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UNITED STATES NUCLEAR REGULATORY COMMISSION'S
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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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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THERMAL-HYDRAULIC SUBCOMMITTEE

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TUESDAY

AUGUST 21, 2018

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ROCKVILLE, MARYLAND

The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 8:30 a.m., Michael L. Corradini, Chairman, presiding.

COMMITTEE MEMBERS:

MICHAEL L. CORRADINI, Chairman

DENNIS C. BLEY, Member

WALTER L. KIRCHNER, Member

JOSE A. MARCH-LEUBA, Member

JOY L. REMPE, Member

GORDON R. SKILLMAN, Member

JOHN W. STETKAR, Member

MATTHEW W. SUNSERI, Member

DESIGNATED FEDERAL OFFICIAL:

WEIDONG WANG

ALSO PRESENT:

STEVE BAJOREK, RES
JON CARMACK, INL
DAN FUNK, DOE NE
JESS GEHIN, INL
JASON HALES, INL
STEVE HAYES, INL
SHANE JOHNSON, DOE
RICHARD LEE, RES
ELIA MERZARI, ANL
DAVE POINTER, ORNL
EVERETT REDMOND, NEI
TANJU SOFU, ANL
CHRIS STANEK, LANL
JEFF WHITT, Framatome*
RICH WILLIAMSON, INL

*Present via telephone

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P R O C E E D I N G S

(8:30 a.m.)

CHAIRMAN CORRADINI: Okay, the meeting will now come to order. This is a meeting of the Thermal-Hydraulics Phenomena Subcommittee, a standing committee of the Advisory Committee on Reactor Safeguards.

My name's Mike Corradini; I'm chairman of the subcommittee. ACRS members in attendance are Dr. Ron Ballinger, Dennis Bley, Matt Sunseri, Joy Rempe, Jose March-Leuba, and Walt Kirchner. And Weidong Wang is the designated federal official for this meeting.

In this meeting, the subcommittee will conduct a information briefing regarding the potential use of Department of Energy computer codes in risk-informed safety analysis for accident-tolerant fuels and light water reactors as well as in non-light water reactors.

The subcommittee will hear presentations by and hold discussions with the Department of Energy's personnel and other interested persons regarding this matter.

We've received no written comments or requests for time to make oral statements from members of the public regarding today's meeting. The entire meeting will be open to public attendance.

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.

The transcript of the meeting is being kept and will be available as stated in the Federal Register's notice. Therefore, we request the participants in this meeting use the microphones located throughout the meeting room when addressing the subcommittee.

Participants should first identify themselves, speak with sufficient clarity and volume, so they may well be heard. Let me add some extemporaneous comments.

First of all, make sure everybody silences their devices. We have a lot of folks in here with a lot of various appliances. Make sure things don't bong, bing, ring, whatever.

Secondly, since this is an information meeting and it's the first of what I expect will be a couple, at least. There's no intention to write a letter report with the full committee.

So this subcommittee will report back to the full committee, but it's my intent not to have a letter at this point. It's too early in the game since this is kind of more of a gathering.

And because of that, let me make it known to the DOE folks that you're going to hear at least seven different opinions from this committee, all of which are not the ACRS position.

They are individual comments by the individual members which you can or not take at will. So that's the final point. Other than that, I think the person to turn to is Shane. Are you going to lead us off today?

MEMBER MARCH-LEUBA: You will need to go through the microphone procedure?

CHAIRMAN CORRADINI: Yes, there's a little green light that goes on. There you go.

MEMBER BLEY: If you push the button.

CHAIRMAN CORRADINI: If you push the button.

MR. JOHNSON: All right, good morning. Mr. Chairman, members of the subcommittee it's a pleasure to be here today to discuss the Department of

Energy's work over the last nine years to develop, demonstrate, and deploy a suite of world-class modeling and simulation capabilities in support of commercial nuclear energy in the United States.

That includes both the existing fleet of light water reactors and the emerging non-water based advanced reactors. Since 2010, the Department has invested nearly $400 million in advanced nuclear energy modeling and simulation.

Executing two similar but distinctly different federal programs, the energy innovation hub for modeling and simulation and the nuclear energy advanced modeling and simulation programs, the Department is committed to developing and deploying state of the art computational platforms for light water-based reactor systems and advanced non-water based reactor systems.

Today's briefings which will be provided by the Department's leading subject matter authorities are focused on modeling accident-tolerant fuels for possible use in the existing fleet of U.S. light water reactors and advanced reactor technologies, molten salt, high-temperature gas, and liquid metal which are currently under development by the private sector.

I believe today's briefings will provide the committee a good overview of the current capabilities and limitations of the codes, and the analytical enhancements afforded by these codes as compared to the legacy codes currently used by both the regulator and licensees.

A key DOE goal of our advanced modeling and simulation program is to enable industry to accelerate reactor and fuel development and commercialization.

For example, we believe these tools can help accelerate licensing as they can help the reactor and fuel vendor community design, execute, and analyze more effective high-value experiments to support the licensing of their technologies.

While these advanced tools will not replace the need for experimentation, they can help identify the most critical experiments and help focus data acquisition from the experiments.

The technical teams working on both the hub products and the NEAMS products represent the best nuclear energy modeling and simulation talent within the DOE laboratory complex.

A very important strength of these teams is the multi-disciplined, multi-laboratory composition of the team membership. In the early days of our program, we established an overarching success metric centered on creating modeling and simulation platforms that would be used by industry for both in-house computational needs and for the development of licensing products for submission to the Nuclear Regulatory Commission.

I'm happy to report that our advanced codes are being used by industry in support of the existing fleet and in support of advanced reactors.

Five test stands have been deployed and are being used by the private sector to analyze and evaluate the operations of the light water fleet.

Four development companies within the advanced reactor community are using our tools for non-water technologies, and several additional companies are evaluating their use.

We also know one private sector firm will be submitting licensing documents later this year which are based on analyses derived from our advanced modeling and simulation codes.

It is my hope that today's discussions will serve to accelerate the technical cooperation between the two agencies, especially in the area of advanced modeling and simulation.

With limited federal budgets at both

agencies, it is important that we cooperate to the fullest extent possible on the development and qualification of these tools which can be used independently in the execution of each agency's missions.

I would be remiss if I didn't acknowledge the important technical contributions of the NRC's Dr. Steve Bajorek and Dr. Kim Webber to our modeling and simulation activities.

While Dr. Webber's contributions have been more recent as part of her professional development assignment to the department, Dr. Bajorek has been intimately involved in our efforts from almost the very beginning of the program.

With regards to the two agencies working together on a common set of computational tools, I do not underestimate the challenge this represents. For far too long, vested and personal interest within the DOE national labs and within the federal staff have opposed our efforts to work together in the execution of our respective responsibilities.

The mere fact that the ACRS requested today's briefing demonstrates that the Department's nuclear energy computational efforts are being recognized by the U.S. technical community, and our modeling and simulation program is on a success path.

A decade ago, the Office of Nuclear Energy had little to no modeling and simulation capabilities. Today you will hear about state of the art computational capabilities that do not exist within the classical legacy codes used to date by licensed applicants for the regulator.

When we began our efforts at developing a suite of world-class tools for analyzing nuclear fuel with reactor technologies, we had many more distractors than supporters.

But here we are today, briefing the Nuclear Regulatory Commission's independent advisory body. We still have plenty of distractors, but as the technical community familiarizes itself with our advanced modeling and simulation capabilities, those distractors are finding it harder to argue against the work we are doing.

Mr. Chairman, this concludes my opening remarks. I appreciate the interest that the committee has in the Department's work, and I look forward to a very spirited discussion of the modeling and simulation work that my colleagues here are going to present to you this morning and this afternoon.

MEMBER MARCH-LEUBA: Shane, Mike has gone over on the procedures for the microphone and the fact that we speak for ourselves and not the committee. He forgot to tell you that we like to interrupt, and so get used to it. I'm going to be the first one to do it.

MR. JOHNSON: Well, you interruption is not an interruption because I'm done. Thank you.

MEMBER MARCH-LEUBA: What is the vision? What vision do you have for this cause? I mean is the DOE going to become a vendor, a nuclear vendor that we license the code and then perform calculations for individual companies?

Are you going to just provide the FORTRAN code and let them figure out what to do? Do you have a vision for the application? How is this going to be implemented?

MR. JOHNSON: Well, for starters, our vision for the codes that we've been producing both for the light water application and the non-water application is simply put together a world-class capability in the codes.

Make them available to industry, let industry decide whether or not they see merit in the code, whether they want to use the code moving forward whether it's for their in-house purposes only, whether it's for, you know, informing where the companies are going with their development plans or hopefully, to ultimately be used in licensing space in interactions with the NRC.

That's the vision, that's the goal. It's to see a common set of tools that could be used by both licensees and regulator so that the intent isn't in setting up an industry that continues to create codes that are being shopped and sold as mine's better than yours and it's better or whatever.

But to have a common set of codes that everyone understands their limitations, their applicability, but that they can be used independently the results of which can be analyzed and gain decision space independent.

MEMBER MARCH-LEUBA: My point is historically the DOE, and the staff of NCR can use codes that as long as they themselves feel confident that they're going to have a benchmark and they provide sufficient confidence to provide complementary calculations.

But a vendor has to use a license code, I mean it has to have been reviewed and approved by the NRC. Certainly, not for everything and they will have to negotiation but anything that goes into tech specs for the final plan has to have an approved version of the NCR with it.

So your vision is not to license the code, you would provide it to the vendors, and the vendors will have to license their own applications.

MR. JOHNSON: Correct.

MEMBER MARCH-LEUBA: That's a significant amount of work.

MEMBER REMPE: Has any vendor said, "Hey, I'd like to take this licensed environment, I'd like to take it for ATF and get it licensed and go forward." Has GE, Westinghouse, or AREVA or Lightbridge said, "We're going to do this"?

MR. JOHNSON: No, that has not been said.

MEMBER REMPE: Why not?

CHAIRMAN CORRADINI: Well, hang on.

MR. JOHNSON: Because of the reasons we've said.

CHAIRMAN CORRADINI: Why don't we, before we get to the end game which I was figuring we're going to get here. But we're here before -- but I do think, I do think I want to hear from the DOE folks but I do thing Joy, and Jose are raising a question that somewhere today we've got to address which from the industry side who has decided to adopt whatever for their use in a particular application?

MEMBER REMPE: Well, where I'm going through with this question is that it seems like DOE has put a lot of money in here and the end game is getting it licensed and approved by NCR.

If Westinghouse or AREVA said, "I'd like to do this, I'm willing to be the guinea pig." I mean, they've gotten money for other activities from DOE. Why I'm surprised they're not saying to DOE, I'm willing to do this with the NRC but none of them, they all want to keep using their own codes for ATF instead of doing that.

MR. JOHNSON: That's my understanding.

MEMBER REMPE: Okay --

MR. JOHNSON: But they can use our codes to do the foundational work that then they can migrate over to their approved licensed codes for actual application.

MEMBER REMPE: The long-term vision, you've put a lot of money into this in the past. I know a lot of laboratories, I think the laboratory I used to work for put in about a million a year.

Of course, they had a three year limit on LDRD, so it was for a different task on the code, they didn't break any laws. But there's been a lot other money beyond what DOE has put into the code, would it continue?

If the NRC were to make this decision, it's a lot; their resources are a lot smaller than DOE's. So knowing how the DOE continuity or their focus on research can change, there's a strong commitment you think in the future that DOE will continue to put in that much money per year?

MR. JOHNSON: That's our hope. We won't pretend to know what future --

MEMBER MARCH-LEUBA: That will be up to leadership.

MEMBER REMPE: Yes, and also, that's the other question.

MR. STANEK: I'll just make one quick comment as far this goes, and we will talk about these issues during the technical presentations today. The comments around accident-tolerant fuel are specific to, so in the morning today we'll talk about accident-tolerant fuel, and in the afternoon we'll talk about advanced reactors.

The interest level in users for the codes that we're developing vary in terms of the maturity level of the concept. And so that's something that we will discuss, but if existing tools are good enough for near-term accident-tolerant fuel concepts, then there's less of an interest in using the code itself.

But there are things that we're doing that are, at a research level, that are influencing vendor codes. And so that's for ATF it's a bit more complicated than it is advanced reactors where we'll see probably more full-adoption of tools.

I will note that for the advanced reactors we have an industry council that consists of the technical working groups. They've asked us to not mention their own interests specifically that they will do that to you. DOE doesn't license reactors.

And so we will today talk about the codes that we're developing and the capabilities. I think we're comfortable in saying that there is interest like Shane said in his remarks. But we will not mention vendors by name as per their requests.

CHAIRMAN CORRADINI: So that's interesting because that's essentially what I was going to ask somewhere today which was you had an industry council, what does the industry say?

So they've explicitly instructed you not to talk about who's interested in what?

MR. STANEK: They want to talk to the NRC themselves.

CHAIRMAN CORRADINI: Okay, then let me as at least a different question because you've gotten ahead of me which is good then I don't have to ask my question later about that.

Can we get the list of who's on your industry council?

MR. STANEK: Of course.

CHAIRMAN CORRADINI: Okay, second part of it is. I think a couple of us were involved in the CASL review a few years ago. So we maybe have some insights there.

One question that's going to come up and I'm assuming it's going to be somewhere in your presentations, is at what point does verification and validation end in your view and then is passed off to the adopter?

Because at least a few years ago that left me personally a bit fuzzy. All right? Because I do think there's going to be a significant amount of validation and verification necessary that might go beyond what you have chosen to do in terms of your programs.

So I think somewhere, whether you do it one by one or at the end, I think that's important for us to understand. Particularly, if you're not going to give us the bottom line answer which is A is adopting X. Okay?

MEMBER KIRCHNER: May I add, Mike, I think the other thing is how NQA-1-ready, if that's a valid phrase, are these codes at the point where DOE decides that they put enough into them and now it's time to hand it over to a vendor, assuming that there's an interested party out there?

And what's the list in terms of cost to get from what's more of a developmental code, some of them I understand are much more mature, to the place they need to be for use in the licensing area?

I'll just throw that one thought on it; I won't use my source term, you know, of course, the department is much involved in this as supporting advanced reactor technologies.

Something that the commission is looking and this committee will review is things like emergency planning. And going to a, for lack of the right terminology, dose-based approach to determining those kinds of things.

The requires a mechanistic source term and how ready those codes are that you're developing for analyses of mechanistic source terms are to be used in the licensing area is going to be very important for any early movers of those advanced technologies.

Thank you, Mike.

CHAIRMAN CORRADINI: Okay.

MEMBER MARCH-LEUBA: Can I ask? I know we're wasting time, Mike, but --

CHAIRMAN CORRADINI: You get the last question.

MEMBER MARCH-LEUBA: -- okay, good, excellent. It is going to be a long question, though. What's the status of these codes, in the sense, I mean is it going to be open source or is it going to be -- my concern is in the '70s the DOE developed some codes, well written.

And then vendors on TRAC and the vendors took it and made a couple of modifications, and it became their proprietary code, and that's the one that's licensed.

So the work of validating TRAC has been repeated dozens of times, every time somebody uses it with their proprietary modifications. So are going to deliver this code as open source so they can do any modifications and then it becomes their proprietary code or are you going to close the code so that you can do some verification for it? Do you have any plans for that?

MR. JOHNSON: Great question, and it's a question we've been wrestling with a bit. I think the original intent of many were open source. But for various reasons, we're finding that that's not a good proposition for the future. So most likely these codes will not available open source.

But if there are modifications that are necessary or desired in the codes, we'll figure out a mechanism by which we can incorporate those changes.

MEMBER MARCH-LEUBA: DOE can do the changes instead of letting them.

MR. JOHNSON: Right, the bottom line is we are, we don't want to see the source codes for many aspects of these tools out in the marketplace.

