS:

DAVID A. PETTI, Chair
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GREGORY H. HALNON, Member

JOSE MARCH-LEUBA, Member
JOY L. REMPE, Member
MATTHEW W. SUNSERI, Member

ACRS CONSULTANTS:
DENNIS BLEY
STEPHEN SCHULTZ

DESIGNATED FEDERAL OFFICIALS:
WEIDONG WANG
CHRISTOPHER BROWN

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Kairos Power Topical Report (KP-TR-014), "Graphite Materials Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor"

P-R-O-C-E-E-D-I-N-G-S

9:30 a.m.

CHAIR PETTI: Okay, it's 9:30 Eastern, so this meeting will now come to order.

Happy New Year, everyone.

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, Jose March-Leuba, Joy Rempe, Matthew Sunseri, Ron Ballinger, Walt Kirchner, and Greg Halnon. I do not see Vesna or Vicki on the line yet.

MR. WANG: Actually, Vesna, I saw her.

CHAIR PETTI: You did? Okay.

Dennis Bley, Consultant, and Steve Schultz, our Consultants, are on the line.

Weidong Wang of the ACRS staff is the Designated Federal Official for this meeting.

During today's meeting, the Subcommittee will review the staff's Safety Evaluation on Topical Report "Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor," Revision 4.

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

Part of the presentations by the Applicant and the 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 the 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, and 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 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 their computer microphone, or phone, by pressing *6.

We'll now proceed with the meeting, and I'd like to start by calling upon NRR staff.

MR. RIVERA: Thank you.

MR. JESSUP: Yes, thank you, Member Petti, for the opportunity to present to the Subcommittee this morning.

My name is Bill Jessup, Chief of Advanced Reactor Licensing Branch 1 in the Division of Advanced Reactors and Non-power Production Utilization Facilities in the Office of Nuclear Reactor Regulation.

Kairos is currently developing non-power and power reactors that would use its fluoride-cooled, high-temperature reactor technology, also referred to as KP-FHR technology.

As you know, the staff is currently reviewing the construction permit application from Kairos for its non-power Hermes Test Reactor that would use the KP-FHR technology.

The two Topical Reports that we're going to be discussing today would apply to both the non-power and power reactors currently under development by Kairos. Therefore, the reviews for the Topical Reports we're going to discuss today will need to be finished before we can complete the construction permit application review.

The first Topical Report on the qualification of graphite materials describes the testing required to qualify, the structural graphite materials used, and the safety-related components of the KP-FHR designs.

The second Topical Report on the qualification of metallic materials focuses on the testing and modeling required to qualify the structural alloys that will be used in the safety-related portion of the KP-FHR designs.

And as the agenda notes, the staff will provide an overview of our review and safety evaluation of each Topical Report following the Kairos presentation on each of the Topical Reports.

I'd also like to note today, during the staff presentations, you'll hear discussions regarding guidance that the staff used for the review of both Topical Reports from Regulatory Guide 1.87, "Acceptability of ASME Code, Section III, Division 5, High Temperature Reactors, Revision 2."

A draft of Reg Guide 1.87, Revision 2, was issued for public comment in August 2021, along with a supplement to the draft that was issued in February 2022.

The staff has resolved public comments received during the public comment period, and we expect that the final draft of Revision 2 will be issued in short order.

Any discussions of guidance from Reg Guide 1.87, Revision 2, during today's presentations and in the Draft Safety Evaluations for each Topical Report represents staff positions that will be reflected accordingly in the final draft of the Reg Guide.

We're looking forward to today's discussions and are always appreciative of the Committee's insights and comments on these very important topics related to the Kairos KP-FHR technology.

And with that, I'll turn it back over to you, Member Petti.

CHAIR PETTI: Okay. Thank you.

So, I guess we'll turn to Kairos and go through the slides that we've seen.

MS. ELLENSON: Hi. This is Margaret Ellenson. I am work for Kairos Power on the licensing team. I'm the lead for this particular Topical Report.

We also greatly appreciate the opportunity to present to the ACRS our presentations. Obviously, we focused on just what is in that Topical Report.

And I have a number of our technical staff here who are going to present along with me, Gabriel

Merick and Chong Chen, in particular.

Yes, we look forward to the discussion and the opportunity to present. Thanks very much. I don't have any further comments unless --

CHAIR PETTI: Okay. So, who in Kairos is going to start then?

MS. ELLENSON: Oh, okay, we're ready to go?

CHAIR PETTI: Yes.

MS. ELLENSON: Okay, great. So, I'm going to begin.

Hi. My name is Margaret Ellenson. I'm on the Kairos Power licensing team. I've been with Kairos for about three years. Prior to that, I was with the NRC for about 15 years. I worked on the Steam Generator Tube Integrity Program as well as fire protection and security issues. So, a wide gamut.

Our purpose today for this Topical Report is to provide an overview of the content of the Graphite Material Qualification Plan that Kairos expects to use to qualify structural graphite materials for use in a KP-FHR. That is a Kairos Power Fluoride Salt-Cooled High-Temperature reactor.

We'll be covering some of the material, some of the content of that Topical Report in this open session, and then, later, we'll be getting into more details about other subjects during the closed session.

And just to double-check, you can all see my slides, is that correct?

CHAIR PETTI: Yes.

MS. ELLENSON: Great. Okay.

Kairos Power is a mission-based organization. Our mission is to enable the world's transition to clean energy, with an ultimate goal of dramatically improving people's quality of life while protecting the environment.

We like to touch base with this mission for each of our meetings and our key milestones. And this Topical Report is one step toward accomplishing that mission.

In particular, graphite is a unique material for use in this regulatory context. So, we're excited to be able to discuss this with ACRS and the content of this Topical Report today.

I wanted to spend a brief moment kind of getting at the purpose of Kairos submitting this particular Topical Report. What we're hoping to accomplish with this report is to align expectations early about the methods that Kairos will use to qualify graphite in a KP-FHR.

As the members here are probably well aware, there are many steps along the way to qualification of a material. And ultimately, qualification is demonstrated in an application-specific Safety Analysis Report.

So, the goal of this particular Topical Report is to identify those methods that can close gaps between existing data and the data or analyses that will be needed to support that qualification in a Safety Analysis Report.

Obviously, the final design of the KP-FHR will be important inputs as well to that qualification. So, what the Topical Report covers is the data, models, and analysis that will be needed to be provided in a future license application.

Okay. I also wanted to provide a quick reminder about our functional containment strategy for a KP-FHR. You probably have seen this particular image or slide before, but, just as a reminder, containment is provided by the TRISO particles in our fuel pebbles.

The second element of functional containment is the Flibe coolant which has good fission product retention properties. I'm bringing this up now because I wanted to make it clear that the concentration of fission products in our coolant, the Flibe coolant, will be maintained at very low levels during operation. And this is unlike other molten salt reactors that might have dissolved fuel. Those dissolved fuel molten salt reactors can develop hot spots due to coolant infiltration into graphite. That's not really something that is an issue for a KP-FHR technology.

I also want --

MEMBER MARCH-LEUBA: Hey, this is Jose. This is Jose March-Leuba.

MS. ELLENSON: Yes? Hi.

MEMBER MARCH-LEUBA: What, approximately, is the retention, the sequestration time of the Flibe in the core? I mean, what's the time course if there was a contamination?

MS. ELLENSON: The residence time for the Flibe in the core or for fission product retention? Those things I think would be heavily design-dependent. So, we don't necessarily have the hard numbers yet for those.

MEMBER MARCH-LEUBA: I'm not looking for the hard numbers. Is it seconds? Is it minutes? Hours? Days? Years? What unit will you use?

MS. ELLENSON: Yes, I'm looking at some of our other design experts around the room here. Just one moment.

Maybe on the order of seconds or minutes.

MEMBER MARCH-LEUBA: Seconds or minutes to move through the core, and then, a fraction of it will go through the cleanup system? Maybe 10 percent or --

MS. ELLENSON: Yes, I wouldn't know. I wouldn't know the fraction. That would be part of the design of the Flibe Inventory Management System.

MEMBER MARCH-LEUBA: So, basically, if I was going to think about daily you will remove, at most once a day, it would be cleaner. So, there won't be any significant concentration increase over time?

MS. ELLENSON: It will be a managed parameter. So, the concentration of fission products and the character, the nature, of the Flibe will be a managed parameter in KP-FHR.

MEMBER MARCH-LEUBA: Okay.

MS. ELLENSON: Yes. Okay.

I also wanted to bring up a reminder with this slide that there are two places where you will find graphite in a KP-FHR core. One is the graphite reflector structure. That's the subject of this Topical Report. There's also graphite in the fuel pebbles themselves. That is out of scope for this particular Topical Report. It is covered by other Topical Reports submitted by Kairos Power.

CHAIR PETTI: So, I just, for the record, so that people don't get confused, the matrix is not graphitized. It's probably better characterized as a carbonaceous material, to differentiate it from the actual reflector, which is a true graphite that goes through high-temperature graphitization.

Thanks.

MS. ELLENSON: Thank you.

MEMBER KIRCHNER: And just for clarification -- this is Walt Kirchner -- so, this report does not qualify these same materials for the primary coolant boundary; just for the vessel?

MS. ELLENSON: Yes, that's correct.

MEMBER KIRCHNER: So, you're illustrating the reactor cavity here and excluding the rest of the primary coolant loop?

MS. ELLENSON: Yes, that's correct.

MEMBER KIRCHNER: Okay. Thank you.

MS. ELLENSON: Okay. All right. I also wanted to take a moment before we get into the details of the qualification plan to talk about the scope of this Topical Report and to make sure that we're aligned on what components are we actually talking about here, and in particular, to clarify the safety functions of this structural graphite in the reactor vessel.

The role of the reflector structure is to support two different safety functions. You can see in this cartoon, which is intentionally cartoonized because it reflects what's common between a test and a power reactor, you could see that the blue and the red here reflect where the coolant is flowing. So, you can see that the graphite reflector forms one part of the conduit or channel through which Flibe coolant will flow.

It also provides the pathway through which reactivity control elements can be inserted. So, the two safety functions there that it supports are the removal of heat from the reactor and the insertion of negative reactivity, or reactivity control, I should say.

However, the way that it supports those safety functions is simply by maintaining its integrity. So, by staying whole, it maintains those channels for the control, reactivity control elements to insert, and it also maintains the flow path for the coolant.

It does not provide a safety function related to moving heat from one place to another. There's other systems that provide that safety function.

So, I just wanted to make sure that we were clear about what the safety functions are that we need to qualify this material for.

MEMBER BROWN: This is Charlie Brown. Can I ask you a question relative to the figure?

MS. ELLENSON: Sure.

MEMBER BROWN: So, the graphite itself is not a heat removal function itself? It's merely a reflector function, and the heat removal is done by other means? That's the way -- I'm not a designer. That's why I'm asking the question the way I'm asking.

MS. ELLENSON: Yes, exactly. Its safety function is to stay whole, so that the coolant can flow the way its designed to. Otherwise, it does not have a function in heat removal.

MEMBER BROWN: Okay. And the second question is, in the Topical Report it talked about the reflector, the graphite reflector, being buoyant in the Flibe coolant flow. I didn't understand how something would be buoyant and just kind of floating around in the flow path. It's not stably, or does it just move around? That's the way I read it.

MS. ELLENSON: Yes, it is designed -- if you see some of the pictures that we have of our ETU unit in New Mexico, you'd see that it, basically, fills the reactor vessel, right, except for this cavity that's in the center, where the actual fuel pebbles will go. The graphite is maintained in a certain orientation, but it doesn't bear any structural loads. That's why we bring up the idea of buoyancy. It's not actually bearing any weight or structural loads, like, for example, a high-temperature gas reactor might.

MEMBER BROWN: Okay. In other words, it is fixed? It's just not --

MS. ELLENSON: It is fixed.

MEMBER BROWN: -- bearing any loads?

MS. ELLENSON: Yes.

MEMBER BROWN: All right. Thank you very much.

MEMBER BALLINGER: Charlie, all they're saying -- this is Ron Ballinger -- all they're saying is that the graphite is less dense than the --

MEMBER BROWN: That part I got. It was the openness of the buoyancy thought process that made it -- I just wanted to make sure I understood the connection, and now I do. I appreciate that. Thank you.

MEMBER BALLINGER: It doesn't have a ballast tank. It doesn't have ballast tanks.

MEMBER BROWN: Right. Okay. Thank you.

MS. ELLENSON: All right. Okay. All right. I briefly wanted to walk through just the organization of this report.

It has what you would expect at the beginning: introductory material, background on nuclear graphite.

The next three bullets on this slide -- unirradiated graphite, irradiated graphite, and environmental compatibility -- those reflect the technical meat of the report.

We also have some conclusions and limitations in there, limitations primarily related to elements where our final design may affect the qualification program that we use.

And then, there's a few appendices that get into some of the details of the analysis and demonstration that we would do in our qualification program.

And just a reminder about the scope, that this report does apply to both a test reactor and a power reactor application, and that seismic qualification is out of scope for this particular report.

Okay. The qualification plan represented in the report largely follows the ASME BPV, Section III, Division 5, Code, and I commonly refer to this as just the Division 5 Code. There's a portion of that Code that specifically addresses graphite materials. It breaks the qualification into three different elements: characterization of as-manufactured graphite mechanical and thermal properties, which we refer to as unirradiated graphite in the report. And that portion of our Topical Report we'll talk about how thermal and mechanical properties are within expected variability.

The Code also specifies a sampling plan to use for those confirmatory tasks. In this section of the report -- this is Chapter 3 -- we also make a connection back to properties related to fatigue, as well as a discussion of purity, which is not necessarily discussed in the Division 5 Code, but we provide some context in the report there.

The second element there, characterization of graphite properties under irradiation, the Topical Report talks about both basic properties and irradiation creep properties. It discusses the use of existing data, new data, existing models, new models, and how those things would be applied to both a test reactor or a power reactor application.

A detailed discussion of those two chapters, the unirradiated graphite and the irradiated graphite, we expect to do in the closed section.

And then, the fifth chapter of the Topical Report is Environmental Compatibility. This is a non-mandatory section under the Code, but Kairos Power reviewed the available phenomena identification studies that have been issued to date. For example, Idaho National Lab, Oak Ridge National Lab, Georgia Tech did some phenomena identification studies for either a molten salt reactor or for graphite use in reactors. We also reviewed relevant literature to identify different phenomena that could be of interest to structural graphite in a KP-FHR application.

And at this point, I'm going to hand over the discussion to my colleague Chong Chen, who is our graphite expert, to be able to give some background on graphite.

Chong, are you able to introduce yourself?

MR. C. CHEN: Yes, sure. Thank you.

My name is Chong Chen, and I'm a graphite engineer. I've work for Kairos since 2020. Before that, I work in GrafTech, formally GrafTech, and SGL Carbon.

And so, a little bit of the background about graphite. Graphite, it, basically, is a carbon organized unit in a structured way. It has a crystalline structure, and basically, it's all carbon content.

And graphite is very thermally stable. In the inert atmosphere it is stable over 3200 degrees C or higher, and essentially, the highest temperature used in any industry.

Mechanical strength, also, is different compared with metal. And the strength increases with temperature. Yes, that's the difference, and also, a very low coefficient of thermal expansion. But one thing that is different compared to metal is graphite is not an anisotropic material. They have a different property in a certain direction.

Graphite also has a certain porosity property, above 20 percent porosity. And the property, due to the pure use in the manufacture process, the property, there's a variability. It's not as uniform as typical metal you will see in the industry.

And the last thing I wanted to mention for graphite is that the billets has a limitation, and it is difficult to make very large billets, especially for fine grain or superfine grain. So, people tend to have a bigger billets to save the cost, but it is sometimes not the case for superfine grain graphite.

CHAIR PETTI: So, just a question then. So, the billets for superfine grade tend to be smaller than the extruded graphites?

MR. C. CHEN: That's correct. It is the case, yes.

CHAIR PETTI: I mean, I know how big the historic grades were. How big would the billet be?

MR. C. CHEN: Well, different industry has a different size. Just to give you a visual, typically, we -- well, the one typical we talk about for this case, the graphite we're going to use, the rocky bottom is 1x2x4 feet in this kind of size. That's just roughly.

CHAIR PETTI: Uh-hum. Good.

MEMBER KIRCHNER: So, Chong, this is Walt Kirchner.

So, that means you'll have to stack these for the reflector in the larger power reactor application?

MR. C. CHEN: Yes.

MEMBER KIRCHNER: I don't remember the dimensions for Hermes, but can you make the reflector out of one stack, one billet?

MR. C. CHEN: No.

MEMBER KIRCHNER: Okay.

MR. C. CHEN: No, no way to make that large graphite. That would be ideal, but it's not the case.

MEMBER KIRCHNER: Okay. Thank you. Thank you.

MEMBER HALNON: This is Greg.

Where is this ET-10, where is it developed or manufactured?

MR. C. CHEN: Okay. Yes. So, ET-10 is the grain graphite produced by IBIDEN. It's the company.

MEMBER HALNON: What country is it being developed in?

MR. C. CHEN: That's a Japanese company.

MEMBER HALNON: Okay. And quality control, how is that maintained, so that you know that you're getting the top quality stuff? And do they have a testing program representative sample or is every billet checked? Or how is that done?

MR. C. CHEN: Yes, I think there were details laid out in, I think more regarding the quantity, and I think in the closed session we'll discuss that.

MEMBER HALNON: Okay.

MEMBER BALLINGER: This is Ron Ballinger.

So, it's ET-10, not 110? And the source for KP-FHR is now limited to that source? Because, a lot of times, the source really determines a lot of the properties.

MR. C. CHEN: Well, yes. And so, once you quantify this, basically, you stay with this material, you're quantified.

MEMBER BALLINGER: Right, but what I mean is, is it down to the source itself, where the precursor material is actually obtained?

MR. C. CHEN: Oh, yes. So, yes, that's another topic. So, how do we control the material we have quantified today will be the same when using it later? So, where there's the best knowledge, the process, we ensure we've got the material down to even stock on the raw material, making the stuff, the graphite.

MEMBER BALLINGER: Yes, okay. That's my general understanding of where you have to start.

MR. C. CHEN: Yes. Yes, you have to control the raw material properties, start with the raw material property.

CHAIR PETTI: Chong, just a question. I was a little confused in the Topical. Here, you say ET-10, but there's also ETU-10. I thought that what was going into Hermes was ETU-10, but that all the testing would be done on ET-10, where the "U" just represents the halide process to get rid of some of the impurities and wouldn't affect the thermal or mechanical properties. Do I have that right?

MR. C. CHEN: I think it's the ET-10 itself, the purities that meet a requirement. So, I think maybe in the early document you see ETU-10, but I think the updated version is ET-10. I think I will refer it to our licensing team and see if that's the case.

CHAIR PETTI: Oh, okay. I don't know which version we were reading, but there was discussion in the document about ETU and the halide process. So, you're saying that you're actually going to qualify and use ETU? You're not going to use the higher purity graphite?

MR. C. CHEN: We will use ET-10, not ETU-10.

CHAIR PETTI: Okay.

MR. C. CHEN: Because ET-10, it's purity; it's to meet the requirement. It's very pure material. So, it's not necessary we go through another purification. It's unnecessary.

CHAIR PETTI: Okay.

MEMBER KIRCHNER: This is Walt.

So, you don't think you need the halide process for ET-10 if you can control the raw materials coming in?

MR. C. CHEN: Yes. Right. Correct.

MEMBER KIRCHNER: Okay. I'll just come back to this in the closed session. I have some questions about impurity levels.

MR. C. CHEN: Sure. Okay. So, okay. If there's no further question, I will continue.

So, graphite has been used -- I guess everybody in this meeting room well understood it has been used in the nuclear reactor for a long time and, also, accumulated some data. In the Topical Report we reference different graphite, and IG-110 is well-known and CGB, it's used in a molten reactor experiment.

Okay. Now we're back to the ET-10 we already talked about. It's isotropic loaded material. By definition, it's the near isotropic material, or that's what we're talking about.

All right. Next slide, please.

Well, environmental compatibility, or just the highlights of what we are looking at. We considered five phenomena which can potentially damage graphite integrity or structure. And we consider from a physical side and we consider infiltration -- and it will be talked about in the closed section -- and also, mechanical reduction, due to the infiltration or impact due to the stress.

And as Margaret pointed out in the earlier stage, in the earlier presentation, in the graphite reflector we are using, it's different compared with a gas-cooled reactor. Basically, it does not have a lot of load on it because the density of graphite is much less than the salt, molten salt's density. And another phenomenon we consider is erosion and abrasion.

On the chemical side, we consider chemical compatibility between the graphite and the Flibe, and also, oxidation, which is only one section of a reactor will have oxidation, potential oxidation, in cases of the leak.

CHAIR PETTI: So, just again, a question here. Here it says ETU-10. So now, I'm confused. Is it ETU or ET-10? Which one is it actually, are you going to actually use in qualifying and doing testing?

MR. C. CHEN: ET-10. ET-10. It must be a typo, I guess.

CHAIR PETTI: Okay. Okay. Thank you.

MR. C. CHEN: All right. Next slide, please.

Okay. I think my colleague Gabriel will cover this slide.

MR. MERICK: Hi. This is Gabriel. One second.

(Pause.)

All right. Sorry for the technical issue here.

My name is Gabriel Merick. I am a materials engineer at Kairos. My expertise is in radiation effects, and for Kairos, I'm leading the radiation testing part and, also, this abrasion and erosion part of the Topical Report.

So, this is part of our environmental compatibility testing. We will be doing some tribology testing to confirm that there's no significant abrasion of our structural graphite. There's no abrasion expected because, as we said earlier, the reflectors are buoyant in the Flibe, and the contact portions are, therefore, very low. Also, structural graphite ET-10 is harder than our fuel pebbles. So, we don't expect abrasion from the pebbles rubbing against the graphite reflector. I'm doing confirmatory testing for that.

The second point there is to confirm that we don't have significant erosion of our structural ET-10 reflectors. And we confirm that with testing of graphite specimen exposed to long-term Flibe flow in our rotating cage loop test systems. Again, we don't expect significant erosion because our Flibe flow velocity is low, especially compared to gas-cooled reactors, and we have the MRSE experience, which demonstrated no signs of erosion on the graphite reflector surfaces after three years of operation.

MEMBER HALNON: So, this is Greg.

Will you be looking at surface roughness as well and try to quantify the difference before and after?

MR. MERICK: Yes, we'll be looking at this and, also, more specifically, wear rates for the first part there.

MEMBER HALNON: Okay. Because that's significant I think in the infiltration discussion we may have later on.

MR. MERICK: Thank you.

MR. C. CHEN: Now, I'm going to pick up here on the slides to talk about chemical compatibility of graphite with Flibe.

The graphite is a very inert material in most chemicals and has been studied, and there is no significant graphite interaction or reaction, chemical reaction, between graphite and Flibe molten salt which leads to graphite structure degradation.

In a molten salt experiment conducted in the '60s demonstrated, in graphite, there's no graphite degradation observed after three years' operation. So, that's very strong evidence.

And one particular reaction considered that could lead to graphite structural degradation, it's called intercalation. And from a later study, we realize this indicated this could not happen under our reactor operation conditions.

And fluorination, which means there is a minor treatment with fluorination possible and it has been reported recently in the literature. And we thoroughly studied the literature results and discussed it with the expert in this area. And we don't think the treatment of surface fluorination will lead to any bulk property change, and there's no bulk fluorination that was observed. That's the key.

Any questions? If no further questions, next slide, please?

DR. BLEY: Yes.

CHAIR PETTI: Just a question.

DR. BLEY: Oh, Dave, go ahead. Sorry.

CHAIR PETTI: My understanding is MSRE only operated for one effective full power year. So, that three years may be a calendar time, but in terms of reactor operation, it's only one. It's fine. I agree with you there's no degradation, but it's not as much operation, I think, as we'd like to see. So, you know, you could get a different experience with a longer operation time.