MEMBER MARCH-LEUBA: I mean, this year, in October now has slipped to December we've reviewed the obligation of RELAP for a vendor. And I mean RELAP has been for 50 years.

But it keeps coming, our proprietary version code X that I have modified for LOCA and it would be nice if you guys don't fall into that trap.

Export control, are these codes going to be export control? Any of these slides are export control? We would have an issue with that.

CHAIRMAN CORRADINI: No, they're open.

This is an open meeting. But since, are you done?

MEMBER MARCH-LEUBA: Yes.

CHAIRMAN CORRADINI: Okay, so if we start getting into areas that require either proprietary or export control issues you're going to have to tell us because we're going to keep on asking.

Okay, I think we're onto Chris. Am I correct?

MR. JOHNSON: Yes.

CHAIRMAN CORRADINI: Okay.

MR. STANEK: Good morning, I should have introduced myself when I was making comments. My name is Chris Stanek. I'm a staff scientist at Los Alamos National Laboratory.

On behalf of all us involved in the technical presentations or the briefing today, let me thank the ACRS for the opportunity to present the status of the DOE advanced modeling and simulation codes.

Before we begin those technical presentations ,I thought I'd say a few brief words that will hopefully provide some useful context and some of those contextual points have already been discussed this morning. Let me make a few of those comments now.

First, as for the guidance from the Chairman and the HERS, today well will limit our presentations to only the advanced code being developed by the DOE.

As you all have noticed from the agenda, and as I mentioned previously, we will focus this morning on accident-tolerant fuel, and in the afternoon we will talk about non-light water reactors.

Since we have limited our presentations to only DOE codes, we will not cover any other codes that may address similar phenomena to the codes we'll be talking about.

However, even though those other codes will not be discussed, we are well aware of these codes and in some cases, very well aware of these codes. And you'll even several instances during the day of how the DOE codes may be being interfaced with these.

But we're simply limited today with the amount of information we want to convey. We've established a boundary condition; we'll focus our comments today only codes that we're developing. We have a lot more to say about that other topic, but that's for another time.

Like I said, the amount of material we

intend to cover today is significant. We've taken care to produce presentations that hopefully provide a clear and concise picture of the codes for you.

However, in the case, that additional information is required, or of interest, we're more than happy to provide at a later date.

The technical presentations themselves will predominantly focus on the descriptions of capability, status, maturing level of the codes, but not discuss deployment of them and this has already been discussed.

Let me say a few words about that. The strategy for deployment is simple. It is that the DOE makes its codes available to the NCR and U.S. companies from which they may generate proprietary versions using their own validation data. There are cases where these commercial licenses are currently being executed.

MEMBER MARCH-LEUBA: I like the word may. They may make their own proprietary codes for a large light water reactor, a vendor may have 50 reactors in operation, and for this aggregate fueling, they may want to go this route.

MR. STANEK: Right.

MEMBER MARCH-LEUBA: But for a small

company that is moving a specialized new mobile reactor, they will not have the resources to do that. So it will be nice if DOE has a package that those little companies could use.

MR. STANEK: In that division, the may there is also intended to provide companies that will be investing a lot of their own resources and experimental data that they can protect data in a proprietary version of the code. Because there are companies that have expressed that to us and we wanted to make that available.

Related to deployment are obviously software quality assurance and the validation basis of the codes that we will discuss. Although in each of the presentation there will be brief mention of these topics, let me say a few words now.

Software quality is taken very seriously in the DOE programs, and all of our code development efforts adhere to very strict software quality principles.

Regarding validation and hopefully we clear up your fuzziness here, Mike, but our approach is to perform sufficient validation that a user then adopts then code.

The user will then very likely, if not be required to perform additional validation for a specific application and that will vary from application to application. We'll hear about a lot of that in the following presentations.

CHAIRMAN CORRADINI: So, maybe this is a good time to ask the question. You don't have to answer this question, maybe just think about it. So I have code X, I don't know what it is, and you guys have some sort of experimental benchmarking list that you now check it against.

And Company A says I'm very interested in code X, code X is either closed or open ,and I don't appreciate that part. But I'm interested in code X, your idea is to basically pass over the tool as well as the base benchmarking that you've done and leave it to them to decide that's enough for them to take the risk to go further, use it, and then apply for a well I was going to say a license. Essentially, apply to the NRC to get an SER for approval to use in a safety analysis. That's your logic.

MR. STANEK: Correct.

CHAIRMAN CORRADINI: Okay, so now I have code X, and I have the NRC, is it really appropriate or is there a conflict of interest issue when I take code X, and both vendor and the regulator uses the same tool?

Historically, the only time I'm aware of that was done was by congressional fiat for EPAct 2005 where they were told that had to do that.

Prior to that, it's been historic that, at least in my memory, is that test data might go in every DOE. NRC may say, "This is important test data that we need to understand a phenomena." The data's there, and then the vendor or the regulator will say, "Here's our evaluation model to look at that data and interpret it and then use it."

Unless I misunderstand, we're philosophically changing; the suggestion is to philosophically change that sort of paradigm. Am I missing something?

MR. STANEK: No, it's a good question and one that we are openly discussing. The DOE role there though I would say is to provide the codes. What the NRC and vendors do is sort of out of our purview.

But I think that is a worthy discussion to have; it's one that we've been involved in with the Office of Research in particular. And I'd direct you to them for the better answer than we can give.

MEMBER MARCH-LEUBA: Let me put in the record some individual member's opinion about that.

In the 1960s, the codes were very simplified by necessity because they had less computer power than your watch.

So you had to have a code which use one kinetics and you will want to use a different code for configuratory what it would be then you use for one be and see that they both agree. So they're approximations, you were trying to benchmark the codes with different representations to see if you got the same answer.

Codes now are so good, especially on the neutronics side that --

CHAIRMAN CORRADINI: Especially when?

MEMBER MARCH-LEUBA: On the neutronics side, and I totally into neutronics too. That there is no need to benchmark one A versus one B. Everybody's had three D, the question is do a six-inch node or a two-meter node.

So it's more on the applications, there is not so much need of independent codes for complementary analysis. There is more need for independent persons running it, independent assumptions, independent input deck.

The code itself becomes so good there is no need to use a different FORTRAN line but that's my opinion.

MEMBER REMPE: So I have --

MR. STANEK: For what it's worth, we agree with that.

MEMBER REMPE: -- so that's, your comment about that you're going to make the codes available to NCR and industry and that you've done sufficient validation is why I asked Shane earlier, what's the vision the DOE has about funding this in the future.

It sounds like you guys are about done and you're just going to be a software maintenance organization. And is that the plan, I mean are you going to expand and go to severe accidents too?

It sounds like, you know, you've gotten there and you're about done.

MR. STANEK: No, I think what you'll hear today, especially in the area of advanced reactors is that there's considerable work to do. That we've developed capabilities that are applicable to the different reactor designs, but there's some key development that needs to be done going forward.

MEMBER REMPE: Okay, so you'll help us understand where the gaps are, I mean, some things I can guess, but I just was kind of wondering about the long-term vision.

But eventually, I guess there's always something else to analyze, and you'll always continue having a program, that's your hope.

MR. STANEK: In the specific technical presentations, there will be mention of the gaps for each of the codes going forward where effort is required.

MEMBER REMPE: Okay.

MEMBER KIRCHNER: Can I go back to your oh, next to the last bullet or sub-bullet? Which strict SQA principles are they adhering to, NQA-1?

MR. STANEK: Yes, and I think I'd leave that for the technical presentations because there is some differences between the codes in terms of --

MEMBER KIRCHNER: Is the strategy to pick benchmarking such that the final product, although usually the codes, having coming out of the world, they're never final. They're always being, evolving.

But it is going to be, the first order here of strategy or objective to provide for both the NRC, well, or the industry, an NQA-1 ready code. In other words, do sufficient benchmarking against experimental data of relevance such that the code would be to post-order ready to be licensed.

Or to be reviewed by the NRC and SER

issues, is that the objective or is that going to be left to industry?

MR. STANEK: Yes, I would say to first order, that is the goal. We do have NQA-1 advisors working with the programs to make sure that that goal is met.

I would say that that's a work in progress. I'm making general statements because there are a number of different codes that I'm referring to. And there will be some discussion of that in the technical presentations regarding the codes and we can follow-up if those we don't get good enough answers to you.

MEMBER KIRCHNER: Thank you.

CHAIRMAN CORRADINI: Why don't you keep on going, Chris.

MR. STANEK: Okay, so we've generated a table that I hope will be a useful key or a legend for the presentations that will follow on accident-tolerant fuel today.

The reason we've done this is that you'll hear a number of different codenames referred to during the two presentations this morning. And the idea is that this table could be referred to as a guide to associate a code name with a specific capability and its intended use.

In the interest of time, I won't introduce the codes. You'll hear plenty about them this afternoon. This table also serves an additional purpose which is essentially a more detailed version of the agenda that we've provided.

And so first this morning we will hear from Steve Hayes from Idaho National Laboratory. He will present an overview of fuel modeling for accident-tolerant fuel.

Given the importance of fuel modeling for that particular topic, this will take up most of the morning. And so Steve's presentation will be split by the coffee break.

After the fuel modeling presentation, Jess Gehin also from Idaho National Laboratory will present both thermal-hydraulics and neutronics efforts for accident-tolerant fuel.

CHAIRMAN CORRADINI: Recent, he went west.

MR. STANEK: Recently, in Idaho National Laboratory.

MEMBER REMPE: So I have question that probably Steve could answer later but whenever I see something like this you have MARMOT and BISON, but later like when you're closing slides you only talk about validation of BISON.

And I think when I see in your presentation too Steve, mainly the validation has been done with BISON, not much on MARMOT.

MR. HAYES: That's an issue I'm going to address here.

MEMBER REMPE: Hard to get data for MARMOT. Right, so I'd like to understand that --

MR. HAYES: I will talk about that.

MEMBER REMPE: -- and how you can have a validated BISON without a validated MARMOT.

MR. HAYES: I'll explain that.

CHAIRMAN CORRADINI: So since you volunteered that one, let me see if I can get you to volunteer something else. So looking at this, I see this for normal operation for AOOs, maybe for certain sets of DBAs but I see nothing here that can do beyond design-based as accident source term. Is that a fair statement?

MR. HAYES: Yes.

CHAIRMAN CORRADINI: Okay, fine.

MR. STANEK: If there are no other questions, please allow me to introduce Steve Hayes who will present the status of our fuel modeling effort for accident-tolerant fuel.

CHAIRMAN CORRADINI: You can drive for him or are you going to make him drive by himself?

MR. HAYES: We're going to change seats.

MEMBER MARCH-LEUBA: You can get the mouse.

CHAIRMAN CORRADINI: You can just look at the screen, the mouse will let you talk.

MEMBER MARCH-LEUBA: You don't have to move, and you can look at his screen. There's nothing on it; you have to close.

MR. HAYES: Okay, let me also say thank you. I'm Steve Hayes from Idaho National Lab. We do appreciate this opportunity to address the committee and answer questions.

So I'll be talking about ATF fuel modeling. Here's the outline of the presentation I'm going to use, and I'm going to start not specifically on modeling.

I'm going to talk about development and testing of a ATF fuels that are going on because that's an important element on validation. How do we foresee getting the data needed to validate these fuels?

One slide on the multiscale, mechanistic modeling approach that DOE's taking in advanced fuels modeling because this is the approach we've been working on for nine years and this is the approach we intend to use for ATF.

So we'll set the stage there and then just literally three or four slides to overview BISON. I think most people are probably familiar, but if not, we'll spend a few minutes on that and certainly answer any questions.

An overview and then specifically we'll update you on the verification validation status and approach. And then the majority of the presentation will be on what we call model enhancements for accident-tolerant fuels.

We're modifying BISON to address all the things that we see potentially coming, doped UO_2, chrome-coated zirconium, FeCrAl cladding, silicon carbide cladding, silicide fuel, and non-cylindrical metallic fuels.

And then we'll end with some remarks about validation, although we'll say some things along the way, and summary and conclusions.

Okay, starting with development and testing of accident-tolerant fuels. Just to set the stage here, we all know that this got started back shortly after Fukushima.

The Fukushima accident was in 2011 and the very next year, 2012, Congress directed the Department of Energy to begin developing fuels that would offer some enhanced accident-tolerance in accidents like Fukushima and some other situations.

And the direction from Congress was pretty specific. They challenged the DOE to insert lead test rods or lead test assemblies of an ATF concept into an operating commercial light-water reactor within ten years.

This came out in 2012 and DOE took it as our direction to have LTAs or LTRs of some ATF concept in an operating reactor by 2022, three years from today.

We regarded that as very challenging at the time. So DOE obviously not taking a lead role in developing and licensing LWR fuels historically, immediately reached out to the industry through what they call, a funding opportunity announcement.

Solicited industry teams to propose concepts that DOE could sponsor. And the three concepts or teams that were selected are shown on this slide. So these are not my most recent slides, sorry about that.

These are the three teams: Framatome,

General Electric, and Westinghouse. And from left to right they go in alphabetical order, but there's another logic to the order too.

And that is from left to right the development and qualification licensing process would appear to become more challenging as you proceed from left to right.

So Framatome, primarily in the near-term is working on chrome-coated Zircaloy cladding and doped UO_2 concepts for improved thermal-connectivity and fuel performance.

Now they also are working on a longer-term track on silicon carbide cladding. I don't list it here because that's a longer-term option for them.

General Electric is working on iron-based cladding. This is the iron-chrome-aluminum variance, FeCrAl, they call it. So that's their main line, although I will say they have in more recent years also started work on coated cladding concepts as well.

And then Westinghouse has got a suite of things they're working on. They are working on chrome-coated Zirlo cladding. They're working on silicon carbide cladding on perhaps a more aggressive track than Framatome which is the reason it makes this slide.

And then completely new fuels that offer improved thermal-connectivity and hopefully higher density. So that's the Westinghouse concepts.

Now all three of these teams have multiple partners with them. They have utility participants, and some of them have lab participants.

MEMBER MARCH-LEUBA: That's what the icons, the lab icons show?

MR. HAYES: Exactly. So this may be a bit dated. For instance, Idaho and Los Alamos were a formal part of the Westinghouse team when it was awarded, when the FOA was awarded.

Oak Ridge was a formal part of GE. Those are still true, but now you'll find the labs being directed to support all of the teams in certain areas as they request.

And that's the other thing to be said here. So under this FOA relationship that DOE has with these three industry teams, it really is the industry teams that are leading the development, qualification, ultimately licensing of their own ATF concepts.

The DOE and the labs working under the direction of DOE are supporting the vendors where they need and ask for support and providing testing of all the concepts.

MEMBER BALLINGER: I have a question about the little item at the bottom. Have you traced the ownership of Lightbridge to its origin?

MR. HAYES: Yes.

MEMBER BALLINGER: What is it?

MR. HAYES: So this is related to my comment, we had thought we provided a revision of these slides that don't have Lightbridge on it. DOE doesn't have a formal relationship with Lightbridge, so we're not really prepared to talk about Lightbridge, I think.

MEMBER BALLINGER: So you pass.

MR. HAYES: I'll pass.

MEMBER REMPE: But, again, I'm not sure I saw it in this slide later on. You have put in BISON, some Lightbridge-type work. Why did you do that if you have no formal relationship? Yes.

MR. HAYES: Yes, so this is what is meant by non-cylindrical metallic fuel. We see some entities out there proposing concepts, like a Lightbridge, that may come along.

And so we're informing the committing on DOE's tools capability, the capability of DOE's tools to address concepts like that.

MEMBER REMPE: Okay.