MR. C. CHEN: You are right, but at this moment, probably the best data, and the most relevant and most useful data --

CHAIR PETTI: Correct. Correct. No, I agree.

MR. C. CHEN: Yes, I agree with you, yes.

MEMBER BALLINGER: This is Ron Ballinger.

Am I to understand that the salt does not wet the graphite?

MR. C. CHEN: Yes. Yes, the salt --

MEMBER BALLINGER: So, that's the source

of all of this good behavior, I think.

MR. C. CHEN: Correct. You are right.

DR. BLEY: This is Dennis Bley.

Could you tell us a little more about intercalation, your second bullet, and if that happens, what would be the problems? I guess where I'm headed is, given your statement here, it would seem the safety analysis is going to have to consider this if we get outside of expected operating conditions.

MR. C. CHEN: Yes. Sure. And intercalation, let me give you one example. In the graphite industry, when we make this flexible graphite, which is you have intercaland go into the graphite structure, and then, you heat treat it. So, the graphite falls apart and turns, from a solid piece, turns into almost like what we call a worm, almost like a cushion, like a marshmallow-type thing, and the total structure is totally destroyed. And that's called intercalation.

This type of reaction is able to destructure -- degradation. You've, basically, lost all the structure, mechanical copy. And so, that's what I am talking about. And for fluoride, there's no evidence this kind of reaction can happen.

So, does that answer your question?

DR. BLEY: Well, almost. So, you're not really hanging your hat on operating conditions? You're hanging your hat on the chemistry and that this cannot happen? Is that what you're saying?

MR. C. CHEN: Well, we look at it based on -- well, actually, there's a literature study that has been done. And you put the graphite in the Flibe, and you simulate to the reactor operation, the temperature, and there, after that, you look at, analyze the graphite structure. And is there any intercalation that happened? And the conclusion from the study is, no, there's no intercalation happening.

DR. BLEY: Okay. So, it's still hinging on operating conditions. So, if we could get higher temperatures than the expected ones in an accident, this is something that ought to be addressed, is what it sounds like to me.

Dave, maybe you're stronger --

CHAIR PETTI: Yes. No, I was trying to put -- what exactly about the operating conditions does it not occur? Is it just because the Flibe doesn't wet?

MR. C. CHEN: No.

CHAIR PETTI: Is there something unique

about the reactor conditions? So, is there another set of conditions where it could happen? That's what we're trying to understand, I think.

MR. C. CHEN: Yes, okay. Let's start with, I think intercalation has a lot to do with the chemistry. And the current study has been done in 600 or 700 degrees. I don't recall exactly what experiment temperature was used. It was in our operation temperature range. And there's no integration observed. But, for this reaction, you could say in an accident condition you could go to a higher temperature. Actually, in a higher temperature, it's not favorable for this type of reaction. So, it will not happen.

And just to give you an example, if this reaction does not happen at 600 degrees C, it's not going to happen in 800 degrees C. Because this means, if you go to a higher temperature, this reaction can't happen. So, not all the reactions go with the temperature. So, that's what I'm trying to point out here.

MEMBER BALLINGER: This is Ron Ballinger again.

But there's no interconnected porosity here, right?

MR. C. CHEN: Graphite porosity is interconnected.

MEMBER BALLINGER: It is interconnected?

MR. C. CHEN: It is.

MEMBER BALLINGER: Oh, okay.

MEMBER KIRCHNER: So, Ron, to follow up on your question, and to try to get at Dennis' point, this intercalation is the result of intrusion by another chemical into the porosity of the graphite? And you're saying that, for use applied, you don't have that? Because it doesn't wet the surface, you don't have that potential? What theory and literature indicate it cannot occur? I mean, what is the physical mechanism that can't occur in the KP-FHR?

MR. C. CHEN: Okay. So, let me step back one step, and now let's differentiate -- I think it may be the true term may be slightly confused. intercalation is chemical reaction. It has nothing to do with porosity and intrusion.

And infiltration, sounds like what you mentioned, is really sort of porosity. You Flibe infiltrate those into the pore structure, and because it's interconnected, it can keep going and become a (audio interference) process.

So, the intercalation is a chemical. It's in the molecular level. As it intercalates, the chemical goes into the graphite layer, between the layer, graphite layer, and then, it, thus, can lead to the structure damage. And that's the chemical way/process to cause graphite structure damage.

And what I am saying here is this reaction is not going to happen in this fluoride salt. There's no evidence the fluoride salt will intercalate into the graphite. Yes, that's what about the intercalation.

And another thing about it that you mentioned is, in infiltration, the Flibe goes into the graphite structure. And whether the Flibe that goes into the graphite structure will cause damage or not is determined by several other factors, which is not what we talk about here. I just want to clarify that.

MEMBER KIRCHNER: But, basically, when you use this term, what you're talking about is attacking the grain boundaries of the graphite structure?

MR. C. CHEN: Related, but not just the -- yes, the reaction will start with the grain boundary, but it will go through, between the graphite layer. So, it's -- yes.

MEMBER BALLINGER: Intercalation is --

CHAIR PETTI: There's a tremendous amount of literature on intercalation in graphite.

MEMBER KIRCHNER: Yes, intercalation is why a lithium ion battery works.

CHAIR PETTI: Exactly.

MR. C. CHEN: Correct. You are right. Yes, you are absolutely right. So, that's why your battery will not last forever, and in and out, in and out, or maybe many times. Eventually, the graphite used in the battery will fall apart. It will lose all the electrical connectivity. That's why the battery will die. That's the intercalation, you're absolutely right.

CHAIR PETTI: I've always believed that any cesium in TRISO particles is actually intercalated in the graphite layer, in the pyrocarbon in the buffer layers, that that's the mechanism. Hard to prove, but just the analogy with lithium in graphite. So, there's a huge amount of literature on it.

But what you're saying is, independent of the ability to wet and infiltrate, just chemically, it doesn't happen?

MR. C. CHEN: Yes. That is, most of the time the reaction does not happen.

CHAIR PETTI: Correct. Okay.

MR. C. CHEN: Okay. So, if there's no

further questions, then let's move on to the next slide, please.

Margaret? All right. Okay, thank you.

So, the next topic is about oxidation. The oxidation may occur at the top of the reflector and where the inert gas, it's the gas in the inert gas space. But, in the air ingress event, this can potentially reduce -- have oxidation occur, for the whole reactor, only on this section.

So, we will assess the effect of oxidation and we'll measure the oxidation kinetic parameter of this ET-10 graphite, and we're also determining the weight loss with the strength. So, you would determine how much weight loss will -- how much strength, it will actually cause so much strength reduction. And then, we'll determine the oxidation profile. So, you're talking about the oxidation penetrating 5 millimeters or 10 millimeters, or so forth, something like that.

The oxidation, and also another thing we are looking at is the graphite submerged in the Flibe, It will also be assessed to determine if this oxidation occurs for the graphite submerged in the molten salt. And then, if we determine there is oxidation going on there, we will associate a strength; reaction will be further assessed.

So, that's about oxidation. Any questions?

CHAIR PETTI: Yes, just a question. You know there's been a tremendous amount of work done in this area for the other graphite grades.

MR. C. CHEN: Yes.

CHAIR PETTI: Do you anticipate ET-10 to have, say, different oxidation kinetics than IG-110? I would expect them to be kind of similar.

MR. C. CHEN: Well, I will say the trend, more or less, is similar, but the degree of oxidation and the kinetics parameter will be grade-dependent. There's a lot to do with the pore structure and the starting material and a purity extraction.

CHAIR PETTI: Right. Okay.

MR. C. CHEN: Any further questions? If no, I am going to pass it back to Margaret.

(No response.)

MS. ELLENSON: Okay, great.

So, just to summarize, the graphite material qualification report will largely follow the ASME BPV Code with a few limited departures, which I know that the NRC staff will talk about further, and we'll talk about further in our closed session.

Our qualification plan will use both a combination of existing data and data from new tests, and seismic qualification is outside of the scope of this particular Topical Report.

There's a few limitations that we have documented in this Topical Report. They're largely related to the need to finalize the design to be able to have those design inputs for the qualification program itself.

So, for example, the height of the vessel relates to the infiltration threshold pressure. Irradiation creep data relates to the component lifetime or the fluence in the final design, whether or not there are freeze (audio interference) -- so, freeze-thaw cycles, just for example are precluded by design for our -- are not within the design basis of a KP-FHR.

Other things about the interactions between any secondary loops, like an intermediate salt loop, an interfacing system, and then, coincident effects of irradiation and oxidation, which, again, that is a design feature. It's a design lever that we can pull to be able to minimize that effect.

There's also future testing that we're going to do related to demonstrating an irradiated fatigue response, following trends from existing datasets, and then, demonstrating in a final application that we are able to develop this envelope for a qualification bound for irradiated properties. And lastly, to provide a design-specific analysis for weight loss due to oxidation.

So, those were the limitations that we had identified, and I believe that this is our last slide for the open session.

CHAIR PETTI: So, I had a broader question, and maybe you can defer to the closed session.

But there's a discussion about the quality program that you plan to use that appears to be in conflict to the quality program that Div 5 expects.

MS. ELLENSON: Sure.

CHAIR PETTI: Can you talk about that?

MS. ELLENSON: Yes. So, Div 5 is really written for a power reactor application, and there are quality standards and a quality program that we are developing for a power reactor application.

In the NRC regulations, there are different standards that applied to a non-power reactor. So, for our test reactor application, we expect to follow the NRC guidance about quality assurance programs, and I believe that that is written up in the introduction of the Topical Report, how we will handle pulling the data into the appropriate quality assurance program related to what type of application we're going to use.

CHAIR PETTI: Okay. That's what I guess I was confused about. If you take data that we'll hear about in the closed session and you're using the test reactor quality standards, how can you use that data for a potential power reactor Div 5 application, given it's not the same? I didn't see that discussed in the Topical, but maybe I missed it.

MS. ELLENSON: Yes. So, the qualifications will be separate and distinct between the test reactor and the power reactor. We will be using the quality assurance standards for a power reactor for any data that we use to rely on for a power reactor application. So, if it happens to be the same dataset, we would do what we would need to do under a quality assurance program to be able to pull that data under the appropriate quality assurance.

CHAIR PETTI: Okay. So, when you get data that could apply to both Hermes and the power reactor, you're going to default to the power reactor QA standards?

MS. ELLENSON: Not necessarily. There are methods that you can use to be able to pull data into a quality assurance program. There may be some methods that are appropriate for a non-power reactor quality assurance program and different methods that one might use for a power reactor quality assurance program. So, it depends on which application, and which application we are using the data for would drive the methods that we would need to use to do quality assurance for that data.

MEMBER BALLINGER: This is Ron Ballinger.

I'm getting ahead of ourselves, but I think, on the metals side, there are words in there to the effect that the QA and data overall circumscribe the test reactor. In other words, they're going to use mostly qualified data for the power reactor, but that data will automatically work for the test reactor. Am I wrong?

MS. ELLENSON: Well, I can't speak for the Metallics Topical Report. I'm not the lead for that one. But, for the Graphite Topical Report, where data is already Q, for example -- there's a great deal of data out there that was already generated under a Q-level program -- obviously, that data could be directly applied to both a power reactor or a test reactor. I was speaking to the situation where data may not yet be Q and we may need to pull it under our quality assurance programs. I would speaking to what we would do in that circumstance.

MEMBER BALLINGER: Thanks.

CHAIR PETTI: So, these are radiation that are being talked about for the high fluence to determine turnaround, et cetera, et cetera. Those really aren't Hermes issues. Those are power reactor issues.

MS. ELLENSON: Yes.

CHAIR PETTI: So, you would conduct those radiations under NQA-1? Is that --

MS. ELLENSON: Yes. So, a power reactor application that would want to have a component lifetime that would go past turnaround, yes, we would do those tests. We would generate that test data under an NQA-A program.