MR. HAYES: Okay, so I mentioned the industry teams have the lead in developing their concepts. DOE and especially the lab are providing testing of all the concepts, and very early in the ATF development cycle DOE stood up a conceptual radiation testing program to support the development of ATFs.

And you see here, each of these columns represent what we call a test series. So ATF-1 was the first one stood up. It's a test series in the advanced test reactor at Idaho.

It makes use of drop-in, double encapsulated testing configurations. So it's not a prototypic condition where the cladding is exposed to coolant. But it is appropriate for collecting some very early data on new fuels, fuel cladding interactions.

And this test series began in 2015; it's still ongoing. We've gotten some of the early low burn-up test articles out already but many are going on to higher burn-up, and we expect that new test articles will be added to this. So this isn't just one experiment, it's a test series that continues.

ATF-2 is a prototypic PWR condition. So this is in a pressurized water loop in the ATR. It's designed to test integral fuel and cladding concepts under PWR conditions.

It just started this year in May, at the end of May, early June the loop went operational with test articles in it, and this is going to continue for some time.

And it's designed so that new articles, new rodlets can be introduced as time goes one and rodlets will be removed for examination.

MEMBER REMPE: So Steve, hold on for a second, let's ask some questions about ATF-2. Which vendor fuels from the prior slide are in ATF-2 now as rodlets? And which will be added in the near-term?

I also have a lot of other questions about what data are you going to get out of ATF-2 ever?

MR. HAYES: So ATF-2 when it started at the end of May, not every concept was ready to take off at the same time. Westinghouse has coated cladding concepts in, Framatome has coated cladding and doped UO_2 in. So that's what's in it today. The first few rodlets.

MEMBER REMPE: And those are the prototypic ones that you showed on the prior slide from Framatome and AREVA, Westinghouse?

MR. HAYES: So Framatome has all of their stuff in ATF-2 currently. Westinghouse has coated Zirlo in there now. GE is expected to deliver FeCrAl cladding test articles in the upcoming year. Hopefully, by about January.

Westinghouse is expected to deliver some fuels and possibly even some silicon carbide cladding that specimens next year.

MEMBER REMPE: Okay, and then what data, I think I heard you should have a thermocouple in ATF-2? That's it?

MR. HAYES: So ATF-2 is capable of doing instrumented fuel tests, in fact, before we started up ATF-2 we did what was called SQT, sensor qualification test, which was the ATF-2 test train without fuel but with instrumentation.

And thermocouples in fuels are possible, LBDTs for measuring gas pressure and gas release are possible, but none of those have been implemented yet in the test articles that are in ATF-2.

CHAIRMAN CORRADINI: So I'm, Joy is much more familiar with this than many of us, so I'm not exactly clear if the instrumentation is just sitting there what exactly is AFT-2 looking at?

MR. HAYES: It's testing miniature fuel rodlets.

CHAIRMAN CORRADINI: But what is being measured? More integral quantities?

MR. HAYES: So there's currently no in situ measurement.

CHAIRMAN CORRADINI: Oh, it's post-test.

MR. HAYES: These are going to be taken --

CHAIRMAN CORRADINI: Okay.

MR. HAYES: -- to target burn-ups and then taken to the hot cell for destructive examines.

CHAIRMAN CORRADINI: Okay.

MEMBER REMPE: So again, because I'm getting ready to talk about the Halden issues. Where are you going to get the data for PWR conditions since Halden is going to shut down?

MR. HAYES: So you see by --

MEMBER REMPE: Yes, but that only says BWR conditions.

MR. HAYES: I know.

MEMBER REMPE: And it used to be Jon Carmack's flight had ATF-HX last time we heard him had P and B, and you've changed it to just B. So where are you going to get the P stuff?

MR. HAYES: Exactly, so all the vendors anticipated doing some testing in Halden, maybe quite a bit. Obviously, with the shutdown of Halden, Halden needs to be, these tests need to be redirected.

And actually, the DOE's had an activity over the last couple of months looking at that. Some of these needed tests that were expected to be in Halden have to be moved. Some of them are going to be moved to ATR. Some of them might be moved to other places.

Cladding only corrosion testing can probably be done at MIT. The BR-2 reactor may do some of these tests. That's something that we're working through right now. We don't have every answer, but we see ways to get there.

MEMBER REMPE: So, okay, you said, "Well, we put LBDT into ATF-2." I didn't hear you say we can put a diameter gauge into ATF-2. I mean the standardized test rigs I didn't see come out of the draft report you guys issued this summer about what you're going to do about Halden.

MR. HAYES: Exactly.

MEMBER REMPE: And that needs to be done where you can get all of the data real-time, not just cook-and-look.

MR. HAYES: You know, I would challenge that a little bit. The in situ instrumentation is the preferred way to go. We don't question that. But as we look at where to move things and get the same sort of data that's not Halden, it's not going to be able; it's not going to be possible to reproduce everything that Halden does somewhere else. We may have to skin the cat in a little bit different ways in some cases.

So the ATF-2 loop is not set up to make online cladding strength measurements. So we may have to get that at interim steps in the canal or even the hot cell.

MEMBER BALLINGER: With respect to Halden as NQA-1, the other two that you mentioned are not.

MR. HAYES: I won't speak for BR-2, but I would say in ATR we are fully capable --

MEMBER BALLINGER: Okay, I was not thinking about MIT and BR-2.

MR. HAYES: Okay.

MEMBER BALLINGER: I think ATR, I'm assuming it's in NQA-1.

MR. HAYES: Yes, ATR is certainly capable of doing NQA-1.

MEMBER BALLINGER: So if you have to go to these other places other than ATR, how do you deal with the quality control issue?

MR. HAYES: So we are talking with the NRC along those lines ,and we dealt with it a little bit in ATF-1 and ATF-2 fabrication of test articles which in some cases vendors did and some cases labs did, and in some cases, even universities contributed.

And so the way we've made it work is the vendor sponsoring the work has to come in and cover all of its subcontractors with its QA program and do whatever it takes to elevate their product.

MEMBER BALLINGER: So the DOE would have to cover the cost of upgrading or whatever needs to be done to NQA-1 for wherever you go, BR-2, MIT, whatever.

MR. HAYES: Well, the upgrade would be necessary. I'll stop short of saying who ought to cover the cost, perhaps DOE, perhaps the vendors.

MEMBER REMPE: So I didn't, again, that will be something that you and the regulator can argue about cook-and-look when you take the fuel out and try to decide about swelling and all of that without a diameter gauge real-time.

But what about thermo-connectivity degradation, how are you going to get that?

MR. HAYES: So as I've said, it is possible to have thermocouples in ATF-2 so we can approach it that way. We also, and I'll speak to this at the end, we also plan to do thermo-connectivity measurements of irradiated fuel specimens in the hot cell.

MEMBER REMPE: Okay.

MR. HAYES: Okay, so that's ATF-1 and 2, ATF-3 is also a test theory starting up probably next month. Just make '19 by a hair's breadth. And this is a test series to be conducted in TREAT, both the static and the loops. And so being conducted in treat, this is looking specifically at off-normal conditions.

MEMBER BLEY: How off-normal are you pushing it?

MR. HAYES: So TREAT will look at both LOCAS and RIAs, as severe as someone wants them to be.

MEMBER BLEY: As someone wants them to be?

MR. HAYES: Obviously, that's not the near-term focus. The near-term focus would be on less aggressive testing.

MEMBER BLEY: Okay.

MR. HAYES: And of course what's going to start up later this year is probably just some shakeout testing on UO_2 and Zirc. But next year, in '19, the first ATF concepts will be tested.

These will be unirradiated ATF concepts but the idea is as time progresses rodlets that are condition in ATF-1 and ATF-2 will be tested in TREAT.

We've already talked about the Halden test series that has to find a new home. There's a test series out here called commercial reactors, and that's LTRs and LTAs. And arguably that started this year, but it will certainly start next year with no dispute.

And then --

CHAIRMAN CORRADINI: So if I might just interrupt, for the commercial, maybe I'm misremembering but what's gone in right now are lead test rods unfueled. Correct?

MR. HAYES: Correct.

CHAIRMAN CORRADINI: Okay, you'll come back to that.

MR. HAYES: I'll address that seriously in about two slides. And then this test series out here envisions rods or rod segments that come from the commercial irradiations being refabricated, instrumented, and going through TREAT testing in the future.

MEMBER BALLINGER: Excuse ignorance, but are there any parallel test programs that are actually being wholly fund by the vendors?

MR. HAYES: I do not believe so.

MEMBER BALLINGER: Not even the chrome

coating?

MR. HAYES: The vendors working through the Halden joint program, I think, got a few things in the Halden over the last couple of years. That's probably the only thing that would fall into that category.

MEMBER BALLINGER: None in Europe?

MR. HAYES: Well, so Framatome is doing, has done a lot of doped UO_2 testing in Europe. Okay, that is true. And Westinghouse may have done some chrome coated cladding in Europe.

MEMBER REMPE: Later on I was going to ask this question but when they just do --

MR. HAYES: But that's somewhat speculation for me, you should address those questions to the vendors.

MEMBER REMPE: Later in your talk, I thought I saw some comparisons of data from the doped UO_2 but it was not with the cladding for ATF is what I was kind of wondering.

MR. HAYES: That's correct.

MEMBER REMPE: And so how they did because of high burn-up fuel interest probably. Right?

MR. HAYES: Right. So this is an overview of the irradiation testing that DOE is performing and plans to perform on ATF concepts. There's also LOCA testing that can be performed outside of the hot cell, outside of the reactor in a hot cell.

So in recent years DOE is has stood up a LOCA testing station in the hot cell at Oak Ridge that is modeled after a similar test stand that has been used for years at Argon.

So that's going to provide testing of ATF concepts as well. And then this slide talks about or highlights the near-term plans for leap test rods or assemblies in commercial reactors.

So here we are in '18, and as Dr. Corradini mentioned GE already this year, I think in February, put in some FeCrAl cladding tubs, they did not have fuel in them, into the Hatch reactor. But they have plans to come back next year with LPAs that include ironclad, which is their name for their FeCrAl cladding now.

As well as ARMOR which is their name for coated Zirc cladding that will have fuel in it in the Clinton reactor.

CHAIRMAN CORRADINI: But maybe I've lost it, what is the coating?

MR. HAYES: For GE?

CHAIRMAN CORRADINI: Yes.

MR. HAYES: I actually don't know what it is.

CHAIRMAN CORRADINI: It hasn't been revealed?

MR. HAYES: It has not been revealed. You would need to direct that question to them.

CHAIRMAN CORRADINI: Okay, that's fine. It was new to me, so I thought maybe you knew.

MR. HAYES: I do not know.

CHAIRMAN CORRADINI: It had a nice name.

MR. HAYES: Yes, it has a great name. Westinghouse this year established a fabrication line at Idaho for making silicide fuel. And next year their plans currently have beginning testing of chrome-coated ZIRLO and silicide fuel rod segments in Byron.

MEMBER REMPE: I was curious about this, they are just starting to get some fuel made out there in at MFC and now they're going to directly take it to Byron without any lab testing or ATR testing first?

MR. HAYES: No, no, silicide fuel has been, is in ATF-1, it's been irradiated --

MEMBER REMPE: Who made the fuel that's in ATF-1, is it --

MR. HAYES: Idaho.

MEMBER REMPE: Idaho made it, so this is like a larger fabrication line?

MR. HAYES: Exactly.

MEMBER REMPE: Okay, I didn't know, I was curious what was going on.

MR. HAYES: This fabrication line would be big enough to make full-size rods --

MEMBER REMPE: Okay.

MR. HAYES: -- for a commercial reactor. The fuel that's already under irradiation in ATF-1 and we already have some preliminary data for silicide fuel, was made at Idaho but not in the big line.

MEMBER REMPE: Okay.

CHAIRMAN CORRADINI: So can we go back a slide? I'm sorry, two slides. So are these all steady-state tests?

MR. HAYES: So ATF-3, the TREAT test series are transient.

CHAIRMAN CORRADINI: I'm sorry, TREAT is that. So are they transient with different time scales? In other words --

MR. HAYES: TREAT is capable of quite a spectrum of timescales.

CHAIRMAN CORRADINI: So it's in the ATF-3 plan to do power bursts as well as to do slow-ramp ups and ramp downs? You know what I'm asking?

MR. HAYES: I know what you're asking, and we've looked at TREAT for the slower ramps and --

CHAIRMAN CORRADINI: Historically, they've published data on that.

MR. HAYES: There is some that can be done in TREAT, and we'll try to make use of TREAT in that area to the greatest extent possible, but for doing a classical ramp test, TREAT is probably not the right one. The kind of ramp testing that Halden does, TREAT is probably not the right one to do that.

CHAIRMAN CORRADINI: Right, I'm kind of sandbagging you because I was at a meeting and one of the NRC staff at the meeting made this point. So then what are you going to do?

MR. HAYES: So this is all part of our Halden capability gap assessment and path forward work, but for classical ramp testing, BR-2 may have some capability. We think we can do something in ATR.

MEMBER REMPE: You have PALM cycle with --

MR. HAYES: Using a PALM-type device.

CHAIRMAN CORRADINI: I don't even, I'm sorry.

MEMBER REMPE: Our actual locating --

MR. HAYES: So we're into --

CHAIRMAN CORRADINI: If we're into detail we can wait until later.

MR. HAYES: Okay.

CHAIRMAN CORRADINI: But you answer my major question as to where does it fit.

MR. HAYES: We haven't forgotten ramp testing, but it's probably not TREAT.

MEMBER BALLINGER: I have question about this, which one of these concepts would require exceeding the 5 percent enrichment limit?

MR. HAYES: The one that probably challenges it would be GE with the FeCrAl cladding. So a lot of the work that GE's doing in the labs are helping them.

It's how thin can you go on the cladding and have enough strength and get a good weld. You increase the fuel diameter to try to buy back some of that neutronic penalty.

It's not clear you can get all the way there in the same assembly design so GE, I think if you talk to them, they might say they're looking at an alternative assembly design to try to save a load of 5 percent.

That's the one that challenges it potentially, and they're trying to make that not happen.

CHAIRMAN CORRADINI: We're a little bit off topic, but it's his fault so I'll pile on. The 5 percent is more a licensing of the fuel fan facility due to the necessary experiments versus an actual hard limit because there a supplier --

MR. HAYES: And transportation.

CHAIRMAN CORRADINI: -- and transportation.

MR. HAYES: That's right.

CHAIRMAN CORRADINI: Okay, fine.

MR. HAYES: That's right those are the real concerns. It's just the activation energy to get over that.

MEMBER REMPE: So before you switch to the modeling thing when Jon Carmack was here last time, I brought up a concern about what are you going to do with ATF fuel if you get to a high temperature than the control rod, will they liquefy?

And, you know, but what's the plan here? Are you going to reflood and all that? Have you guys done anything else about that?

CHAIRMAN CORRADINI: With all due respect to my colleague, they went away at TMI before the current fuel, so they go away.

MEMBER REMPE: Yes, but if we're claiming we have accident tolerance now, and we have, you know, reduced risk. We have increased safety. What I'm kind of wondering is, do we have an increased concern about an atlas?

MR. HAYES: So actually I would direct you to EPRI who's doing a lot of studies in this regard using MAP and MELCOR and from what I've seen, control rods may not be the second thing to go.

MEMBER REMPE: May not be the second thing?

MR. HAYES: Second thing to go, they may not be.

MEMBER REMPE: Well, I was concerned they'd be first thing to go because you're at lower temperatures, so you have a reactor with intact geometry.

MR. HAYES: EPRI is doing those analyses but from what I've seen them present --

MEMBER REMPE: The control rods are going to stay.

MR. HAYES: The controls rods do not go before fuel.

MEMBER REMPE: I mean at TMI, as Mike mentioned the control rods went, so I'm real curious because we used to talk about after the tolerance.

MR. HAYES: So DOE is not doing that assessment.

MEMBER REMPE: Okay, somebody probably needs to do something on that.

CHAIRMAN CORRADINI: But I mean we don't want to design your research program for you so we'll keep on going.

MR. HAYES: The last one just so I don't forget, Framatome is working this area as well so Framatome has already had some doped UO_2 fuel in LaSalle for a period of time.

And they're actually doing some pool-side exams on it this year, and next year they have plans to start chrome-coated in Vogtle testing in both.

So legitimately by next year, 2019, several years ahead of schedule, all the ATF teams will have things in commercial reactors.

MEMBER REMPE: But what was cladding the on the chromia-doped fuels?

MR. HAYES: It was nothing unorthodox.

MEMBER REMPE: So it wasn't the ATF cladding.

MR. HAYES: It was not the ATF cladding.

MEMBER REMPE: Okay.

MR. HAYES: Exactly. Okay, that's all --

CHAIRMAN CORRADINI: You did a great job.

MR. HAYES: -- the experimental background to set the stage. And now we're moving into the modeling area. And specifically for the next few slides, we're going to be talking about DOE's approach which is multiscale, mechanistic modeling of nuclear fuels.

We use this slide a lot, you've probably seen it, and we use it to try portray what we mean by multiscale, mechanistic modeling of nuclear fuels. The objective is to use hierarchical multiscale modeling for improved mechanistic development of models of fuel performance.

Okay, we're emphasizing mechanistic fuel behavior models because we think if we have mechanistic models that brings at least three benefits.

Number one is even if some of these mechanistic models require some calibration they should minimize form errors because they have physics built in they should provide insight where experimental data may be sparse.

And this remains to be seen, but the proposition is they may require less data for validation. We're not saying no data; we're saying less data.

MEMBER REMPE: Is that because of the physics-based approach?

MR. HAYES: Exactly.

MEMBER REMPE: Which you can't get data from MARMOT because so far your comparisons are with the integral data. Right?

MR. HAYES: So let me address that issue right now. That's what I'll do here. So these are the three scales that we typically talk about.

The engineering-scale is the scale at which most of your classic fuel performance codes operate at. That's the scale at which BISON operates. So BISON is in that model of classical fuel performance codes. Okay?

You're meshing up pellets and cladding, and you're getting engineering scale predictions of cladding diameter changes and fuel swelling and fission gas release and perhaps a probably of cladding breach. Things like that.

Now BISON by itself is just another fuel performance code, it has some advantages, but the real advantages come when you marry it to these lower-length scales.

And the two lower-length scales we talk about are the mesoscale, that's what the modelers like to call it. I call it the scale of microstructure. You're resolving microstructure, and that tool that DOE has developed to do that is MARMOT.

Okay, what MARMOT does is it attempts to simulate the micro-structure of fuel and how it changes, how it evolves under radiation.

CHAIRMAN CORRADINI: So let me ask you this, this is, I know colleagues that do this but I don't get it. So is MARMOT going to tell me fuel thermo-connectivity degradation theoretically?

MR. HAYES: Yes.

CHAIRMAN CORRADINI: Therefore I need an experiment to validate that. I'm just --

MR. HAYES: Yes and no.

CHAIRMAN CORRADINI: -- okay.

MR. HAYES: I'm about to address it.

CHAIRMAN CORRADINI: All right, because I'm just trying to nail down some properties --

MR. HAYES: You're right.

CHAIRMAN CORRADINI: -- at the grain that I get.

MEMBER BLEY: Before you go ahead, Steve --

MR. HAYES: Yes.

MEMBER BLEY: -- I'm not, we no longer have on the committee I think the person to ask the question I want to poke at here a little.

The detailed chemistry of what's going on here affects the situation well, and that's not physics, that's chemistry. Is that being picked up and modeled?

How well is that covered because as I understand it, this gets very complex on the chemicals side?

MR. HAYES: You're right, and there are some areas where we look at chemistry more explicitly, like in the metal fuels area.

MEMBER BLEY: I'm kind of hanging on where we heard how good the codes are now.

MR. HAYES: But to be honest --

MEMBER BLEY: And if we miss something in this area I don't know how good the codes are at all.

MR. HAYES: -- yes, there's not a huge amount work we've done on the chemical area.

MEMBER BLEY: It seems an area where we could go very wrong from the things I hear from experiments that, I'm not an expert there at all.

CHAIRMAN CORRADINI: I mean, I think where

Dennis is kind of, I know the colleague that we're missing, and he'd at least have ten questions by now.

But at least from my perspective, I'm just looking for an experimental basis such that if I see a deviation from the theoretical basis, I can then back out a) an explanation or at least b) an empirical correlation to modify.

MEMBER BLEY: Which is necessary but you need more experiments than one to cover these other sorts of things.

CHAIRMAN CORRADINI: Then you would planted.

MEMBER BLEY: Maybe a lot yes.

MR. HAYES: So let me get there in about a minute.

MEMBER BLEY: Sure, that's fine, that's fine.

MR. HAYES: I'm not ignoring you.

CHAIRMAN CORRADINI: By the way, you can tell us to be quiet.

MR. HAYES: Oh no, we're here to answer your questions. Seriously, that's what we want to do. Okay, so MARMOT is this tool that simulates how micro-structure changes under radiation.

And the real advance in recent years has been if I know what the microstructure looks like, even more so than chemistry, if I know what the microstructure looks like then I can accurately tell you what the properties of material are going to be and what the fuel behaviors are going to be.

Okay, that's the proposition. Now as I say that, MARMOT is a much more difficult tool to use than BISON. It requires a lot of inputs that are difficult to come up with experimentally.

And so that's the importance of these atomistic simulations. Now DOE NE is not developing any new tools to do atomistic simulations. We're using tools that are out there and well-known to people who work in this area.

And we're using them in a couple of different ways. In some areas, they do help us identify important mechanisms. But in every case they allow us to calculate material parameters at the microstructure scale that are important inputs to MARMOT.

So they really let MARMOT do what it does. And MARMOT tells us how micro-structure changes and then based on that we assess how properties and performance change.

And then we build new models based on that understanding which we implement in BISON. Okay? It is possible to run MARMOT and BISON in a couple fashion, but that's the main way of doing business.

The main way of doing business is doing the science and the simulations here at the lower-length scales, and building a mechanistic models that then gets implemented in BISON that can bring some of that physical understanding to the engineering scale.

MEMBER KIRCHNER: Now for somebody who's very naive in this area, you're getting information out of MARMOT that leads to modeling and BISON. That's an offline process or is this somehow built into the routine?

MR. HAYES: No, that's an offline process, that's a lot of work by expert scientists, exactly.

MEMBER BLEY: And a lot of that --

CHAIRMAN CORRADINI: So Steve in MARMOT a lot of it is presumed in advance, like the microstructure I would assume. So that you can evolve --

MR. HAYES: Exactly.

CHAIRMAN CORRADINI: -- analysis on grain boundaries and --

MR. HAYES: Exactly, so the input conditions to a MARMOT simulation are all these things.

CHAIRMAN CORRADINI: -- What does the micro-structure look like at time zero? I may have more to say about that at the end.

So to address this issue of validation. So everyone assumes that I have to do all my validation on a new mechanistic model at the MARMOT level.

First comment there is we are doing as much validation at the MARMOT level as we can. Some of the experiments needed to validate some of these results are difficult and complicated.

And we're undertaking some of them, some of the we just can or won't. That's doesn't mean that the models developed that this scale are not validation.

They get implemented in BISON and then BISON is validated on an integral level with these new models in it.

MEMBER REMPE: Is the empirical correlation you put into FRAPCON or FRAP-T?

MR. HAYES: It depends on the property, but for in since in the area of thermo-connectivity it's nothing like it.

MEMBER REMPE: Nothing like it at all.

MR. HAYES: In the area of gas behavior it's nothing like it.

MEMBER MARCH-LEUBA: I'm sorry, is that how you present it?

MR. HAYES: Pardon me?

MEMBER MARCH-LEUBA: Does it not reproduce today?

MR. HAYES: No, no, it does reproduce today. What I'm saying in response to Joy is the form of the, it's not just a polynomial fit to a new set of data that gets put into the BISON.

It's a more sophisticated formulation that attempts to retain as much as the physics from the lower-length scales as it can.

MEMBER MARCH-LEUBA: But again, it gives you the same answer.

MR. HAYES: Or better.

MEMBER REMPE: Well, it gives you answer between two data points you have. A long time ago we were going to do a science-based approach, and we could go and extrapolate beyond where the data is.

But right now, frankly, if you're saying you're validated, you have the same problem that you'd have with FRAPCON that you have to stay between the upper and lower bounds for where you've validated it because it sounds to me, and maybe I'm putting words in your mouth, you can't get all the data you need from MARMOT to validate those models you put into BISON.

So we shouldn't be going and extrapolating beyond their data. Right?

CHAIRMAN CORRADINI: But I mean --

MR. HAYES: Not for a regulatory discussion.

CHAIRMAN CORRADINI: So let me heretical, I'm sure there's somebody back in Idaho who's going to whack me good on this. If MARMOT is a stand-alone, so a neutronically it's like I built all my macroscopic squash sections then I go do my criticality calculations.

MR. HAYES: It's a cross-section generator.

CHAIRMAN CORRADINI: Right.

MR. HAYES: Exactly.

CHAIRMAN CORRADINI: Okay, so that could be put into FRAP-T or FAST.

MR. HAYES: Exactly, so there is truth to what you're saying there. The mechanistic models that are developed using MARMOT and these lower-length scale techniques, we are implementing them in BISON and then doing the bulk of our validation at the BISON level.

But someone else could implement those models in another code.

CHAIRMAN CORRADINI: Okay.

MR. HAYES: That is true, and has happened in some instances.

CHAIRMAN CORRADINI: All right, I'm not aware. The only reason I as is the analogy in neutronics seems very similar that you're going to do an offline pre-calculation, what I'll call needed macroscopic properties, and then do the --

MR. HAYES: That's absolutely correct. That's a good analogy.

MEMBER REMPE: If that's true then, the external inputs are the same, you'll look at burn-up, you'll look temperature of the core, things like that if I were trying take this new formulation and put it into FRAPCON or FRAP-T.

There's nothing else you're requiring that's not in FRAP-T or FRAPCON?

MR. HAYES: No, that's not always the case. In some cases, that may be the case, but in other cases it's far from the case. So, for instance, thermo-connectivity and its degradation.

The model or correlation in a legacy code may be, you know, temperature, and O-to-M, and burn-up, and that's all you need. And for the assessment in the models, we use you need some micro-structural information that the legacy codes may not have.

MEMBER REMPE: Such as.

MR. HAYES: Grain size, grain size distribution, porosity, not just a value but some knowledge about --

MEMBER REMPE: So you have knowledge about that for the whole core, all the fuel in it? I mean, are you just taking an average value for porosity? I mean, are you doing --

MR. HAYES: Well, so for the MARMOT simulations we have good knowledge for development of the model. Now, you're right, you get to the engineering scale, and you're probably not going to have all that information available for every PIN, so you have to make some assumptions.

MEMBER BALLINGER: You probably realize now that you're talking to a bunch heretics but let me ask an obvious question. If MARMOT can't be extrapolated, if BISON can't be extrapolated then what is the value of doing this other than capturing margin in an accident or something like that?

So and if it's capturing margin, how much margin do you get back, do you think you're going to get back. Like, for the example, in the infamous 50.46 hit area, how much margin do you think you're going to get?

MR. HAYES: So there may be, may well be some utilities or vendors who want to go after margin. We think these will be tools that will help them. I can't answer quantitatively that question.

But let me answer the first part of your question by saying I don't see these tools as being accepted in the near-term making extrapolations beyond experimental databases in a regulatory environment, a licensing discussion.

But vendors could use these tools in spaces like that to give them insight for things they want to go after. Now they may have to go and collect a data point there to have a discussion with the NRC.

But it gives them a tool, an informed tool, maybe not a well-validated tool in these far-reaching areas.

But a tool with enough physics into it they can do some meaning exploration. That's the way DOE, this is the way the lab people use it. We use BISON in some of our advanced fuel development areas like metal fuels for fast reactors.

And this is the way we use the tool to find places we'd want to look at more closely.

MEMBER BALLINGER: Again, another heretical question, Company X begins with an F decides that they might want to use this. They've got to make a judgment on the value to them.

MR. HAYES: Right.

MEMBER BALLINGER: And that means to them how much money am I going to make if I make use of these tools to improve my design? So --

MR. HAYES: You're right, and that's an evaluation they have to --

MEMBER BALLINGER: -- they have to be convinced that there's going to be a margin.

MR. HAYES: Exactly.

CHAIRMAN CORRADINI: So Chris mentioned this earlier, and I'll mention it again at the end. DOE doesn't see it's role or even its ability to take every one of these tools all the way across the finish line and say, "This thing is validated entirely for your specific fuel design.

You just need to go pick it up and go have the conversation with the NRC. We're taking it far enough to give that vendor confidence. This is really a tool that can provide me some benefit.

They're going to have to step in and do some proprietary validate of their specific concept to add to the broad base that broad base validation that DOE has done. To have those final conversations with a regulator.

MEMBER KIRCHNER: Steve, to what extent has MARMOT been used to --

MEMBER BALLINGER: There's a wealth of data out there, for existing fuel. To what extent have you validated MARMOT and its ability to predict evolution of structure under irradiation and thermal effects.

MR. HAYES: So MARMOT does have it's how what we call assessment report that's built up every year. More and more validation cases are added to it. And --

MEMBER KIRCHNER: So how well --

MR. HAYES: In certain areas, it's undergone a lot of validation, like grain growth which is incredibly important, grain grown and densification. You'll find a lot of separate effects or experimental studies in the MARMOT assessment support show that it can simulate things like that well.

CHAIRMAN CORRADINI: So we want you to get through you introduction so we can go to break.

MR. HAYES: Thank you, okay it won't take much longer probably.

MR. JOHNSON: I know, that's why I brought it up.

MR. HAYES: Okay, so that's what we're trying to do. So all of this stuff down here is basically building models. And anyone can jump in and play in this area if they want to but this is a more technical area to operate in.

MEMBER MARCH-LEUBA: Yes, that's a concern I'm having here is, if you give this to a vendor, do they have anybody who knows how to use it? Or do they need to hire somebody from a lab that's been working on it for the last ten years.

MR. HAYES: Exactly, so a vendor wants to use BISON and have the basic models in there that already do most of what they need. And that's what DOE views as its role.

MR. STANEK: But we're starting to see that the vendors are hiring people like that.

MR. HAYES: Some vendors want to do this, they're the minority, but some do. Okay, three or four slides and then it's probably a good time for a break.

So high-level BISON overview. BISON is the fuel performance code we've been talking about. I'm going to have one slide on overview and then a few slides discussing issues related to verification and validation.

So the high level view of BISON. BISON is a MOOSE-based application. I'll say that right up front, it's built on the MOOSE platform, if you know what that means it means something to you, if you don't, it's not super relevant to the conversation.

But being a MOOSE-based application BISON is a finite element-based tool for doing fuel performance. It solves the fully-coupled thermo-mechanics and species or mass diffusion equations in as many dimensions as you want to do it, one, two, or three-D.

It's applicable both to steady-state and transient, so this is a big step forward in fuel performance tools, one code does both.

It has capability and used for L-W-R, conventional L-W-R fuels, ATF, TRISO, metallic fuels. Again, this is a bit of an innovation, but one fuel performance code does it all.

CHAIRMAN CORRADINI: If we get to it

later, then I'll stop, but I was under the impression that from the standpoint of a similarity if I had FRAPCON and FRAPTRAN together ,the capabilities are similar.

MR. HAYES: Exactly.