CHAIR PETTI: I mean, I guess I may want to explore this with the staff, but I've always -- my experience, in talking to the quality people that I had interface with was always two flags of quality. You end up always in a problem somewhere. There will be something. What you don't want is you spent the time, you spent the money under the test reactor QA to get some data, and then, for some reason, they say, no, that's not good enough for the power reactor. And you have to go back and do it all over again. And that's what I'm hoping doesn't happen.

MS. ELLENSON: Yes. Yes, and the data that I'm talking about is not necessarily new data that would be generated, but historical data that we want to bring under --

CHAIR PETTI: Okay. Yes, historical data I can understand you can, yes, you can pull stuff.

MS. ELLENSON: Uh-hum. You can use different methods.

CHAIR PETTI: Right. That I understand, right.

MEMBER BALLINGER: For the benefit of the other members, can you tell us what turnaround is?

MS. ELLENSON: Oh, maybe I could have someone else speak to that, our radiation expert.

MEMBER BALLINGER: Okay. It's a term of art.

MS. ELLENSON: Yes. So, when graphite is irradiated, the fast neutrons lead to dimensional change. The graphite starts to shrink, and then, expands and gets back to its initial density. The point at which the shrinkage is maximum is called the "turnaround." And when the graphite gets back to its initial dimension or density, it's called "crossover."

MEMBER BALLINGER: Thanks. I'm sure now everybody knows.

MEMBER KIRCHNER: Well, I think the important thing, Ron, is that -- this is Walt -- is that, you know, they stay below that fluence for the Hermes Test Reactor. It becomes a lifetime issue for the power reactor.

CHAIR PETTI: Right, and there's a big concern, historically -- I'm saying go back 20-30 years --

MEMBER KIRCHNER: Yes.

CHAIR PETTI: -- nobody designed reactor cores that went beyond turnaround.

MEMBER KIRCHNER: Exactly.

CHAIR PETTI: They always fitted to a sort of limit.

MEMBER KIRCHNER: Yes.

CHAIR PETTI: Now, there's discussions about, well, maybe we can go that way, as long as -- you know, between that and where your dimensional change goes back to zero, can you take advantage of that because it gives you greater lifetime, et cetera, et cetera?

MEMBER KIRCHNER: Yes.

CHAIR PETTI: And that's a big discussion with people who want to use graphite in cores because it's expensive, et cetera, et cetera.

MEMBER KIRCHNER: Right.

CHAIR PETTI: Yes.

MEMBER KIRCHNER: And there are secondary issues that the members would be aware of, and that is things like, if you're putting control rods into the reflector, that becomes one of the issues you have to demonstrate that you're not going to interfere with, create a blockage --

CHAIR PETTI: Yes.

MEMBER KIRCHNER: -- in the shutdown mechanisms, as an example.

CHAIR PETTI: Make sure the holes are where you think they are.

MEMBER KIRCHNER: Yes, and they're still straight.

CHAIR PETTI: Right. Exactly.

I had, again, another question, but it may be more appropriate for the closed session.

I've actually looked at a lot of graphite stuff over the years, and there's always properties and, you know, there's against the grain, through grain, with the grain, et cetera, et cetera. You get all these material properties.

And what I've never fully understood -- and I think it depends on each designer -- how you take that data and actually use it in the thermomechanical analysis. Do you pick the most conservative number for each material property, so that you know you're conservative? Or do you try to get more sophisticated in using these different anisotropic values in your thermomechanical analysis?

MR. C. CHEN: I can briefly discuss a little bit. So, to clarify, yes, you're right, many graphite, it's not anisotropic material. You have a with-grain and against-grain direction property. It's up to the designer how to use it.

And so, we know the property just, for example, some reactivity, and the with-grain is always higher than against-grain. So, we want to use, take advantage of this kind of a property, we can design this way, but I think it is more a design question.

CHAIR PETTI: Yes. Because, then, you have to know that all the grains are with-grain in one direction, and it gets complicated, is what I always thought.

MR. C. CHEN: Yes. And so, that's why,

when we measure the property, we will make sure all of the property in both directions.

CHAIR PETTI: Right.

Okay. Any other questions, Members? If not, we'll go over to staff.

(No response.)

Okay. Thank you, Kairos.

Let's get the staff presentation now.

MR. RIVERA: All right. This is Richie. Okay, the safety presentation now. Let me switch to ours.

Just to confirm, can --

CHAIR PETTI: I can see the slides.

MR. RIVERA: Sorry, I'm trying to -- give me one brief second, please.

(Pause.)

Weidong, can you confirm if you can see the screens?

MR. WANG: Yes.

MR. RIVERA: I'll switch to full screen in a second. Okay.

Sorry about that.

I will pass on the mic to Alex Chereskin, who is the lead reviewer for this Topical Report.

MR. CHERESKIN: All right. Good morning,

everyone. This is Alex Chereskin.

First, I would like to confirm that you guys can hear me and that I'm speaking loud enough into the microphone.

CHAIR PETTI: No problem. We can hear you.

MR. CHERESKIN: Great. Thank you.

So, as Richie said, my name is Alex Chereskin, and I'll be presenting the NRC staff review of the Kairos Graphite Qualification Topical Report today. I'm also joined by Matt Gordon and Meg Audrain, who were also technical reviewers on the review of this Topical Report.

Next slide, Richie.

Kairos Power requested a review and approval on the Topical Report related to graphite material qualification for the KP-FHR design. And as noted earlier, this qualification applies to the structural graphite only.

In general, Kairos proposed to qualify its graphite consistent with the NRC staff-endorsed ASME Code, Section III, Division 5, with deviations that were noted in the Topical Report and evaluated by the NRC staff.

This qualification plan applies to both

the power and non-power test reactor designs, with differences that were, again, described in the Topical Report and evaluated by the NRC staff.

One thing to note is that the NRC staff's review focused on evaluating the qualification program against applicable requirements from Section III and Division 5. And because we were evaluating the qualification program, this is not an evaluation of things like component design and calculating a probability of failure of graphite components.

The staff's review focused on the overall qualification framework, and this includes evaluation against Section III, Division 5, requirements that are being endorsed in Regulatory Guide 1.87, Revision 2, as Bill noted earlier; use of existing graphite qualification data, unirradiated graphite testing -- or radiation testing for graphite, oxidation testing, and molten salt testing.

Richie, next slide, please.

This slide contains the regulatory basis for the NRC staff review. Portions of the regulatory basis include the sections from Part 50 and 52 related to information that is required to be provided in licensing applications, and information related to the graphite material properties fits that and will need to be supplied as part of a license application.

The NRC staff also evaluated the qualification program against KP-FHR PDC that had been previously heard by the NRC staff in KP-TR-003-NP-A. And as shown below, there are a few KP-FHR PDC that rely on graphite components to be met.

The first one is KP-FHR PDC 1, which is Quality Standards and Records, and that requires SSCs that are safety-significant to be designed to quality standards commensurate with safety significance. In this case, we're looking at ASME Code, Section III, Division 5.

PDC 34, the Residual Heat Removal, and PDC 35, which is Passive Residual Heat Removal, which requires systems remove residual heat, and graphite components, as discussed earlier, need to maintain a structural integrity in order to maintain the physical geometry of the core, in order to support the core cooling.

Additionally, there is KP-FHR PDC 74, which is the Reactor Vessel and Reactor System Structural Design Basis, and this requires that the reactor vessel system supports the integrity of the graphite during postulated accidents in order to ensure geometry for passive heat removal, and also, to allow sufficient insertion of the neutron absorbers.

Next slide, please.

So, this slide covers the NRC staff evaluation of the proposed qualification of unirradiated graphite properties in the Kairos Topical Report. The NRC staff found that the proposed testing plan will satisfy the requirements of Section III, Division 5, and the requirements in the ASME Code include HHA-2210, 3100, and 4100, as these provisions of the Code outline the required properties that need to be measured in order to qualify a grade of graphite.

And so, the staff found that the proposed testing program was acceptable because the properties required by HHA-III-3100, as-manufactured graphite, will be tested as part of the unirradiated testing program with appropriate temperature intervals that meet Code requirements.

Additionally, staff found this approach acceptable because the sample size and cutting patterns that are in the proposed qualification program are consistent with HHA-III-4100, as-manufactured graphite.

Kairos Power did propose two deviations from the Code requirements which the NRC staff evaluated.

The first one is to test certain parameters at room temperature. The staff found this acceptable, as it is conservative, because, for unirradiated graphite, the properties listed will improve as temperature increases.

The second deviation proposed by Kairos Power is to not test fracture toughness. And the Topical Report states that Kairos will not rely on this to demonstrate that graphite components can perform their safety functions and that the damage tolerance discussions are outside the scope of this Topical Report.

The staff found this acceptable, subject to Limitation Condition No. 7 in the Topical Report, which states that Kairos Power must demonstrate how full acceptance is performed without the fracture toughness of graphite.

And so, the last bullet on this slide -- oh, sorry, there's one more bullet there.

In addition, in the unirradiated testing, Kairos Power stated that fatigue testing will be performed. This is consistent with HHA-3140 and the ASME Code, which states that fatigue shall be considered in a graphite deployment design.

The staff found it acceptable to perform the low cycle fatigue testing. These will provide the data needed to design graphite components against the effects of fatigue, consistent with HHA-3140. And the staff found it acceptable to use the historical data trends, subject to that limitation and Condition 2.a, which would require Kairos to perform their low cycle fatigue testing and demonstrate that the ET-10 graphite follows the same trends as the graphite cited in the Topical Report.

In addition, Kairos proposed to use ASTM D7219 in order to guide their purity standards, which is consistent with Section III, Division 5, HHA-I-1110, "Material Specification."

Kairos Power also noted that they will define the graphite specification needed for the KP-FHR technology based on the requirements of the graphite components in that specific design.

Are there any questions on this slide before we move on?

CHAIR PETTI: Yes, I had a question on the fracture toughness limitation. I think I followed the logic in the limitation, which is, when one does inspections and sees a defect, a flaw, usually, one uses the fracture toughness as part of the evaluation to figure out if the flaw is significant or not.

Was there more beyond that than what's actually written there? I mean, are there other techniques that one can use without using fracture toughness that you guys were aware of?

MEMBER BALLINGER: Yes, this is a question I had, too. And I was going to reserve it for the closed session. But are they measuring the Weibull modulus of this stuff? That's another way to sort of get --

MR. CHERESKIN: Sure.

MEMBER BALLINGER: -- at the issue of fracture toughness, and it's an easier measurement to make.

CHAIR PETTI: I can tell you that it can be done. It's been done for the historic grades --

MEMBER BALLINGER: Yes.

CHAIR PETTI: -- all the work that INL and Oak Ridge have done for NGNP, yes.

MEMBER BALLINGER: Yes.

MR. CHERESKIN: I'll try to address the question here, and if needed, we can talk more, I guess, about the specifics of testing in the closed session.

But, in general, the Topical Report did

not provide, I'll say, the final disposition of how this would be performed, although there is a very brief discussion about damage tolerance, which is a term that kind of came out of the U.K. experience with the gas reactors, finding that graphite performance could still perform their safety functions, even given extensive cracking. So, there is some information that is available to show that it may be possible to demonstrate components can perform their safety functions, even with cracks in the component.

CHAIR PETTI: Okay. Keep going, I guess.

MEMBER KIRCHNER: Dave?

CHAIR PETTI: Yes?

MEMBER KIRCHNER: Dave, this is Walt.

CHAIR PETTI: Go ahead.

MEMBER KIRCHNER: On the purity standards, now, normally, for the gas-cooled reactors, it's more a question of neutronics. But here, the purity standards would be a concern if you had contaminants getting into the Flibe coolant system.

How did the staff look at that? Did you look at it from a chemical standpoint or from a neutronics standpoint?

MR. CHERESKIN: Yes, just to clarify, when you're talking about impurities getting into the coolant, is that a reference to potentially interacting with what is present in the graphite?