CHAIRMAN CORRADINI: The end-state capabilities are similar, how I got there are different.

MR. HAYES: Right.

CHAIRMAN CORRADINI: The one that confuses me is --

MR. HAYES: The BISON is one code that does what the tandem of FRAPCON and FRAPTRAN does.

CHAIRMAN CORRADINI: -- the one thing that confuses me, when you say TRISO, the kernel or the actual compact? Because --

MR. HAYES: Vastly more has been done on the particle, the coated particle.

CHAIRMAN CORRADINI: So we're talking 200 microns, 250 microns versus the compact which is really the issue at hand with the --

MR. HAYES: But there's been plenty of work, BISON can do the compact too.

MEMBER REMPE: Did you take the PARFUME models and put them into BISON or did you do something different?

MR. HAYES: That's always the first step, you put into BISON the existing model. In TRISO's case, PARFUME models, then you work on developing more mechanistic models to replace the legacy, the legacy models as they become available.

I'm going to skip these next two because I'll say something about that in a minute. But not just transient, we're talking about full LOCA and RIA simulation capability in the case of an LWR.

CHAIRMAN CORRADINI: So I mean, okay, but for RIA I thought BISON was limited like FRAPCON and FRAPTRAN that they can't go to melt?

MR. HAYES: It doesn't have models in it currently to progress past melt.

CHAIRMAN CORRADINI: And my understanding was now we're getting to what I thought you were saying is legacy codes was FRAPTRAN and -- ,but I thought staff was developing FAST which actually can go beyond that for their fuel performance.

MR. HAYES: So I'm not able to speak of that.

CHAIRMAN CORRADINI: That's fine. Okay.

MEMBER REMPE: So you can't do melting but do you, I mean, fuel starts degrading before it reaches melting temperatures with cladding, you can't even liquefy and have cladding fuel interactions with the Zircoloy. Right? Or the ARMOUR or whatever it is.

MR. HAYES: The first models are not going to track a liquid phase. And then the last point to speak directly to your issue of before is BISON, MOOSE which is the framework, and BISON which is the application were stood up from day one to follow an NQA-1 development process, and that has never changed.

What makes BISON different? We try to illustrate that with these four little captions. BISON in one sense is like any other classical fuel performance code, but in certain respects, it can be quite different.

The first, and at least three, and really all four of these have some direct relevance to ATF. So one thing is it truly is a code that can handle arbitrary geometries with its finite element formulation.

There's no geometry it can't handle so if your ATF concept is non-cylindrical, no problem for BISON. It was built from the very beginning to go after multiple fuel packs. So the way the models and the properties and the behavior models are implemented in the code, it's very easy to introduce new models that have an application to a particular fuel or not.

So this is where most of the ATF concepts are going to fall, they're going to need new models for certain types of behaviors and BISON readily accommodates that.

A third capability and this is what comes with any MOOSE-based application is coupling to other codes. And this may not be a high priority thing in every instance, but in some cases, you may want to couple fuel performance to some other type of physics to do a coupled simulation.

The picture here is of BISON coupled to TREATS, and actually Jess, Jess will say something about that in his talk later. But BISON and any MOOSE-based application really is designed to facilitate coupling to other codes.

And then lastly all MOOSE-based applications, BISON, being the flagship are designed to operate efficiently on a high-performance computer. Not let me immediately dispel a few myths.

You do not need a high-performance computer to run BISON. You can run it on your desktop computer. Most of our developers and users do that, as long as your problem's simple enough. But if you want to develop or need to develop complicated, difficult problem and run it in 3D or something like that BISON is designed to be thrown out on high-performance machine and operate very efficiently.

So if you need that capability, you've got it.

MEMBER REMPE: What about ease of use? Like, again, I know you can answer simple models, easy to get going and things like that. But how difficult is it to develop models to learn to use them?

CHAIRMAN CORRADINI: A think a regular fuel, a fuels engineer that's used to you know developing FRAPCON input files or what have you won't find BISON terribly more challenging. There'll be a few things that will have to be done differently.

The biggest issue is if you need a complicated geometry you're going to have to generate a mesh. And certainly, a BISON just automatically can do a cylindrical geometry and things like that.

But if you want to develop a complicated geometry, you have to build the mesh for it.

MEMBER REMPE: So it's not been keeping up, do you have like user works shops and training things? Do you even have an Internet?

MR. HAYES: Oh, yes.

MEMBER REMPE: I guess you can't have an international community but university -- Now there's a big BISON user community, BISON training is done at Idaho typically a couple of times a year. And we take training on the road if someone asks for it.

MR. HAYES: If someone asks for it.

MEMBER REMPE: Is it mainly universities that come? Or is it plant staff or university, or vendor staff or whose?

MR. HAYES: There's considerable universities but also a lot of lab people and vendor people.

CHAIRMAN CORRADINI: So how are you going --

MR. HAYES: NRC, NRC.

CHAIRMAN CORRADINI: So how are you going with your four slides?

MR. HAYES: Pretty good. Verification, this one won't take long, but MOOSE and certainly BISON is supported by the thousands of unit and regression tests that follows all the standard protocols, all new code. Must be supported by verification testing.

All tests must pass prior to merging it with the official version if anything gets flagged as a problem it won't be merged until though programs are resolved. Again, hitting this issue of NQA-1 of BISON is regularly per NQA-1 standards, and it's always satisfactory.

We provided some documentation in advance on verification, things like that. One of the things we gave you was this journal articulate which does a good job summarizing where we stand on BISON for verification.

Verification in certain senses is easier than validation. So validation is obviously the bigger task and so a couple slides, and then I think it's time for a break on the status of bison validation for conventional LWR fuels.

So what we're talking about is for UO_2 and Zircaloy. You can see her 75 integral and ramp type experiments are in the assessment database. A 47 LOCUS matching RIAs. I just give you these numbers.

You can go look at all the specifics in the assessment report to say, "These types of numbers are very similar to a FRAPCON, FRAPTRAN-type assessment base.

Now as is already mentioned some vendor's come along and they have proprietary that DOE, in general, doesn't have access to. And they do some additional validation, so there are some assessment reports out there that are proprietary that have additional data. But what you'll find in here is the open stuff that the DOE has done.

MEMBER REMPE: How does the interface work because they have a version that they've used and they've validated it and has their proprietary reports. And then you guys change a different model, and so now version X is version X+1.

Have you had any interference with it?

MR. HAYES: There's a couple of ways that manifests itself. One, at the end of every fiscal year there is a frozen version of BISON because some people lack frozen versions of BISON, and an assessment for a report role out with everything, with all the results, you know, tied very specifically to that frozen version.

That being said, all of the assessment cases are rerun every night. And anything done to the code the previous day that disrupts any agreement, you know, comes back with some sort of a red flag.

And so those tend to resolved right away so even though there's not going to be a frozen version with a published BISON assessment report until the end of the year, on any given day of that year the version of BISON that is operating is essentially validated to that state.

But again, vendor has done something different. Have you ever had them call up say, "Hey, a year ago it worked, and now it doesn't." I mean, there's always something that you didn't get with your kid's case.

MEMBER REMPE: And you've had that happen so far and figured it out?

MR. HAYES: There's a ticket tracking thing. Any user can put in a ticket, "Hey, something's wrong, and it gets resolved." Absolutely.

MEMBER REMPE: If you've ever used it before -- okay.

MR. HAYES: Now a lot of these vendor assessment reports through the vendor may not have modified the code. In some cases, they may, but in many cases, they haven't modified the code they just have more experiments from Halden that were, you know, proprietary, so they just have additional data to compare to.

MEMBER REMPE: Okay.

CHAIRMAN CORRADINI: But if I, I know we're delaying you, but if I have, I'm still trying to think through the connection. So I've got BISON and

I know BISON is maybe the source is not public but I've got a public version which Company X and Company Y adopt.

Company X and Y may change the correlation --

MR. HAYES: They may.

CHAIRMAN CORRADINI: -- and that becomes the proprietary thing which they must then submit to the regulator for a review and analysis.

MR. HAYES: And then the full burden of validating that version is on them.

CHAIRMAN CORRADINI: Right.

MEMBER REMPE: Right.

MR. HAYES: Even in that case they're going to be able to take credit for things we've done.

CHAIRMAN CORRADINI: But to get to Joy's and Jose where they're talking about modifications then they have to continually do a comparison check with the base version with whatever their proprietary changes are.

MR. HAYES: That right.

CHAIRMAN CORRADINI: Okay.

MEMBER MARCH-LEUBA: And whenever they approve this they will put out a specific version if you don't approve an SER the most recent version that

INL published.

MR. HAYES: Understood, you're right, and this is why we periodically have these frozen versions. We understand that in the regulatory space that's the way it's going to need to work.

The assessment report is massive, and you probably don't want to look through it but we've given you also a real nice paper that kind of summarizes the high-level results of BISON compared to LWR's.

And then this is the last one. So if you look at the assessment report, I mean, it will go experiment by experiment, this is how the rod functioned, and these are the data collected and compares to that specific experiment.

But also in the assessment report, you'll find these higher level analyses where everything is brought together. How does BISON do just overall in getting fuel temperature correct or PCMI or fission gas release or something related to LOCO?

So that's all in the assessment report as well, and the punch line is I absolutely believe is that you're going to find BISON for standard LWR is state of the art.

I mean, it does as well or better than any code out there.

MEMBER MARCH-LEUBA: Have you done a comparison those pound lines there, the plus/minus along these lines, how does this compare to FRAPCON.

Is it have or is it twice?

MR. HAYES: Jason, what would you say about that?

MR. HALES: About the same.

MEMBER REMPE: You have to come up to the mike and say your name. You just can't answer, sorry.

CHAIRMAN CORRADINI: He did it to you, go on up.

MR. HAYES: So this is Jason Hales he manages the BISON department.

MR. HALES: I'm Jason Hales from INL, this answer's going to be pretty much a letdown because I can't answer for FRAPCON. I don't know how it compares honestly. What I do know is that Steve said, "If you can compare the BISON results to the experimental data it compares very well, and we're comfortable with it.

MR. HALES: I'm Jason HALES from INL. This answer's going to pretty much a letdown because I can't answer for FRAPCON. I don't know how it compares honestly, what I do know is that Steve said, did he compare BISON results to the experimental data it compares very well and we're comfortable with that.

How it compares to another code is that something that we've. We don't take time compare our output to the put of another code. We prefer to do validation and compare the data, the experimental data.

CHAIRMAN CORRADINI: So let me ask it from an uncertainly standpoint. So I've got a set of experiments they have their own internal uncertainty. Does it fail within the uncertainty band of the data?

MR. HAYES: Yes, we're very comfortable with that. That's another whole issue, the uncertainty with a lot of these experiments is rather large, sometimes uncomfortably large. Things like the power in the reactor are not known very well.

And so given all the uncertainty, yes, we're very comfortable with where the experimental data lies.

MEMBER REMPE: So if I look at your fission gas release spot and I blow it up on my little computer to see, it doesn't, I mean it looks like there are more thanks that are showing higher measured than I predicted. Am I right?

MR. HAYES: So performance is not measured on the same scale for every property. So for fuel temperature, you typically look at plus or minus 10 percent. Okay, for fission gas release you typically look at plus or minus a factor of two. But this is true for all codes.

MEMBER REMPE: So other codes probably would also be below the line on that one too. Is that what you're saying?

CHAIRMAN CORRADINI: We're going to have to separately check that out.

MEMBER REMPE: Yes, I just was kind of curious. Also, on your material properties --

MR. HAYES: And there's a good discussion of that in this paper.

MEMBER REMPE: Okay, and the material proprieties did you start off with like, something like map probe that has, is a function of temperature and burn-ups for all those. And so when you talk about the ATF later today, you'll talk about what you do when you don't have some of the properties.

MR. HAYES: So the very first thing, almost, I don't know if it's day two or three of BISON development, they linked in all of the MAP properties and models.

But over time, you know, those proprietary and model and behavior models get updated with better models. That doesn't mean you can't still select the MAP probe data if that's what you want to do.

MEMBER REMPE: Oh, okay.

MEMBER MARCH-LEUBA: I'm just the additional report, it defines well the range of public ability, for example, all those red and blue elephants were showing there are for PWR.

That doesn't mean you work for a build-up like you are.

MEMBER MARCH-LEUBA: Is very important for your evaluation.

MR. HAYES: Yes.

MR. HALES: And it is well defined?

MR. HAYES: Yes, in the assessment report it's well-defined.

MEMBER MARCH-LEUBA: If it gets approved now, approved SER, it will have a bunch of limitations. And yes, if I were you, you can predict UO_2 doesn't mean you can predict the silicide.

MR. HAYES: Oh, of course, of course yes.

MEMBER MARCH-LEUBA: That's what I mean. You really feel that you have to keep in mind that whenever you product this you have to say, I can use it for --

MR. HAYES: Exactly, if all this was to

set the stage for our model enhancements for ATF to say that they BISON we have, and the multiscale modeling approach we've has borne out good results applied to UO_2.

So the advertisement is we're going to approach these ATF concepts in the same way, use the same methodology, and over tie we should get similar results. That's the proposition.

CHAIRMAN CORRADINI: Okay, why don't we take a break, and come back at 10:30 and shockingly we're not so bad in time.

(Whereas, the above-entitled event went off the record at 10:18 a.m. and resumed at 10:30 a.m.)

CHAIRMAN CORRADINI: Okay, so I think Steve we gave you a break and now you're back on.

MR. HAYES: I appreciate that, yes, and we're going to try to accelerate a few things. A lot of what we have going forward for the rest of this is just a status of where we are on the different concepts and maybe not so much discussion is needed but as much as is appropriate.

So model enhancements for ATFs, so all that was to set the stage to allow me to say that DOE believes BISON is a state of the art field performance code.

It hasn't reached its final state even for UO_2 and Zircoloy we're continuing to develop new and improvement mechanistic models that are going to improve it.

But even where it is it's exceptionally well verified, it's extensively validated, and we would say ready for use for current LWR fuels for anyone who would want to do that.

But all that is to say that in our judgment, BISON is the right platform on which to implement enhancements to simulate accident-tolerant fuels.

And DOE started doing this back in 2015, so in 2015 DOE-funded what it called a high-impact problem, a HIP, on ATF. And Jason Hales who I called to the microphone a minute ago, was the PI on this project and if you have a lot of detailed questions moving forward, he'll probably answer a lot of the questions.

And what the HIP was was a concentrated three-year where DOE spent $3 million a year for three years to sort of jump start ATF modeling in the MARMOT/BISON world.

Now the HIP ended in 2017, but that

doesn't mean that DOE has stopped its support. ATF is an integral part of any modeling programs moving forward since that time.

And the fuel modelers working in the area of BISON and MARMOT have a very close working relationship with the ATF programs and personnel both at the laboratories and the industry teams.

Particularly with a view to the test programs that are going on and the data that will be coming out of them because that will be critically important.

MEMBER REMPE: Which, so they modeled all of the concepts for all of the vendors that you showed earlier on Slide 5. Right?

MR. HAYES: That's what we're talking about --

MEMBER REMPE: For the HIP, they did consider each of the vendor fuels?

MR. HAYES: No.

MEMBER REMPE: One of the vendor fuels?

MR. HAYES: I have a slide especially for you on that.

MEMBER REMPE: Just for me? Okay.

MR. HAYES: I'm going to explain that.

MEMBER REMPE: Okay, I thought it would

be an easy answer.

MR. HAYES: It's better if you see it than just hear it. Okay, so this slide just is meant to communicate that we're not reinventing the mechanistic modeling approach.

We're using the approach that DOE's been using in the area of fuels for the last nine years. And it's sort of a four-pronged approach, and that is any time you start with a new fuel in the BISON framework, you just stand up basic properties and model for behavior using anything that you have, a legacy models, or adapt UO_2 models or there may be existing models for some of these materials.

Just to get BISON up and running, all the while then you're working on developing new mechanistic models using these lower-length scale techniques that I've discussed.

And this is where a ton of the work is going on in ATF right now. Another important thing is sensitivity analyses, when very early in the development of Bison it was coupled to Sandia's DAKOTA code.

And so we run DAKOTA with BISON regularly to do sensitivity analyses especially when we're starting in a new fuel. We do sensitivity analyses to help us prioritize what properties or what behavior models for a given fuel type have the biggest effect.

And then we use that to prioritize which mechanistic models we work on before others. And then ongoing assessment and validation is this part of the process.

Okay, Joy, this explains, this is the highlights from the high-impact problem. So when the HIP was originally stood up in 2015, silicide fuel and FeCrAl cladding were the two big concepts getting the most attention then.

So the way the HIP was written and the way it started it focused mostly on these two systems. But before the HIP was over, coded, cladding concepts and doped UO_2 were emerging as interesting concepts as well.

And so they were brought into the HIP in the later phases as well. So these are specifically things that the HIP addressed. The program since the HIP has expanded to include even more.

MEMBER REMPE: So again I was just trying to understand what the objective of the high-impact problem was and it sounds like it wasn't really an analysis problem it was more trying to expand the capabilities of BISON to address what was perceived to be an accident-tolerant fuel assisted time.

It was more model development --

MR. HAYES: That's exactly right.

MEMBER REMPE: It was a lot more model development than a problem that you tried to analyze.

MR. HAYES: That's exactly right. Enhancing the exhibiting tools to address emerging ATF concepts. And the idea early on was to provide a tool to DOE to help assess the ATF concept they were funding.

MEMBER REMPE: So again, where I was kind of going on that question eventually was that my understanding is that there's not a lot of high-temperature data and there's not a lot irradiated mater proprietary data for these materials

And so some of you properties you've put in for ATF are guesses, right, and --

MR. HALES: In some cases that would be true.

MEMBER REMPE: And this would hopefully help you focus?

MR. HAYES: We have some tables coming that try to summarize where we stand for the various concepts. And not every box is checked on every concept, you're right.

Okay, so this is the table that attempts to give the 30,000-foot view of where we are on all these categories of ATF features from doped UO_2, coated cladding, FeCrAl cladding, silicon carbide, silicide fuel and metallic fuel.

And so this first column says we have a complete set of models for what you see here. So that means there's a model that allows you to do a simulation of all these concepts.

For some, it's better than others. For doped UO_2 fuel, we've spent a lot of time looking at the fission gas release modifications needed. Much less so for the mechanical response but we expect there to be some, so we're not completely there.

Coded cladding as you say, we can simulate coded claddings now although there's very limited actually there's no irradiation effects yet. FeCrAl is in pretty good shape. Silicide fuel, metallic fuel in good shape. Silicon carbide cladding we'll be the first to say that's a work in progress. We can do simulations of it but only recently has that reached that level.

So you can see the yes or no, on the evaluation, on base irradiations, so we don't have any irradiation data yet on coated cladding or silicon carbide as a cladding, although, there's a lot irradiation data on silicon carbine.

CHAIRMAN CORRADINI: Was the doped UO_2 fuel irradiations vendors supplied or you did?

MR. HAYES: In my anticipation, it was vendor supply.

MR. STANEK: The answer's both, so there are priorities, as far as we understand there are proprietary irradiations that have been done on doped UO_2 as Ron was mentioning, in Europe.

But there are open Halden tests that have, in particular, fission gas release data for doped UO_2.

MR. HAYES: In fact, we're going to show one of those.

MEMBER KIRCHNER: Just looking at the right-hand column, it's improved fission gas, diffusivity for fission gas, are you seeing much later fission gas release with doped UO_2 fuel?

MR. HAYES: We're seeing lower.

MEMBER KIRCHNER: I'm misreading that. So you're seeing what, Steve?

MR. HAYES: These are the areas where we are continuing to focus the work.

MEMBER KIRCHNER: I could see you might be improving your diffusivity model but are you seeing higher release of fission gas and doped fuel?

MR. HAYES: Well, I think in general we're seeing lower fission gas release and doped.

MEMBER KIRCHNER: So this more about your model and you estimating --

MR. HAYES: This is about the model.

MEMBER KIRCHNER: -- of the fission gas release not the performance of the fuel. Right?

MR. HAYES: Exactly. This is an evaluation of where the model stands, not an assessment of the concepts.

MEMBER REMPE: I'm curious support user needs. In NRC space, if they use or need something they belong to the user group. Do you have somebody that has metallic fuel who's paid to join your user groups and you're supporting their user needs?

Or is this DOE decides how much each user gets?

MR. HAYES: So there are, the user support bucket is not an unlimited bucket. But I think the team does a good job of supporting needs. So you mentioned metallic fuel. We actually have one vendor who has a fairly aggressive way of working with us, and we're trying to address needs that they have.

A lot of these needs come from the DOE program developing metallic fuels as well. Not for ATF applications.

MEMBER REMPE: Yes, but this is an ATF slide, so that's why I was curious. Okay.

CHAIRMAN CORRADINI: So let me, I don't want to, if you're finished I have a question, kind of an overall question.

So my interpretation at least from the yes and nos that BISON is similar. I keep on doing a comparison in my mind because I'm unfamiliar with BISON. BISON is similar to FRAPCAN and FRAPTRAN for normal operation in AOOs.

And where does it extend it into DBAs? In other words, to put it more crudely, what does it off technically that isn't already there in the current code set?

What I hear is it might be doing it faster better from an uncertainty standpoint, but in terms of the current code set, it's similar.

Am I understanding this though?

MR. HAYES: Similar.

CHAIRMAN CORRADINI: Okay, fine.

MR. HAYES: Faster and better, similar.

CHAIRMAN CORRADINI: So if you were to go to, well, now let me ask my second question. So maybe I misheard Chris when he said it earlier. Your industrial support group or NEI support group, I'm not sure what it is.

But we'll call it industry advisory group has told you you cannot tell us who's adopting BISON from the industry? I'm pressing this point because you took my surprise, I figured you come up here wave a flag and say, "Company X, Y, and Z are adopting it, and ergo it's clearly better than what they've got and therefore you guys ought to consider it."

But I heard the exact opposite which took me by surprise.

MR. HAYES: So let me clarify those initial comments. So the industry council that I was referring to is specifically focused on non-LWRs.

CHAIRMAN CORRADINI: Oh, okay, fine.

MR. HAYES: So that group does not --

CHAIRMAN CORRADINI: Okay, I misheard.

MR. HAYES: -- talk about ATF at all.

CHAIRMAN CORRADINI: So then I'll ask the question now since we need three actors in the game --

MR. HAYES: Exactly.

CHAIRMAN CORRADINI: Framatome, Westinghouse, and GE, which one of them has decided to take BISON as their base tool for their safety analysis justification for ATF?

MR. HAYES: I don't think any would say that.

CHAIRMAN CORRADINI: Why?

MR. HAYES: That being said, both Westinghouse and Framatome have test stands that they're evaluating --

CHAIRMAN CORRADINI: Oh, fine.

MR. HAYES: -- BISON with.

CHAIRMAN CORRADINI: So they're in the process --

MR. HAYES: They have now announced --

CHAIRMAN CORRADINI: They're in the process of evaluating.

MR. HAYES: -- the decision was made that we're using BISON. But they're both, they're using and testing BISON.

CHAIRMAN CORRADINI: So they're evaluating.

MR. HAYES: They're evaluating BISON.

CHAIRMAN CORRADINI: Okay. Okay. Thank you.

MR. HAYES: Okay. So that's the high level overview. And now we're going to have a status on each one of the concepts in particular.

So doped UO2 model summary, so the first column assesses whether or not there's a model in BISON. And in some of these cases for the types of doping we're talking about, you're not expecting significant changes in basic material properties. And so a lot of times you can make use of regular UO2 data.

As I've already mentioned, we know there's some work to be done in the area of mechanical behavior for doped UO2. And that's not in the code yet.

Most of the effort that has been put towards this concept is towards understanding fission gas release. And just as an illustration --

MEMBER REMPE: Could I -- I'm sorry. Could you go back? That LLS-informed, that's the MARMOT-informed --

MR. HAYES: This means we're working on -- so, in almost all these cases, we're working on mechanistic models that will ultimately we believe make it into BISON.

If there's a no here, that means there's no model in BISON that's been developed from this mechanistic process in this category.

But in the area of --

MEMBER REMPE: Is that the MARMOT?

MR. HAYES: -- thermal conductivity degradation and fission gas release, the answer is yes. There are models in BISON today that have been informed by this lower length scale process.

MEMBER REMPE: But LLS, that's really the MARMOT informing of BISON. So you don't have any MARMOT models in BISON. You just have a regular empirical fit for thermal conductivity degradation?

MR. HAYES: Thermal conductivity degradation is in the area where there's --

MEMBER REMPE: There is a MARMOT one. But for the other ones, for like mechanical properties, there's no MARMOT --

MR. HAYES: There's no MARMOT model.

MEMBER REMPE: -- informed modeling.

MR. HAYES: Exactly.

MEMBER REMPE: Okay.

MR. HAYES: I said not all the boxes were going to be checked.

CHAIRMAN CORRADINI: Oh, yes. That's fine. That's fine. That's fine.

MR. HAYES: But this is a work in progress.

CHAIRMAN CORRADINI: Understood. What is a basic thermal property?

MR. HAYES: You know, un-irradiated thermal conductivity and thermal expansion, these material properties --

CHAIRMAN CORRADINI: Oh, thermal expansion.

MR. HAYES: -- things like that, specific heat. These basic properties, un-irradiated, you know, that have to go in.

MEMBER REMPE: So --

MR. HAYES: And then you work on the degradation under irradiation and things of that nature.

MEMBER REMPE: So the data for developing this model was because of the fact that they did some testing of Cr2O3-doped UO2 fuel without the cladding for ATF. Is that a true statement, too?

MR. HAYES: That's right.

MEMBER REMPE: I think that's what you told me earlier, right?

MR. HAYES: That's right. So experimental data means we have some data in hand to begin evaluating the modeling that we're doing.

MEMBER REMPE: But in some of these

properties, I could see, it seems like some of them might be influenced by the cladding. Like would the creep not be influenced by the cladding and --

MR. HAYES: The creep of the fuel? Not really.

MEMBER REMPE: Not in any pellet-clad material and mechanical interactions?

MR. HAYES: That's certainly a phenomena that has to be addressed. But I don't think the creep model of the fuel itself is impacted by --

MEMBER REMPE: Okay.

MR. HAYES: -- those considerations.

And so, like Chris was saying, we have this Halden experiment, this rod from a Halden experiment, which was an irradiation of chromia-doped UO2. It wasn't sponsored by the ATF program. But this is data we're assessing against.

And so you've got online temperature measurements that we're comparing to and fission gas release.

And a word of caution here is this rod operated at very high temperature, a higher temperature than would be the norm. And so it released much more fission gas than would be expected in normal operations of an LWR. That being said, the

BISON is predicting it or reproducing it fairly well.

And the reason we like looking at experiments like this, in general, if you're familiar with fuel modeling, it's much harder to get good agreement on high fission gas release results than low fission gas release results.

And so don't look at this and think that chromia-doped UO2 is going to normally release 15 percent of its fission gas. It won't. In fact, the trend is it releases less than undoped UO2. But the models are working fairly well.

MEMBER BALLINGER: You caught me by surprise. At 15 percent, it's not going to make any difference. Where it really makes a difference is at the low end for real operations.

MR. HAYES: No, I agree. But my point was it's easier to find agreement with those low fission gas release measurements. It's harder to get agreement with the higher values. The higher values are only going to show up under more extreme conditions.

Chrome-coated cladding, so this was actually added later in the process than you might imagine. But there's certainly functional models now in BISON to model chrome-coated cladding. We're beginning to get experimental data that we need to do assessments.

This is an area, it's a pretty simple modification to BISON. We don't have any lower length scale work that has fed into that. And it's not clear that it's needed in the near term.

One thing, I thought there was an asterisk here. It might have gotten deleted. In the area of creep, this footnote goes with creep.

We don't have any irradiation performance effects on chrome-coated cladding currently. So that's an unknown. Although, we have chrome-coated cladding in ATF-2. And we'll be getting data.

And so, as an example of simulations of coatings using BISON, you can see them here. So we don't have a lot of experimental data.

So what you see here is sort of a study where we're comparing the mechanical response of coated versus non-coated Zircaloy cladding. So this is the strain results on Zircaloy for instance, and then how that changes when you add various thicknesses of coatings.

And in these two cases, the coating that was added was FeCrAl. Now, none of the vendors are looking at FeCrAl as a coating. Although, MIT has a research project where they're looking at FeCrAl as a potential coating.

But the reason is because when these analyses were done we didn't have all the data we needed for the chrome coating, which we do have now.

We did look at chromium early on. And we didn't have a chrome creep model. And that led to unrealistically high stresses. So we knew we had to get that in.

But what you see in these two cases where it's a FeCrAl coating of 20 microns or 40 microns is the coating is pretty stiff. It's much stiffer than Zircaloy. And it adds considerable stiffness to the cladding overall. And chrome follows this behavior, although probably not to as great of an extent.

But one thing that became apparent to us is someone could use BISON as a tool for optimizing cladding or coating thickness, for instance.

FeCrAl cladding, here's the basic status report, good models in BISON that allows you to do a calculation, to do a simulation. We don't have yet any data on irradiation creep. But FeCrAl cladding is in Hatch, as we've already mentioned. It is in ATF-1. And it will be going into ATF-2 this next year.

This is an area where we have lower length scale, you know, mechanistic model development going on in the area of mechanical properties and creep.

CHAIRMAN CORRADINI: So, just a side question, there's so much other zirc in a BWR that if this is really accident-tolerant, the cladding may not be the driver. I could magically change out all the cladding and still have a problem. I'm assuming --

MR. HAYES: Understood.

CHAIRMAN CORRADINI: -- you're aware of that.

MR. HAYES: We are aware of it.

CHAIRMAN CORRADINI: Okay.

MR. HAYES: And there are projects looking at alternative materials for channel boxes and things like that. That's not part of --

CHAIRMAN CORRADINI: Okay, fine.

MR. HAYES: -- this activity.

CHAIRMAN CORRADINI: The reason I guess I'm asking the question is, in some sense, I'm sensing that it's not just, even though it's called accident-tolerant, I sense it has other potential normal operation benefits --

MR. HAYES: FeCrAl cladding --

CHAIRMAN CORRADINI: Well, that the industry --

MR. HAYES: -- or all of these?

CHAIRMAN CORRADINI: All --

MR. HAYES: Industry hopes that a lot of these concepts will bring some benefits --

CHAIRMAN CORRADINI: Okay.

MR. HAYES: -- to normal operations that go beyond just the benefits in accident considerations.

And this is just an illustration for you of the FeCrAl burst model. To be frank, it's an empirical model at the moment. But it's implemented and working well, allowing us to do some comparisons with bursting of Zircaloy.

And in many cases, the burst behavior seems to be very similar to Zircaloy. Although, some experimental results seem to indicate that the burst opening may look quite a bit different than Zircaloy.

Silicide fuel, this is actually an area where we had a jumpstart even before the high impact problem. There was a university project even before that that started developing some models for BISON, especially in the area of creep for silicide fuel.

And so this is an area where BISON is fairly mature. And quite a bit of lower length scale model development work has been done, especially in the area of thermal conductivity, swelling, fission gas release.

CHAIRMAN CORRADINI: Are there any experiments on oxidation?

MR. HAYES: Of silicide fuel?