MEMBER KIRCHNER: Yes, versus neutronic considerations, uh-hum. Normally, like back in the HDGR programs, you were worried, especially if you had a solid core, not a pebble-bed core, you were worried about the boron equivalent of the contaminants that are in the graphite, as-manufactured. Here, there's the potential for different considerations like the coolant interaction with the contaminants.

MR. CHERESKIN: And this has also been the NRC staff evaluation. But the purity limits that are in the ASTM standard, you know, they do include like things such as ash content and, also, boron equivalency. And those would provide some assurance that those limits are reasonable, when you consider like their potential to accelerate oxidation of the graphite.

MEMBER KIRCHNER: Okay. All right. It's a different look at the issue of contaminants vis-a-vis the historical concerns for gas-cooled reactors.

CHAIR PETTI: Well, my understanding is just that this whole area, these graphites that they make today are just so much better than what were made, you know, 25-30 years ago for like Fort St.

Vrain. The technology, because graphite is used in other industries, has really improved.

And I can remember having big discussions about what the purity specification was for putting in an irradiation test, and the glow discharge mass spect show stuff was really clean compared to what people remember --

MEMBER KIRCHNER: Yes, my experience is dated and it's H451.

CHAIR PETTI: Right.

MEMBER KIRCHNER: So, a long way back.

Okay. Thank you.

MR. CHERESKIN: Okay. If there are no further questions, I think we can move to the next slide.

(No response.)

Okay. So, okay, I've lost my place here. Okay.

This slide continues the NRC staff's evaluation of the unirradiated material properties section of the Topical Report. So, graphite anisotropy, you know, it will occur. All grades will exhibit probably some degree of it. However, the magnitude is grade-dependent, and the mechanical property is also statistical in nature. And because the properties will vary both within the billet and between production lots of graphite, the designer will need to account for these variations.

The staff had found the Kairos program for intra-billet variability acceptable because their unirradiated qualification plan is consistent with the sample size and cutting patterns within HHA-III-4000, and that provides reasonable assurance that intra-billet variation can be quantified and factored into the graphite component design.

Additionally, as stated in the Topical Report, Kairos Power plans to use lot-to-lot variation data from the graphite manufacturer in order to be able to examine the lot-to-lot variation in graphite properties. And in addition, that data was shown to be consistent with the Appendix C of the Topical Report which discusses how to demonstrate historical data is applicable to the as-manufactured graphite. And that contains some provisions, you know, what would need to be demonstrated to ensure that you can compare those datasets.

Are there any questions on this slide?

MEMBER KIRCHNER: This is Walt again.

Is there a lot of historical data with ET-10?

MR. CHERESKIN: So, I am not aware of exactly how much data the manufacturer has.

MEMBER KIRCHNER: So, could you just, you know, for the record, just tell us -- say you were using H451 data, which was pretty good graphite in its day. How do you interpolate between that and ET-10??

MR. CHERESKIN: So, we would not be -- sorry, the intent here is not to use other graphite property data to evaluate that lot-to-lot variation. This would be using the manufacturer's data for the unirradiated properties to determine the variation over time in the production lots of that graphite.

The reference to historic data is because there is a Code article that lays out the requirements to use data that may have been collected some years ago, to ensure you can use that and verify it against the recent or current production lots. It was not meant to say that it would be used with another graphite grade.

MEMBER KIRCHNER: Okay. I misunderstood that. Thank you for the clarification.

MR. CHERESKIN: No problem.

All right. I think we can move on to the next slide then.

Okay. So, this slide discusses the NRC

staff's evaluation of -- now, we're getting into Section 4 of the Topical Report, which discusses the graphite qualification program for the irradiated basic properties of the graphite. And when I say that, it means the properties that are not irradiation creep, but, as you can see on this slide, stuff like dimensional change and strength, and whatnot.

And the NRC staff found the qualification plan in the Topical Report acceptable because Kairos will use irradiated property data for all the basic properties, consistent with the properties that are required by HHA-2220.

Additionally, the Topical Report states that the irradiated properties will bound the qualification envelope of the anticipated temperature fluence profile conditions that will be found in the KP-FHR design. This is supported by NRC staff Limitation Condition 9 which requires Kairos to demonstrate the data will bound the final design for the temperature irradiation envelope, once that has been finalized.

In addition, Kairos will use the process described in Appendix B that we were just talking about on the use of historical data to demonstrate that the irradiated property test data is applicable to the as-manufactured graphite production lots.

And so, part of the ASME Code requirements for demonstrating historical data is applicable, those are found in HHA-5000. And additionally, the proposed process from Kairos Power will demonstrate that the graphite meets the definition of the same grade as found in HAB-9200 of the ASME Code, to confirm that the irradiated test data is applicable to the current production lots.

And the final bullet on this slide just touches on some of the limitations and conditions that are applicable to this section, which, again, would require the Applicant Kairos Power to demonstrate that the data bounds the plant conditions; that the data meets applicable QA requirements, and that uncertainties in the irradiated data are accounted for in the design.

Are there questions on this slide before we move on to irradiation creep?

(No response.)

All right. Hearing none, Richie, can you go to the next slide, please?

So, this slide and I believe the next slide are going to touch on a topic that was actually the focus of a question earlier. So, covering just some background on irradiated graphite behavior, in order to kind of set the stage for the brief discussion.

And so, just a little bit of background is that graphite will initially shrink volumetrically with increasing dose, and then, once it hits a point called "turnaround," it expands. And so, that's kind of what we had covered before.

The dimension change is also a function of temperature. A higher temperature and you will reach that turnaround point at a lower dose.

And so, two other points that the staff wanted to note was that not all components will experience this turnaround point at the same time, as you will have, likely, a gradient for flow temperature and fluence across the scope of your graphite components.

And one of the reasons why turnaround is important is because that interface within a component of where you have volumetric densification and expansion may cause cracking at that location.

And so, on the next slide -- Richie, if you would go to that -- the staff had just put together a quick diagram to kind of show what turnaround looks like as a function of temperature and fluence.

And you can see where those red and blue arrows are. That just demonstrates the change from volumetric densification to expansion. And we just kind of wanted to provide that as a visual in order to support the next slide or two.

MEMBER HALNON: All right. Just one quick question.

After the turnaround point at the bottom part where the arrows are, is there other concerns on the upswing there before you get to, say, zero percent change again that makes the turnaround point even more important than just bottoming out?

MR. CHERESKIN: Yes. And so, I think, actually, that's something that we're going to talk about in the next slide or two. So, just to give a preview, I mean, that is probably the area where tertiary creep may start to occur. And so, that's something we're going to discuss a little bit more in either of the next one or two slides, I believe.

MEMBER HALNON: All right. I'll sit back and learn then. Thanks.

MR. CHERESKIN: If there are no further questions, we can go to the next slide.

(No response.)

All right. Hearing none, this slide forms the NRC staff evaluation of the proposed irradiation creep program, qualifications programs, for both the power and non-power test reactor designs.

The staff found the proposed qualification plan for the power reactor irradiation creep acceptable because the test program will bound the KP-FHR qualification envelope and the number of proposed samples is consistent with other creep experiments.

Again, this is subject to some limitations and conditions, and the first one being that Kairos demonstrates that tertiary creep is identified, if it occurs during the creep testing. The data that is obtained from these creep tests is sufficient to model the creep. Again, going back to the bounding qualification envelope, and ensuring that dimensional changes of the irradiated graphite are measured in both the against- and with-grain directions.

For the non-power reactor irradiation creep program, there are some differences, and that's what we are going to focus on here. The non-power reactor irradiated creep qualification plan will rely on data from other grades of graphite to develop a creep model.

And the NRC staff found this acceptable

because the quality graphite in the non-power test reactor will not reach turnaround. And so, kind of building off those previous slides, this is important for a couple of reasons.

The first being that, after turnaround changes to properties found less predictable and more limiting, and as we discussed earlier, post-turnaround components could be partially in biometric densification and expansion, which may cause some cracks. And additionally, this would be prior to the onset of tertiary creep, which is important because at that point the creep behavior would be changing, and additional data might be needed to accurately model what that tertiary creep looks like.

And so, the staff has reasonable assurance that, using the historical data shown in the Topical Report, that a conservative creep coefficient can be determined. And one other reason why the staff found this approach acceptable is because this is just for the non-power test reactor design, which is consistent with the minimum regulation provision in the Atomic Energy Act.

And again, this qualification program is subject to certain limitations and conditions in order to have Kairos demonstrate that the creep model is conservative. The graphite in the non-power reactor design is limited to pre-turnaround, and this is just applicable to the non-power reactor, given that part of the rationale is the minimum regulation clause in the AEA; and also, to demonstrate there's no stress-driven failure pre-turnaround.

Are there any questions on this slide before I move forward?

CHAIR PETTI: Yes. Just as I understand it, once you get beyond turnaround, the issue about whether the graphite is going to start to crack as it swells all depends on what's going on with creep. If creep can take out those stresses, then you reduce the chances of cracks. And so, that's why there's this big focus on trying to understand the creep behavior beyond turnaround. Is that how you guys sort of see it?

MR. CHERESKIN: Yes, I think so, and I think that's a good point to raise; that creep is necessary in graphite components, as it will counteract those stresses to counteract the cracking. So, I think we have a common understanding there.

CHAIR PETTI: So, in my opinion, this is still sort of an open question with all these graphites post-turnaround, and it's where I think most of technology development and research, there is a lot focused on that because it tells you how long your graphite is going to last.

So, thanks.

MR. CHERESKIN: Yes. Okay. If there are no further questions, I think we can go to the next slide.

This slide covers the NRC staff evaluation of the oxidized properties portion of the graphite qualification program. And so, this moves to Section 5 of the Topical Report, which describes qualification testing to determine properties of the oxidized graphite. And this was evaluated against ASME Code HHA-III-3200, which described the required properties of oxidized graphite to be measured.

And so, the staff found the Kairos Power oxidation program testing acceptable because the proposed testing will cover a range of temperatures for oxidation, including in the kinetic oxidation regime. The reason why I point that out is because, when you are in the kinetic regime, it allows the oxygen to penetrate deeper into the graphite, resulting in a larger strength loss for the amount of oxidation that occurs.

Staff also found this acceptable. Like

Kairos described earlier, they will develop the mass loss versus strength loss relationship for the ET-10 graphite and follow ASTM D7042 for oxidation testing.

There were two deviations from the Code requirements that Kairos proposed that the staff found acceptable, the first being that they do not measure the unoxidized elastic modulus, as -- sorry. They will not measure the oxidized elastic modulus because using the unoxidized values will yield more conservative values in stress analyses.

Additionally, they will not measure the thermal conductivity of the oxidized graphite. My staff found this acceptable because Kairos has stated that it will not credit heat dissipation from the top portion of the reflector in its accident analyses.

Are there questions on this slide before we move on?

(No response.)

Okay. Next slide, please, Richie.

So now, we come to the NRC staff evaluation of testing in the KP-FHR environment, which was covered earlier by Kairos in their presentation.

So, in the KP-FHR design, the graphite will be exposed to flowing Flibe, as well as moving pebbles, which presents the potential for Flibe infiltration to the graphite, abrasion, and erosion. ASME Code HHA-3143 requires an evaluation of abrasion if there's relative movement between graphite components and fuel of a pebble-bed reactor.

Additionally, Section III, Division 5, requires the designer to consider environmental effects, although, currently, in the Code there are no specific rules for the molten salt environments. And so, the staff evaluated the Kairos-proposed qualification testing program and found it acceptable because it will determine the impacts of abrasion, erosion, and Flibe infiltration. It will address the potential for mass loss due to abrasion and erosion, consistent with HHA-3143. And additionally, it will look at the loss of strength due to Flibe infiltration, as that should be considered in order to be able to assess the structural integrity of graphite components in the KP-FHR design.

Are there questions on this slide before we move on?

MEMBER KIRCHNER: I have one comment or comment that we can take up in the closed session.

But, apropos to the discussion about dimensional change earlier, and the fact that the billets that are going to be produced are not full height for the reflector, it means you're going to stack lots. So, one also has to be cognizant that you can have abrasion between the graphite components, not just graphite components in fuel, but actual individual components that make up the reflector region of the design.