CHAIRMAN CORRADINI: Yes, I've got --

MR. HAYES: Yes, there are.

CHAIRMAN CORRADINI: I've got an awful good source to make hydrogen.

MR. HAYES: There are oxidation studies of silicide. And there are corrosion studies of silicide.

CHAIRMAN CORRADINI: Okay.

MR. HAYES: The tool, the modeling tools don't address those phenomena. The experimental programs are looking at those.

CHAIRMAN CORRADINI: I mean, this is more of a technical question. So I'll wait.

MR. HAYES: And just to give you an example of the thermal conductivity modeling for silicide, so this plot here on the left is thermal conductivity of silicide fuel versus radial position.

So this would be at a center line of a fuel pellet and the surface of a fuel pellet. And this is what the thermal conductivity profile would look like un-irradiated. And you can see degraded to a certain burn-up level this is what the model predicts.

And some of what you're seeing is also reflected over here in this plot, which is thermal conductivity versus temperature. The big difference with silicide is silicide thermal conductivity goes up with temperature more like a metal, whereas the curve here for oxide fuel goes down.

And the models predicting degradation of silicide fuel, you see it here. The silicide fuel, like any fuel, will degrade under radiation. But all indications are, even worst-case scenarios, it's going to be far better than UO2.

Silicon carbide cladding, this probably requires a big caveat. This is an area we started working in probably much later than all the other areas.

It says, yes, there are models in BISON for pretty much everything. Even swelling could probably be a yes now, although these are just recently implemented. So there's not much assessment of these models that have been done yet. And that's just now beginning. It's not that we're not going to do it. It's just now beginning.

There is a lot of experimental data, even irradiation data, on silicon carbide. So there is a wealth of data in general, not -- this is not data generated as part of an integral fuel pin.

And so here's some, just to show you that the silicon carbide cladding model in BISON is working. We're not comparing to experimental data. But we are part of the MIT group that has been looking at silicon carbide as, and applications to cladding.

And they set up an early benchmarking problem on stress and strain. And, you know, the models in BISON are consistent with all the other models in, or all the other codes in that benchmarking activity.

And then this, then the last one is non-cylindrical metallic fuel. Metallic fuel is actually an area that was receiving quite a bit of attention in BISON even before ATF came along for FAST reactors. So there was considerable metallic fuel capability in BISON to begin with.

Now, obviously, some of that is directly applicable to ATF type concepts and some needs additional work. But there are good models for metallic fuel in BISON for just about everything. And there are some important lower length scale models that are being developed as well.

These noes down here is radial pin power distribution. Of course, in an LWR where you get flux depression inside of a fuel pin, you have to account for that in your temperature calculation. BISON can handle that quite readily for cylindrical geometries.

If you go to a non-cylindrical geometry, you're going to have to do something about that. And nothing's been done about that in BISON yet. It's on the to-do list.

And this gives you an example for the kinds of things that we're talking about. Because of its arbitrary geometry capability, BISON could simulate an ATF concept that looks like this. Because of its ability to couple to other physics tools, a concept like this might need to look at CFD in the coolant channel.

And so BISON can and does couple with NEK5000, for instance, to do something like that. You'll hear more about NEK5000 this afternoon.

Okay. That's a quick run-through of all the concepts and sort of the status for where BISON is on the various concepts.

Now, just a few slides on validation. And I understand this is important.

So the first point to be made is data generation needed for ATF validation is underway. It's early in the process, but it's underway.

DOE-sponsored testing of ATF concepts is in progress. It has been for several years. We have a very close partnership with the three industry ATF teams, Framatome, GE, and Westinghouse. And all their concepts are being tested. And they have a lot more testing that will come.

Now, the DOE program, very highly, heavily relies on testing in ATR and TREAT. We had envisioned some testing in Halden, some important testing. And as we've already discussed, that needs to be redirected. And we're working on that now.

One thing, and, Joy, I know this is a concern of yours. It's a concern of ours, too, and that is the in situ instrumentation that has become a real hallmark of the Halden experiments. Most of the other places we're looking to move experiments don't have that kind of historical legacy.

So we have already, DOE has taken the initiative to partner with the Halden staff moving forward. And they're going to help us with those issues, instrumentation and how to appropriately implement them wherever these experiments go. We don't just assume that we're going to get that right without their help.

Here's a bullet that you should pay close attention to. And that is we do foresee a need for an expanded use of LTR/LTA programs in commercial reactors just to generate the volume of subsequent test specimens, irradiated test specimens we're going to need.

Without Halden -- and one of the advantages of Halden was instrumentation. Another advantage is it was just a whole reactor dedicated to the LWR fuel testing mission.

And most of these other reactors were now going to have to go to are not going to be wholly dedicated to that mission. They're going to do pieces and parts of it.

And so we do have a need for just a larger volume of irradiated fuels and materials to be generated that can then be subjected to PIE or possibly refabrication, reinstrumentation for subsequent, more specific testing, maybe an ATR, TREAT, LOCA facility. And we're hoping that materials from those LTRs and LTAs can feed some of that.

But the bottom line here is fuel behavior data needed for ATF validation is being generated. I mean, what you see here is silicide fuel in the hot cell in Idaho. It's low burn-up. It's at about 10 gigawatt-days per ton. But we're beginning to get data on it.

MEMBER REMPE: But just a caution of, I know some guys from NR who used to laugh about that Bruno would take the capsule out of ATR, shake it up a bit, and then send it over to the hot cell.

And out-of-pile data is great. But you, it's a lot better to get it in-pile if you can if at all because --

MR. HAYES: We understand in situ measurements are the priority. But we're not discounting data generated in the hot cell as being important and relevant as well.

Okay. So, that being said, we have some serious challenges in the area of validation for ATF. I've already mentioned this once in passing.

You know, we're at the early phase of ATF fuel development. So we're not five decades or six decades into looking at the same fuel system. So there's, it's a given there's going to be less experimental data in the near term for validating ATF performance models and codes.

I think Shane said in his opening remarks that we don't believe modeling and simulation is going to replace experiments, not at all. We still need experimental data. And as someone mentioned or alluded to earlier, we still need experimental data that's going to bound operations.

We're not saying in regulatory space that we're going to, we envision the regulator to accept extrapolations far beyond the place where data exists.

And these challenges really require a close integration between modelers, experimenters, the industry ATF teams, and the regulator to maximize the quality and applicability of data. And just to comment on that, this close integration is in the process of developing. And we're all talking.

The multiscale, mechanistic modeling approach to developing fuel behavior models, and these are models that are informed from the level of microstructure, that creates a validation challenge as well. And we understand that.

But we want to draw attention to an important distinction. We are working on separate effects, so-called separate effects experiments that can play a role in validating MARMOT-type models. We're doing work in that area. But to be honest, that is not going to be the main area where validation happens.

The validation is still going to be predominantly functioning at the integral pin level in BISON using these new mechanistic models. And that's really --

MEMBER KIRCHNER: Steve, I was --

MR. HAYES: -- no different than the way the world works today.

MEMBER KIRCHNER: I was looking at your tables, just glancing through them. And the pattern that I think I see is that there's less LLS-informed back, informed models in the cladding area than there is in the fuel.

MR. HAYES: That's probably right, yes.

MEMBER KIRCHNER: I would have thought that's the easier problem.

CHAIRMAN CORRADINI: Or is it what you said about chromium cladding that it's not important?

MR. HAYES: Well --

CHAIRMAN CORRADINI: I mean, I'm trying to understand --

MR. HAYES: Yes, so some of that comes out of the sensitivity analyses which show, you know, what properties or behaviors are going to make the most difference. And we sort of go after those first.

But there are probably some cladding things that will fall into that area, mechanical behavior of FeCrAl. But I think that's an area where work is happening, for instance.

CHAIRMAN CORRADINI: If I might just -- because I think we're at the end, and I don't want to delay you from ending so Jess has his time.

But my global interpretation is that there's a lot of data to be gathered. So let me ask the question. It's really not to Shane. But I'll ask you, and then you'll turn to Shane.

Is it more a matter of DOE partnering with the NRC and industry to gather the appropriate needed data, identifying that as a, I'll call it a team effort than it is to worry about the models, because as I, unless I misinterpreted all the slides, it's the data gathering to me that is the crucial element to move this forward, whether I use BISON or FRAP or FAST or FALCON --

MR. HAYES: I think that's an incredibly important area where DOE and NRC needs to work closely together with the vendor teams. If we want to get the right data sooner rather than later, we need to all agree on what the right data is early.

MEMBER REMPE: So, and this has been going on for a while. I'm surprised. Earlier you said this is under development. I'm surprised, knowing that how long this ATF program has been going on, that the regulator is just now coming in saying, no, you need X, Y, and Z data.

MR. HAYES: And the regulator doesn't say it quite like that. But they do help guide us. Maybe DOE didn't reach out to them as early as we should have. But whatever the history is, I would say now it's functioning --

MEMBER REMPE: It's --

MR. HAYES: -- very well.

MEMBER REMPE: Okay.

MEMBER BLEY: Steve, I want to ask something going back to something Walt asked in the earlier session. And I understand most all the validations done at the BISON level.

But for the MARMOT model in this microstructure modeling, Walt asked, given all the data that's out there, have you confirmed that it's predicting the right microstructure, and you said, yes, we've done some of that.

MR. HAYES: Some, yes.

MEMBER BLEY: Can you give me a little idea about how much of that you've done? And when you've done it, I can think of three possible outcomes. You do it and look and you say, yes, it predicted pretty well. Or you look and say something's off. And you dig in and figure out what it is. And maybe you change --

MR. HAYES: -- on the model.

MEMBER BLEY: -- some basic physics part of the model or something that's kind of general. Or you do some fine tuning to make it work, which might not apply to anything else that comes along later. What kind of things have you run into?

MR. HAYES: So we really try to avoid the latter --

MEMBER BLEY: I hope so.

MR. HAYES: -- fine tuning. And at one point earlier, I said something about calibrating models. And there's certain people who, you know, probably wish I didn't even say that. But, you know, there's going to be some calibration, of course.

But the DOE multiscale modeling effort, it really tries to avoid that as much as possible, because then that's when you get --

MEMBER BLEY: But sort of what I'm asking is when you've tried this what have you found. I mean, you believe you got the right stuff in there.

And at the, over at the engineering scale, it's confirmed and everything looks nice. But we could have some weird stuff coming over there that just happens to work.

MR. HAYES: Right. And the honest answer is we don't know as much about that as we should. But this last bullet actually speaks to this issue.

MEMBER BLEY: Yes.

MR. HAYES: So, rather than going off and doing a huge amount of separate effects testing, the approach DOE is taking is a little bit different. And that is, you know, the mainstay of our testing is still going to be integral fuel rods, miniature maybe, but still integral fuel rods.

But we can still get at some of the microstructural validation if we'll do two things, one, on the front end, do a much better job of characterizing the microstructure of those fuels so that we have the input data for MARMOT or a BISON, a MARMOT-informed BISON model that we don't always have for those historical experiments that we're analyzing. So we can do a better job of that.

And then on the back end, okay, maybe it's cook and look. I don't like that term. But we irradiate a fuel up to a certain burn-up. We take it to the hot cell.

And now we've stood up these new facilities like the irradiation, Irradiated Materials Characterization Laboratory at the INL. This is a hot cell, miniature hot cell, with the ability to begin characterizing irradiated fuels on a microstructural level. Okay.

So we're going to get the microstructure on the front end. We're going to get it on the back end. That's not a separate effects test. But it's data that can address some of these validation issues for these MARMOT-generated models.

CHAIRMAN CORRADINI: So we're getting close to the end. Can we end?

MR. HAYES: Yes.

CHAIRMAN CORRADINI: Are we there almost?

MR. HAYES: We're there.

MR. STANEK: Can I make one very quick condition to Steve's comments about the lower length scale modeling, which is you asked a question what have we found when we do this.

CHAIRMAN CORRADINI: Yes.

MR. STANEK: And I think, generally speaking, even for phenomena that we think we know exceptionally well, we always seem to find something very fundamental that we didn't understand.

And at the engineering scale for UO2 zirc, there's sufficient empirical data to develop empirical models that that missing physics isn't necessarily important.

But what it's really doing is setting this, allowing us as a, have a springboard into ATF and advanced reactor fuel to really understand what those, what that missing physics is, so now we can focus on those things that we didn't fully understand --

MEMBER BLEY: Okay. That's not surprising I think. Can you give us a hint of how much of that you've been able to do and how much -- you just said there's more of this planned. But how much more and when's it coming? And are there are any reports out at that level?

MR. HAYES: Oh, sure, sure.

MEMBER BLEY: I don't know if we got those or not. I didn't see --

MR. HAYES: We didn't give you a lot of MARMOT level stuff. We gave you mostly BISON stuff. But there's a MARMOT assessment report. I think we provided the link. And there's tons of papers that we could share with you.

It's in the pipeline. I mean, these things take a few years to really --

MEMBER BLEY: So about ten years you'll come back and tell us about that or --

MR. HAYES: It doesn't take ten years. I mean, it took, you know, four or five years on the UO2 side. But we have a head start.

I think we're seeing some benefit already, real results that are good, say, in the area of fission gas release of chromia-doped UO2, major good results there. And we're going to have similar successes across the board in the next year or two I would say.

MEMBER KIRCHNER: Now, those good results for fission gas predictions, are those based on empirical models or are they lower length scale?

MR. HAYES: No, the chromia-doped stuff is mechanistic models.

MEMBER KIRCHNER: And what's the major driver in fission gas release in those?

MR. HAYES: This is one of the scientific experts in that area. I'll let him --

CHAIRMAN CORRADINI: Briefly.

MR. HAYES: Briefly.

MEMBER KIRCHNER: Do you see the

restructuring and cracking of UO2 or does it hold together better? Is it --

MR. STANEK: There's no way to make this brief.

(Laughter.)

MEMBER KIRCHNER: Is it a surface area grain boundary effect or is it --

MR. STANEK: So there's a competition that the -- what we found, very quickly, is that the dopant in solution has an effect on not only the graining structure, which is typically through grain size --

MEMBER KIRCHNER: Right.

MR. STANEK: -- but it also impacts the diffusivity of the fission gas since we have competing factors between grain size and diffusivity --

MEMBER KIRCHNER: Right.

MR. STANEK: -- which you need to do a BISON calculation with the real power history to evaluate.

And what you find is that even though the diffusivity at higher temperature is significantly greater than let's say un-doped UO2, that effect is mostly at high temperature. And so the reason that we're observing higher retention of fission gas is for the reason that the grain sizes are larger.

MEMBER KIRCHNER: Thank you.

CHAIRMAN CORRADINI: Okay. So I want to give Jess as much as possible. So we're going to probably delay lunch until 12:15 to give you almost what you supposedly were supposed to have.

MR. GEHIN: Okay. We'll pull up the presentation here. I'm Jess Gehin from Idaho National Laboratory. I've been there for three months, formerly of Oak Ridge National Laboratory for 25 years. So --

CHAIRMAN CORRADINI: So you're still an Oak Ridger at heart.

MR. GEHIN: I'm rapidly converting. So I'm going to be talking --

CHAIRMAN CORRADINI: Just one of many.

MR. GEHIN: Yes. So I'm very happy to be out of Idaho, a very nice place to be. A little longer trip to Washington, D.C., but that's part of the job.

I'm happy to be here to talk about neutronics and thermal hydraulics modeling. We'll spend maybe about an hour or so, as Mike mentioned, on this and go through what DOE has been working on there. So I appreciate the opportunity to talk about what we've been doing.

So the presentation will follow very similar to the fuels presentation. I'll give a quick introduction of the codes, code descriptions, what we've been doing on code validation, look at the capabilities and gaps for accident-tolerant fuels, and have some conclusions, so pretty straightforward.