MR. CHERESKIN: Okay. And I think we can --

MEMBER KIRCHNER: You could have, for example, you could have flow-induced vibration. That would be a design issue to look at, such that that could cause abrasion of block-to-block, depending on how they're locked together, et cetera.

MR. CHERESKIN: Understood, and I think we can discuss that further in the closed session.

Are there any further questions before we move to what I believe is the conclusion slide?

(No response.)

All right. Richie, could you go to the next slide, please?

Okay. So, to conclude, the staff reviewed Topical Report KP-TR-014, Revision 4, and concluded that the graphite material qualification program was acceptable for the ET-10 graphite to be used by the KP-FHR design.

I did just want to reiterate that this was not a review of the overall graphite component design or anything like a performance-monitoring program, as it's focused on the plan to qualify the ET-10 graphite to ASME Code requirements.

The staff approval is subject to limitations and conditions that were proposed both by Kairos and the NRC staff. And in addition, this qualification program will meet applicable PDCs that were discussed earlier in part, as the qualification program considers the appropriate conditions -- thermal, radiation, oxidation in the molten salt environment -- relevant to the design, and it also meets the Section III, Division 5, rules, with the noted exceptions, which will provide reasonable assurance that the graphite components can be designed to maintain their structural integrity within the qualification envelope.

Additionally, I wanted to note that this review was performed to the 2017 edition of Section III, Division 5, which is what is being endorsed in Regulatory Guide 1.87. And so, there is a limitation/condition to say that this review was performed to that edition in the Code and is applicable for that edition.

And as noted, this will meet the relevant PDC, as the qualification program is consistent with the ASME Code which relates to PDC 1, use of standards appropriate with safety significance of components. And additionally, graphite component integrity is needed to achieve PDCs 34, 35, and 74, as was described earlier, for the functions of passive residual heat removal and insertion of reactivity elements.

I believe this is the last slide. So, are there any further questions?

CHAIR PETTI: Members, any questions?

(No response.)

I guess not. So, thank you.

MR. CHERESKIN: Okay.

CHAIR PETTI: So, we have about eight minutes before we're going to take our break, and then, move into the closed session.

So, let me open to the public. Any comments from the public? Unmute yourself, state your name and your comment.

(No response.)

Okay. I'm not hearing any.

Why don't we take a break until half past the hour, and we will start up on the closed Teams link at that point. Everybody should have the closed link.

Thank you.

MEMBER BROWN: So, 11:30, is that what you said, Dave?

CHAIR PETTI: Correct. Correct.

MEMBER BROWN: Okay.

(Whereupon, the above-entitled matter went off the record at 11:08 a.m.

MEMBER KIRCHNER: Ron, Walt, I'm here.

MEMBER BALLINGER: Ah, okay, Walt.

MEMBER DIMITRIJEVIC: I am here, too.

MEMBER BALLINGER: And Vesna. Boy, I've

Kairos Power

Graphite Material Qualification Topical Report

ACRS Kairos Power Subcommittee Meeting

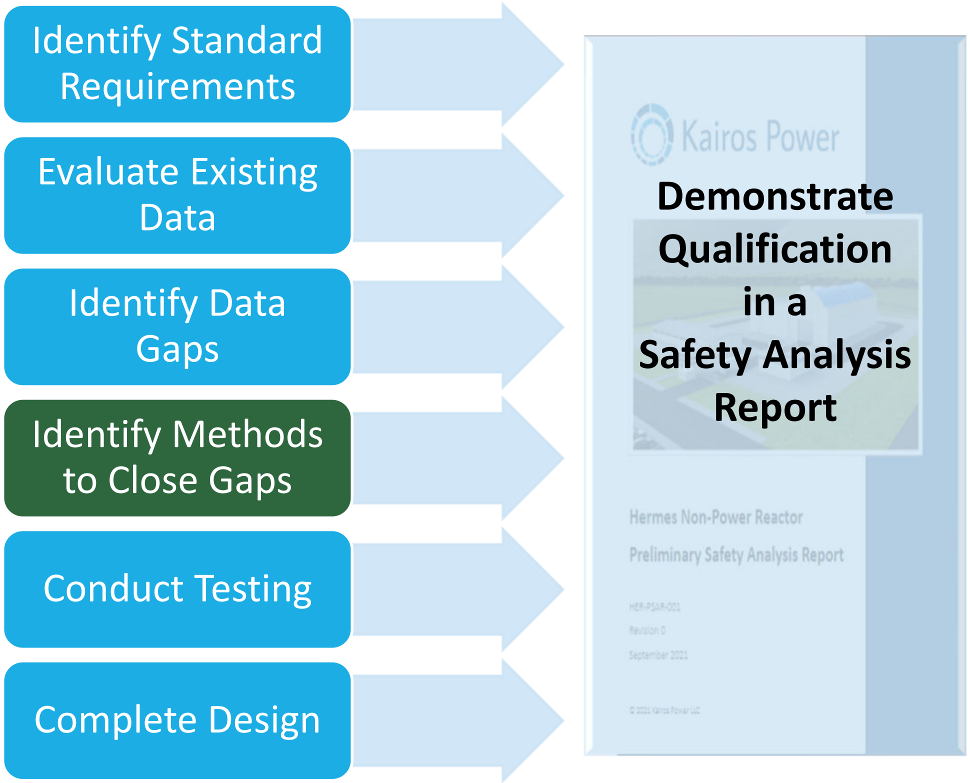
January 12, 2023

OPEN SESSION

Kairos Power’s mission is to enable the world’s transition to clean energy, with the ultimate goal of dramatically improving people’s quality of life while protecting the environment.

Introduction

- This report presents the methods for qualifying structural graphite for use in KP-FHRs
  - Qualification is subject to the conditions in topical report
- This report is applicable to a test or power KP-FHR provided that the report conditions are met



Identify Standard Requirements

Evaluate Existing Data

Identify Data Gaps

Identify Methods to Close Gaps

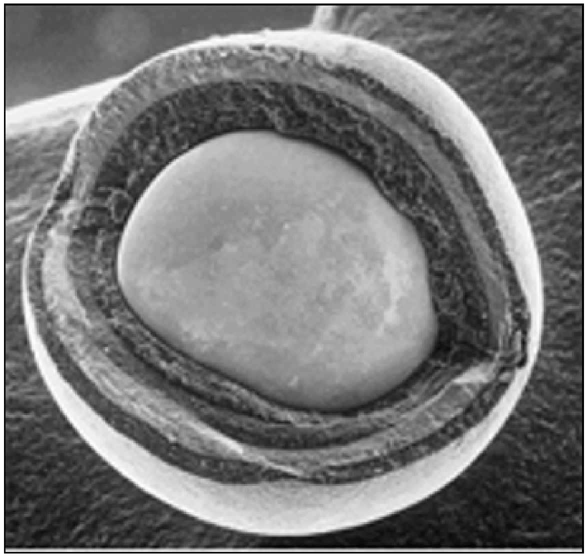
Conduct Testing

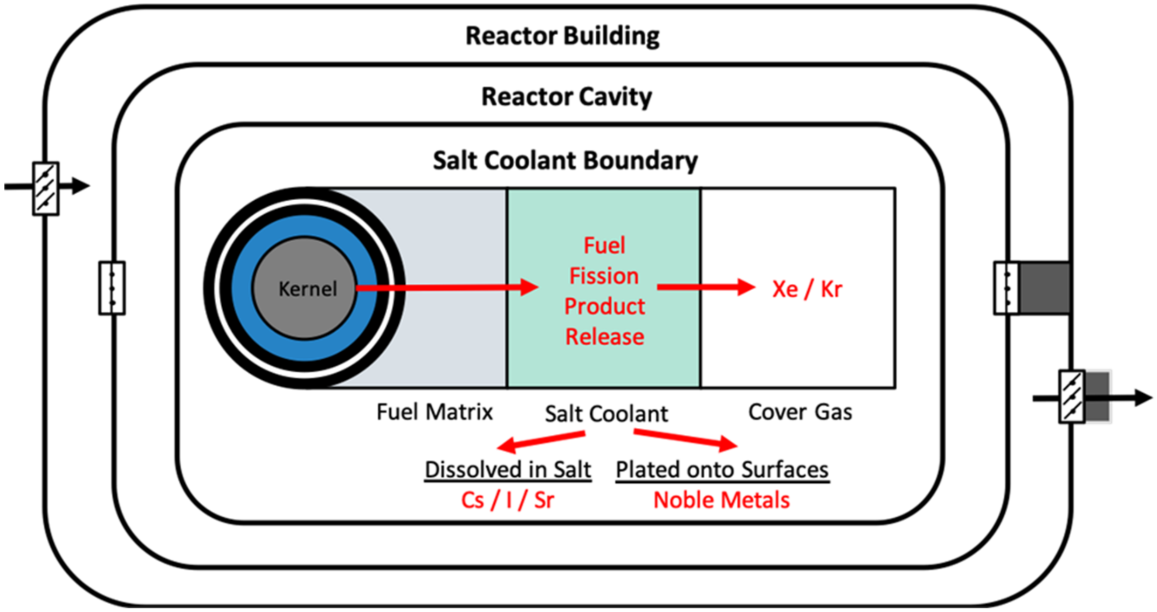
Complete Design

Demonstrate Qualification in a Safety Analysis Report

Fission Product Retention in the KP-FHR

Coated Particle Fuel
[High Temperature Gas Reactors]



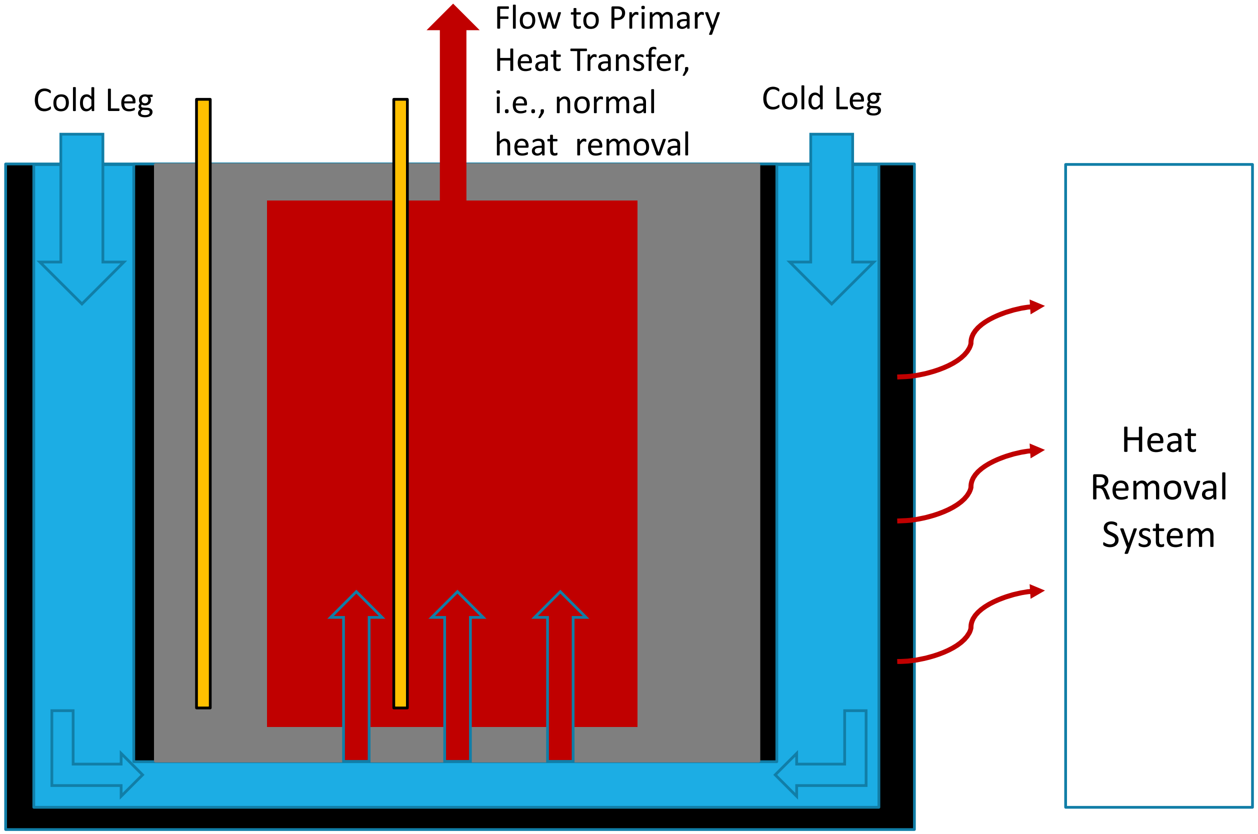


Test and Power KP-FHRs

- The reflector provides a physical pathway for maintaining core cooling and a physical pathway for reactivity control element insertions.
- Structural integrity ensures the safety functions can be met.

Downcomer Region
Active Core Region
Negative Reactivity Insertion
Graphite
Vessel/Core Barrell

* not to scale



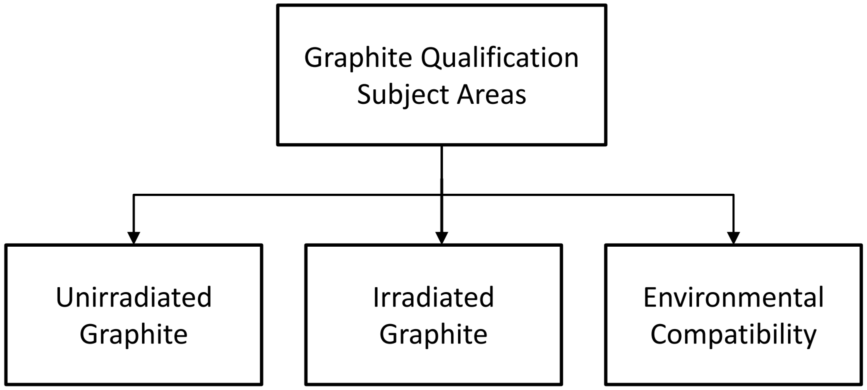
Structural Graphite Topical Report Organization

- Introduction
  - KP-FHR Technologies
  - Regulatory Information
- Nuclear Graphite
  - Background
  - Phenomena Identification and Ranking
- Unirradiated Graphite
- Irradiated Graphite
- Environmental Compatibility
- Conclusions and Limitations

- Appendix A: Data Analysis
- Appendix B: ETU-10 Demonstration of Historical Data Applicability
- Appendix C: Parameter Estimation and Uncertainty Assessment
- Appendix D: Comparison of IG-110 and ETU-10 Material Properties
- Scope:
  - The report applies to both a test reactor and a power reactor.
  - Seismic qualification is out of scope for the report.

ASME Code Application

- The qualification plan follows the ASME BPV, Section III, Division 5 code (the “Division 5 Code”)
  - A portion of the code specifically addresses graphite materials
- The Division 5 Code organizes qualification into three elements:
  - Characterization of as-manufactured graphite mechanical and thermal properties,
  - Characterization of graphite properties under irradiation
  - Environmental compatibility


Graphite Qualification Subject Areas

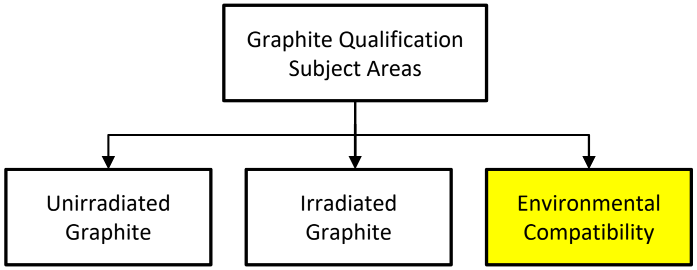
Unirradiated Graphite

Irradiated Graphite

Environmental Compatibility

Background on Graphite

- Characteristics of graphite (vs metallic material)
  - All graphite grades are 99.9%+ carbon.
  - Thermally stable in inert environment, as high as ~3,200°C
  - Mechanical strength increases with temperature
  - Low coefficient of thermal expansion
  - Anisotropic property
  - Up to ~20% porosity
  - High property variability
  - Graphite billet size limitation, difficult to make large-billet, superfine grain graphite.
- Graphite has been used in nuclear reactors for decades and extensive knowledge has accumulated about the material.
  - The topical report also references relevant data about other grades of graphite, for example IG-110 (isomolded, superfine) and CGB grades (extruded, medium grain).
- ET-10 is a superfine grain graphite with nearly isotropic properties that will be qualified for use in a KP-FHR.



Graphite Qualification Subject Areas

Unirradiated Graphite

Irradiated Graphite

Environmental Compatibility

Environmental Compatibility

Chapter 5: Environmental Compatibility

- Five phenomena relevant to interaction between Flibe and ETU-10
- Physical Factors
  - Infiltration (See Section 5.1.1) - Closed Session
  - Stress (See Section 5.1.2)
    - Graphite reflector bears no structural loads, unlike the HTGR.
  - Erosion and Abrasion (See Section 5.2)
- Chemical Factors
  - Chemical compatibility with Flibe (See Section 5.1.3)
  - Oxidation (See Section 5.3)

Abrasion and Erosion

- Kairos Power will perform confirmatory tribology testing in Flibe to demonstrate that no significant abrasion of the structural graphite occurs due to contact between the reflector and pebbles
  - No abrasion expected as contact forces are low and ET-10 is harder than the pebbles
- Kairos Power will perform confirmatory erosion examination of ET-10 specimens exposed to long-term Flibe flow in rotating cage loop (RCLs):
  - Erosion is an issue for gas-cooled reactors where the gas flow velocity was 1-2 orders of magnitude higher than the flow velocity of Flibe in a KP-FHR
  - MRSE experience: No obvious signs of erosion on graphite surface after 3 years of operation

Chemical Compatibility with Flibe

There are no known chemical reactions between graphite and Fluoride leading to degradation.

- MSRE experience: No graphite degradation was observed after 3 years of operation
- Intercalation: Theory and literature data indicate it cannot occur under KP-FHR operating conditions
- Fluorination: Kairos Power has evaluated available literature results and found that although there was indication of trace surface fluorination, no bulk fluorination was observed. Bulk fluorination would be necessary to affect graphite mechanical properties.

Oxidation during air ingress event

- Oxidation may occur at the top of the reflector (inert gas space) under air ingress events, which could potentially reduce graphite strength.
  - The effect of air oxidation will be assessed:
    - Measure the ET-10 oxidation kinetic parameters
    - Determine the weight loss vs strength
    - Determine oxidation depth profile
- Oxidation of graphite submerged in Flibe will also be assessed to determine if oxidation occurs. If so, the associated strength reduction will be assessed.

Summary

- The qualification plan in the Graphite Material Qualification Topical Report describes the plan to qualify ET-10 for safety-related structural graphite component design for use in a KP-FHR.
- The qualification plan conforms with the ASME BPV, Section III, Division 5, Code with limited departures.
  - Quantification of mechanical properties as-manufactured ET-10 at room temperature which is conservative for use in future modeling.
  - Fracture toughness will not be measured.
- The qualification plan will use existing data and data from new tests.
  - Existing data for basic irradiation properties and irradiation creep support design of a graphite reflector with a 4-year lifetime (pre-turnaround conditions).
  - A combination of existing basic irradiation properties data and quantification of existing irradiation creep data will support design of a graphite reflector with a lifetime under beyond turnaround conditions.
  - A combination of confirmatory testing and use of existing data to demonstrate environmental compatibility of ET-10 in Flibe.
- Seismic qualification of the reflector structure is outside the scope of the topical report.

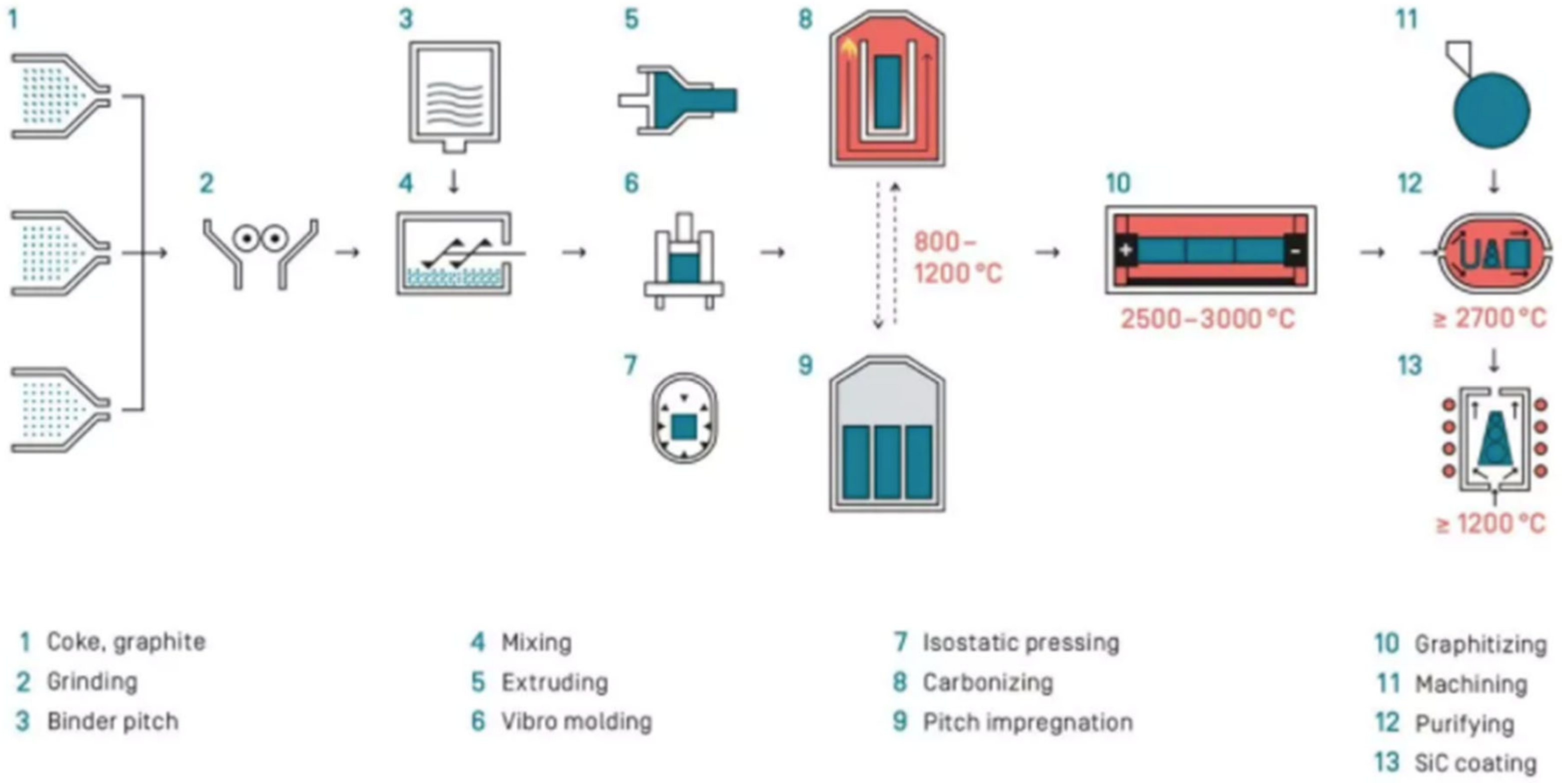
Limitations

- Flibe infiltration is not a consideration for the KP-FHR when limited to reactor vessel fluid heights up to 4m.
- Additional irradiation creep data from testing of ETU-10 is not required when the turnaround fluence is greater than the component lifetime.
- Graphite qualification presumes the reflector does not undergo freeze-thaw cycles.
- A future license application will evaluate and justify the effects of unplanned intermediate salt infiltration into the primary loop, if the reactor design uses intermediate salt in an interfacing heat transfer loop.
- The reflector structure and reactor vessel design preclude the coincident effects of oxidation and irradiation such that the structural integrity of the top of the reflector would be unable to perform its safety function.

Limitations (continued)

- A future license application will demonstrate that ET-10 unirradiated fatigue response follows the same trends as H-451 and PGX.
- A future license application that relies on the qualification program in this report will demonstrate that the data relied on for qualification bounds the analysis for irradiated properties.
- A design specific analysis of the effect of weight loss due to graphite block oxidation on structural integrity of the reflector material will be provided in a future license application that references the qualification program described in this report.

Backup: Graphite Manufacturing Process



Source: SGL Carbon website. https://www.sglcarbon.com/en/markets-solutions/material/sigrafine-isostatic-graphite/

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NRC Evaluation of KP-TR-014-P, “Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)”, Rev. 4

Alex Chereskin
Matt Gordon
Meg Audrain
US Nuclear Regulatory Commission

January 12, 2023

Introduction

- Kairos Power, LLC requested staff review and approval of KP-TR-014-P, Rev. 4, “Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)”
- KP-TR-014-P, Rev 4 provides a methodology by which the Kairos ET-10 graphite 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:
  - Evaluation against ASME Code Section III Division 5 requirements (Regulatory Guide 1.87, Revision 2)
  - Use of existing data
  - Unirradiated testing
  - Irradiation testing
  - Oxidation testing
  - Molten salt testing

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

The following Kairos PDC are applicable to this topical report and were previously approved by the NRC staff (KP-TR-003-NP-A):

KP-FHR PDC 1, "Quality standards and records"
KP-FHR PDC 34, "Residual heat removal"
KP-FHR PDC 35, "Passive residual heat removal"
KP-FHR PDC 74, "Reactor vessel and reactor system structural design basis"

Staff Evaluation

Qualification of Unirradiated Graphite

- The NRC staff found that the proposed testing plan will satisfy the requirements of ASME Code Section III Division 5 (Section III Division 5) Article HHA-III-3100, “As-Manufactured Graphite"
  - Sample size and cutting patterns consistent with HHA-III-4100, “As-Manufactured Graphite”
  - Conservative to use room temperature strength and modulus because these properties improve with temperature for unirradiated graphite
  - No fracture toughness if Limitation and Condition 7 is met
  - Fatigue testing will be performed
    - Limitation and Condition 2.a
- Use of purity standards in ASTM D7219-08 is consistent with Section III Division 5 HHA-I-1110, “Material Specification"
  - The staff finds it acceptable to define the graphite specification for unirradiated and irradiated properties based on the requirements of graphite components in the KP-FHR

Staff Evaluation (Cont'd)

- <u>Qualification of Unirradiated Graphite (Cont’d)</u>
  - Graphite anisotropy is grade dependent and mechanical properties are statistical in nature
    - Vary within billet and between lots
  - Intra-billet variability of properties consistent with HHA-III-4000
  - Lot-to-lot variation will use data from the graphite manufacturer and compare to as-manufactured graphite
    - Limitation and Condition 2.b
  - Use of historical data consistent with HHA-III-5000, “Use of Historical Data”

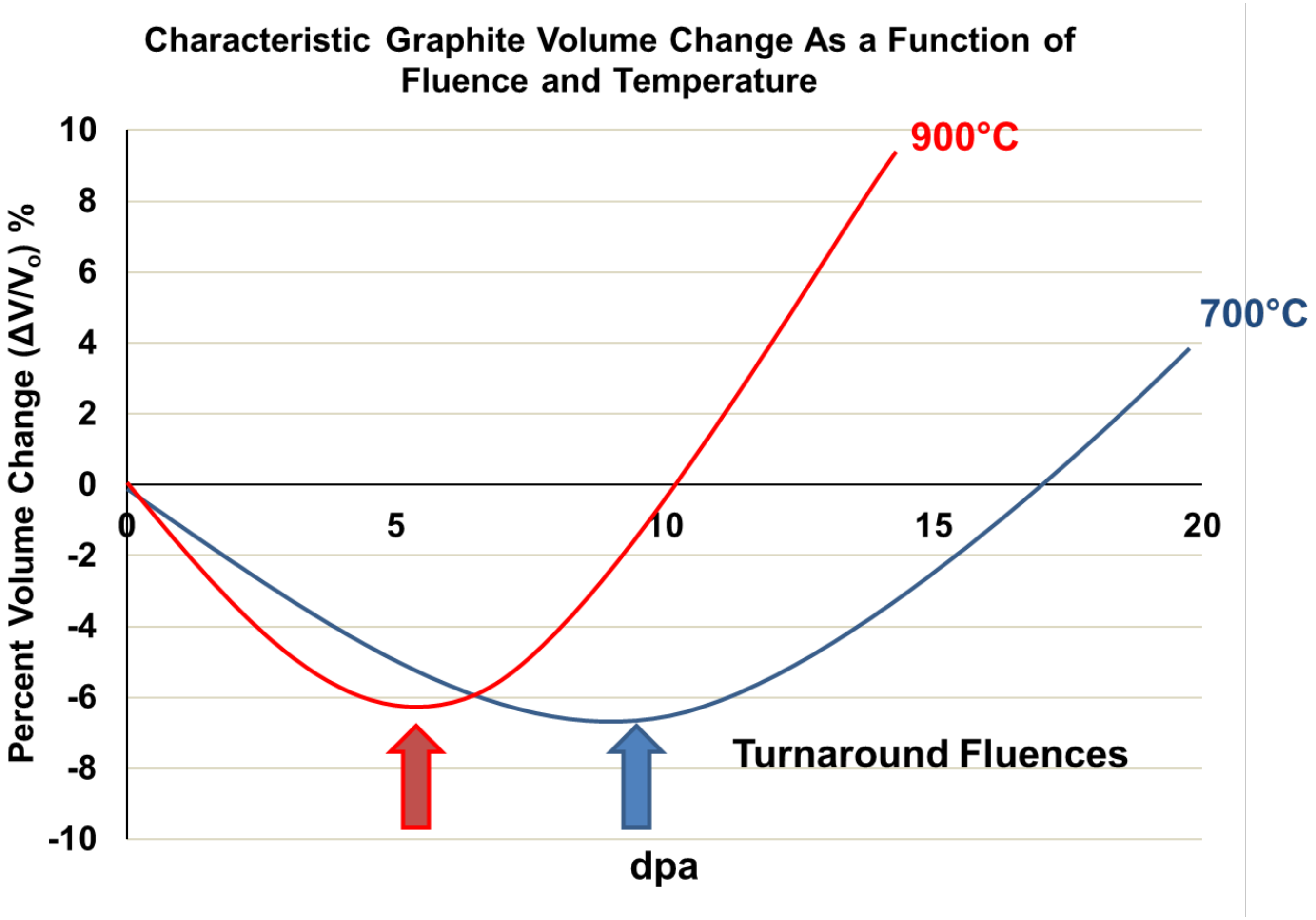
Staff Evaluation (Cont'd)

- Irradiated Properties
  - HHA-2220, "Irradiated Material Properties" requires measurements for irradiated properties
    - Dimensional change, CTE, strength, thermal conductivity, and elastic modulus
    - Damage dose and temperature range shall cover qualification envelope
  - The NRC staff found the qualification plan acceptable because KP is using irradiated property data from ORNL for all properties above, except creep
    - Data will be shown to bound qualification envelope (Limitation and Condition 2.c)
    - KP will demonstrate consistency with HHA-III-5000, “Use of Historical Data” for ORNL test data
  - Limitations and Conditions 6, 9, and 10
    - Require applicant to demonstrate plant conditions bounded by data, all data meets ASME QA requirements, and that data uncertainties are accounted for in design

Staff Evaluation (Cont'd)

- Irradiated Graphite Behavior
  - – Graphite initially shrinks volumetrically with increasing dose, and then expands
  - – Dimensional change also a function of temperature
  - – Turnaround is the point where contraction turns to expansion
    - Not all components will experience turnaround at the same time
    - Interface within components of volumetric densification and expansion which may cause cracks

Staff Evaluation (Cont'd)



Staff Evaluation (Cont'd)

- <u>Power Reactor Irradiated Creep</u>
  - The staff found the proposed testing for irradiated creep acceptable because it will bound the KP-FHR qualification envelope and the number of samples is consistent with other creep experiments (e.g. AGC-3 experiments)
  - Limitation and Conditions 2.e, 2.f, 8, 9, and 11
    - Ensure tertiary creep is identified, data is sufficient to model creep, data bounds qualification envelope, and dimensional changes measured in both AG and WG directions
- <u>Non-Power Reactor Irradiated Creep</u>
  - Data from other grades of graphite will be used to develop a creep model
  - The NRC finds this acceptable
    - All graphite will be pre-turnaround
      - Important because after turnaround changes become less predictable and more limiting
      - Additionally, post-turnaround components would partially be in volumetric densification and expansion which may cause cracks
      - Prior to onset of tertiary creep
    - Reasonable assurance a conservative creep coefficient can be determined
    - Acceptable because non-power reactor minimum regulation consistent with the AEA
  - Limitation and Conditions 2.g, 12.a through e
    - Demonstrate that creep model is conservative, limited to pre-turnaround, applicable to non-power reactor, and demonstrate no stress-driven failure pre-turnaround

Staff Evaluation (Cont'd)

- <u>Oxidized Properties</u>
  - HHA-III-3200, “Oxidized Graphite,” requires properties of oxidized graphite to be measured
    - Strength, elastic modulus, thermal conductivity
  - The staff found the KP oxidation testing acceptable
    - Covers a range of temperatures including the kinetic oxidation regime
    - Will develop mass vs. strength loss for ET-10 graphite
    - Follows ASTM D7542 for oxidation testing
    - Acceptable to use unoxidized elastic modulus because it will yield more conservative values in stress analyses
    - Acceptable to not measure thermal conductivity of oxidized graphite because KP stated the design will not credit heat dissipation from the top portion of the reflector.

Staff Evaluation (Cont'd)

- KP-FHR Environment
  - Graphite in the KP-FHR will be exposed to flowing Flibe as well as moving pebbles
    - Potential for infiltration, abrasion, and erosion
    - HHA-3143, "Abrasion and Erosion," requires an evaluation of abrasion if there is relative movement between graphite components and fuel of a pebble bed reactor
    - Section III Division 5 requires designer to consider environmental effects although no specific rules for molten salt environments
    - Limitation and Condition 2.h
  - The NRC staff found the proposed qualification testing acceptable to determine the impacts of abrasion, erosion, and Flibe infiltration
    - Potential mass loss for abrasion and erosion consistent with HHA-3143
    - Loss of strength due to Flibe infiltration should be considered in order to assess structural integrity of graphite components

Conclusions

- The staff reviewed the topical report KP-TR-014-P, Rev. 4 and concludes that the graphite material qualification program is acceptable for ET-10 graphite to be used in either non-power or power designs of the KP-FHR.
    - Does not include review of design, monitoring, damage tolerance, etc.
- Subject to NRC staff limitations and conditions
- KP proposed limitations are necessary and appropriate
- Will meet applicable PDCs, in part
    - Considers all conditions (thermal, irradiation, oxidation, coolant) relevant to design
    - Meeting Section III Division 5 rules provides reasonable assurance structural integrity is maintained within qualification envelope
        - Limitation and Condition 3
    - Graphite components will be qualified to ASME Code consistent with PDC 1
    - Graphite component integrity is needed to achieve PDCs 34, 35, and 74

Questions?

References

- B. J. Marsden, M. Haverty, W. Bodel, G. N. Hall, A. N. Jones, P. M. Mummery & M. Treifi (2016) Dimensional change, irradiation creep and thermal/mechanical property changes in nuclear graphite, International Materials Reviews, 61:3, 155-182, DOI: [10.1080/09506608.2015.1136460](https://doi.org/10.1080/09506608.2015.1136460)
- Windes, William E., Rohrbaugh, David T., Swank, David W., INL/EXT-19-54726, "AGC-Irradiation Creep Strain Data Analysis," Revision 0, July 2019.