In terms of introduction, DOE has been developing fully coupled and resolved multi-physics core simulation models for light water reactors. The capability being developed under the hub is called Virtual Environment for Reactor Applications, VERA. This has been solely developed on light water reactor development.

And you'll hear me talk many times about the focus of this being on getting pin-by-pin detail. One way we differentiate ourselves from industry methods is that we directly calculate this pin detail. So this is for the neutronics pin-by-pin rod powers, which is shown over on the right-hand side there.

Thermal hydraulics, we use subchannel for full core. And to get this by the rod subchannels, I'll show you a picture of what that means.

Fuel temperature distributions, also rod-by-rod, either directly using a code like BISON or using BISON to generate fuel temperature tables that can go in so we can get direct rod-by-rod.

One of the areas that we're working on -- and I should have said, these tools are being directed at a set of what we call challenge problems or areas that we have identified with industry to work on.

One of these is crud. So there is a chemistry model for crud build-up. And we also do very detailed isotopic depletion, so, in general, and I'll go through this in more detail, more resolution in detail than industry codes.

As I mentioned, it's primarily developed for LWR's current operating plants. The emphasis, therefore, has been on zirconium clad UO2 fuel in PWRs, primarily for operational performance and safety issues.

I mentioned a set of challenge problems, which are things like crud-induced power shift, crud-induced localized corrosion, pellet clad interaction, which are more operational issues.

And then, more on the safety issues, looking at reactivity insertion accidents, LOCA, and DNB are sort of the hallmarks of things that we've been looking at for UO2 fuels.

MEMBER KIRCHNER: And in VERA now, can you do LOCA?

MR. GEHIN: The emphasis on LOCA, and I'll have a slide on that, has been on the fuel performance that --

MEMBER KIRCHNER: Yes.

MR. GEHIN: -- Steve has talked about. So, when I get to that slide to address it, when we look at thermal hydraulics at LOCA, we're really planning to couple to existing system codes.

We're not developing as part of this effort a system code capability. So, when it comes to thermal hydraulics for LOCA, we're looking to establish codes there.

There's strong industry engagement in development in using these capabilities, particularly for the hub. Westinghouse is a partner. So they have these codes. They're applying these codes.

And I'll show you in a minute what the codes are when it comes to neutronics and thermal hydraulics. It also applies to the fuel performance capabilities as well. And this includes, you know, an evaluation of these codes for applicability to accident-tolerant fuel.

Overall applicability to accident-tolerant fuel, so these codes, when you look at the neutronics and thermal hydraulics, they've been developed and demonstrated for LWRs, particularly PWR applications. The BWR capability is not as matured.

Steady-state operation, investigation of crud-induced power shift, fuel pellet-cladding interaction, I've already mentioned this, operational transients, startup, shutdown, power maneuver, select transients, such as reactivity insertion accidents, and departure from nucleate boiling.

So our current application set hasn't been on every, you know, accident scenario and condition that may exist.

When it comes to physics and thermal hydraulics, the materials and geometry of most of the concepts, particularly the cylindrical concepts, are within the VERA capabilities. Some modifications in development will be needed for these non-cylindrical fuel geometries.

But the physics models, when I talked about the neutronics, are fully applicable to these other geometries. You just need to put those geometry capabilities into the code. And I'll elaborate on that.

When it comes to the thermal hydraulics subchannel, it's generally a bit more cruder. And this is where we rely more on CFD directly or CFD informing the subchannel. And I'll give an example of that.

They're validated and used for current fuels, of course, zirconium-clad UO2. And we believe they can be extended for ATF concepts.

MEMBER KIRCHNER: Just to be clear, sorry to dwell on this. I mean, we're developing accident-tolerant fuels to withstand accidents. These are, well, RIAs are one category.

MR. GEHIN: Right.

MEMBER KIRCHNER: But clearly LOCA is the design basis accident for most of the current fleet. So you would then switch to a different code set to do the --

MR. GEHIN: Well, we've been supporting, you know --

MEMBER KIRCHNER: Or you would use BISON and what you've got with this --

MR. GEHIN: We would use --

MEMBER KIRCHNER: -- and then that would be the initial state?

MR. GEHIN: No, the way we would apply this capability for LOCA is we would use this capability to get to the initial conditions of a LOCA, whether it's getting metal into cycle in some detail.

That would use, and I'll get to the codes in a minute, you know, the neutronics, thermal hydraulics, and BISON to get to that point.

At that point, you would switch over to an accident analysis that would have to necessarily involve a systems code like TRACE as an example or RELAP. And that, in the case of accident-tolerant fuels, we would envision using TRACE with BISON. And we've made some, have done some initial work with the NRC on coupling those codes for that specific application.

When we scoped out the work for the program where much of this was developed under and looked at the set of problems that we were going to tackle, we had decided taking on the development of an advanced systems code was beyond the scope that we could do. So we focused on the fuel part of that for the LOCA system. Okay.

CHAIRMAN CORRADINI: So I'm kind of going back to --

MEMBER BLEY: Mic.

CHAIRMAN CORRADINI: Oh, I'm sorry. Excuse me, a little green light. Yes, my green light monitor found me --

So, normal operation AOOs and selected

DBAs --

MR. GEHIN: Yes.

CHAIRMAN CORRADINI: -- is where you're seeing --

MR. GEHIN: These are where we've chosen with and --

CHAIRMAN CORRADINI: That's fine. I just wanted to make sure I got it right.

MR. GEHIN: I'll just maybe give you a clarification. You're right. Yes, we went through at the start of the, particularly the hub program and did an assessment of --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- of areas with industry input. Those were the areas selected. It does include LOCA, but it's not full scope LOCA.

CHAIRMAN CORRADINI: Well, I mean, just to cut to a fun topic, critical heat flux, critical heat flux under normal operation, you still have to do an experiment.

MR. GEHIN: Absolutely.

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: And --

CHAIRMAN CORRADINI: Just wanted to check.

MR. GEHIN: Yes. Now, we'll talk a little bit about that. We are seeking to develop improved models. But they're all going to have to be --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- validated against experiments. So --

CHAIRMAN CORRADINI: Okay, thanks. Thanks, Jess.

MR. GEHIN: Okay. So now I'll talk a little bit about the codes and code coupling for simulations. So you heard about BISON extensively.

On neutronics and thermal hydraulics, the codes, particularly neutronics, we developed a three dimensional whole core neutron transport simulator. It uses 51 energy groups, and I'll compare and contrast these with LWR methods in a little bit, with detailed cross sections.

And you're going to see a lot of detailed pictures, details generated directly. There aren't homogenization, dehomogenizations and things like that.

For isotopic inventory, we used the ORIGEN capability that provides extensive detail there. And so we have the capability to run this with a different number of nuclides, those important only for neutronics.

And if you want to get into looking at inventories that could feed source terms, that can be supported as well.

And then what's very common in neutronics is to support these, particularly in the verification of the Monte Carlo codes. So we've been developing a Monte Carlo code called SHIFT that has very good parallel performance so we can run extremely high fidelity models and check out physics for the deterministic impact approach.

So those are the three codes. I'll go over those in a little bit more detail.

The thermal hydraulics in the lower right is focused at the core level on a subchannel capability COBRA-TF or abbreviated CTF. This is a subchannel capability. You're probably familiar with it because it's been around and used significantly.

Transient two-fluid, three-field model, we apply it at every coolant channel, you know, rod channel to get the detail at the rod surface. And that reflects at the core level at least, you know, four regions around a fuel pin that get represented by different thermal hydraulic conditions that can be supplemented with CFD analysis.

It lists CFD here. We've used commercial

CFD, particularly in the hub, STAR-CCM+. We also use DOE-developed capabilities, NEK5000, that you'll hear more about as well.

CHAIRMAN CORRADINI: You're going to, we're going to hear later about what you used the CFD for. I'm trying to understand.

MR. GEHIN: Yes, I'll talk --

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: I'll talk about that. But primarily what we've been working on there is getting more detailed flow distributions to improve subchannel predictions. We've also been working on improving multi-phase CFD predictions. But I'm not going to go into detail on that.

CHAIRMAN CORRADINI: So it would be, I mean, just to get to a detail, it would be essentially going, doing a local calculation to what I'll call improve upon the correlation within CTF about the crossflow resistance.

MR. GEHIN: That types of thing, the flow, you know, the impacts of mixing vanes --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- inflow, things that subchannel generally doesn't have models to pick up that type of detail, yet you'd want to try to reflect that at a whole core level.

CHAIRMAN CORRADINI: Thank you.

MEMBER REMPE: So --

MR. GEHIN: Yes.

MEMBER REMPE: -- if, you mentioned earlier you'd couple to TRACE if you were going to do the thermal hydraulics. If you do it like an ATWS-I, would you get rid of the PARCS part of TRACE and use your stuff that you've developed? And has that been figured out yet or that's in the future?

MR. GEHIN: You can do that. It sort of depends on what you believe is important and how you want to do your analysis.

For example, the typical analysis for a LOCA, you usually don't model every rod in the core. You bound that with a peak rod and maybe average rod. And that can be done by coupling BISON with TRACE, and you choose those rods and rod towers.

We've been discussing but haven't really pursued significantly coupling the full rod-by-rod detail yet with the systems code to do that type of analysis.

But it's something that we'd be interested in, something that CTF with some, a little bit of development work could be applied to that type of area as well if you want to do the full detail. It's really up to the user in that case to decide whether they want to go after that level of detail.

MEMBER REMPE: So there's not a firm plan on what the approach will be yet.

MR. GEHIN: Well, the current -- and I've got a slide on this. So maybe we'll talk --

MEMBER REMPE: Wait till later. That's fine.

MR. GEHIN: I'll tell you what we've been doing. And I think it's correct to say there isn't a decided plan on the approach for that. Whereas, I think that, you know, maintaining connections with the current methodology but with more advanced tools seems to be what's being discussed more.

Okay. I'm going to talk a little bit of details about each of the codes. MPACT is a 3D core pin-resolved neutronics code. So this is optimized for determining pin-by-pin neutron flux distribution.

And what I mean by pin-by-pin is that the fuel rod, and if you sort of look at the diagram in the upper right, each fuel rod is modeled in detail at the rod level for each core. So this is modeled with transport theory, method-of-characteristics, which is a general geometry transport, which is why I'm saying it can be extended to other fuel types so that we really only applied it to cylindrical.

This is applied in a 2D plane across the whole reactor, where most of the neutronics hydrogen-80 is. So, if you have differing fuel pins, you have burnable absorbers, you have control rods, all that hydrogen-80, if you look on a plane, you'll see that hydrogen-80.

If you do things like put in, you know, different fuel rods or different fuel assemblies, those can be directly modeled with this pin-by-pin capability. And it's a pretty efficient way to do that.

Now, these pins are, of course, coupled with a 3D coarse mesh solution. And so you can get a full 3D rod-by-rod solution looking at all the local hydrogen-80s?

As I mentioned, currently models cylindrical fuel rods without standard approximations that are made in industry codes. The industry methods are typically based on nodal methods where you model the full geometry detail only at the lattice level. So we model it at the full core level.

Pin powers, we compute explicitly. We don't do pin, we don't need to do pin power reconstruction. We don't homogenize anything.

There's a direct feedback calculation. There's no cross section functionalization. If you're familiar with that, the typical industry approach will functionalize the cross section data as temperature, density, boron concentration --

CHAIRMAN CORRADINI: You mean a series of --

MR. GEHIN: -- and make a table. So we just do this directly. So there's no approximations on the, you know, the assumed form of those functional bits.

And all of this is to get this rod-by-rod detail. Because of the problems that I mentioned here, the areas that we're working on are all rod-by-rod phenomena that we wanted to capture. And we want to do that in a way that's beyond the capabilities of what already exists. Our emphasis --

MEMBER KIRCHNER: Can I here, Jess? But I assume you use N death 7 or whatever.

MR. GEHIN: Yes, we use the latest cross section libraries. I don't want to get too much in the detail. But if you look at the processing of the libraries that's done using standard tools, we use standard resonance processing approaches, a subgroup method that actually is applicable for these types of problems with the hydrogen-80. But we keep all those models up to date.

I had mentioned the emphasis has been on PWR development. There are BWR capabilities, but they have not been developed and validated to the extent of the PWR capabilities. Those are in progress and planned to continue.

And then, you know, these physics methods, as I mentioned, are fully applicable to ATF. So, when you look at transport with fine energy group with general geometry, there really aren't limitations there.

The limitations or the things that you'd want to look at is to ensure the neutron cross section data and the inputs meet your requirements. For most cases, they're generally acceptable.

CHAIRMAN CORRADINI: I guess as I'm -- I'll ask the question I asked about the fuel. So what industries have adopted MPACT?

MR. GEHIN: So it's in an assessment phase. I'd say it's the same sort of situation. Westinghouse has been a partner in developing this. So they're --

CHAIRMAN CORRADINI: Well, I guess, I

thought you were going to tell me Westinghouse.

MR. GEHIN: Yes.

CHAIRMAN CORRADINI: But they have not switched over.

MR. GEHIN: I mean, yes, I mean, it's really their call to decide when they switch over. They're in an assessment phase.

So one of the -- you know, there are existing tools, of course, they use. And they're looking at these advanced tools. And one of you pointed out to determine is there the value there to invest the --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- the money into bringing these tools in.

We've worked very hard to make these tools usable and accepted by industry. But in the end, it's their decision --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- whether they do that. And we've been very fortunate to work with Westinghouse and other industry organizations to get data and feedback.

We also have an industry council. There's about 20 members of that, including vendors and utilities, that provide strong feedback as well and data as well.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: In fact, an example of the data is in the lower right. You know, this is the typical type of measurements you get as flux maps from an operating reactor that we then can compare to. You don't get the detailed pin-by-pin, of course, from the reactor.

But these flux maps, and we've got a lot of them now for a lot of reactor types, as I have showed, have been very valuable to understand the deployments of the codes.

CHAIRMAN CORRADINI: So what we're looking at is a subassembly somewhere in the core and the little wiggles are the axial variation?

MR. GEHIN: Yes. And so what this is, it's a representation of a quarter core of a PWR.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: There are --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- detectors in various locations around the core, and these move up and down.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: These are flux maps done once a quarter or so. They've been mapped into one quarter.

And this is kind of small and blurry, but we've got numerous maps where we've compared our calculations directly to measured results. You can look at the RMS errors and show that we're getting very good predictions. So we're pretty comfortable with that.

The Monte Carlo capability, you're probably familiar with Monte Carlo codes and some of the more, the ones that are a little bit out, used more like MCMP.

This shift is a Monte Carlo code in some ways similar to MCMP except it's been designed to scale on very large computers. And the value to that is that we can then run enough particle histories to get statistical uncertainties down at a finer resolution to areas that are less than one percent or half percent so we can ensure that it's not the statistical uncertainties affecting the comparisons.

Some of these simulations take, you know, a trillion-particle histories, which are large scale simulations. And so the way we've used this code is to get the best possible answer we can to help verify the deterministic code.

And in some cases, you can see here the distribution for AP1000 provided evidence that the MPACT code, deterministic code, does give good local details that can't be measured.

So Monte Carlo is the most direct physics, neutronics physics simulation capable of detailed 3D geometry without approximation, representation of fuel, ex-core geometry. So we use this looking at vessel and ex-core measurements.

We can get the detailed isotopics and temperature distributions from MPACT to put it into this so we can do verifications at state, you know, at different burn-up state points as well.

Combined, as I mentioned, with large scale computer, this provides the best available means to verify more approximate physics models. And it's been widely used with that. As I mentioned, we use this to verify MPACT for many cases, including the AP1000 case showed there.

MEMBER MARCH-LEUBA: What thermal-hydraulics have you used for the Monte Carlo?

MR. GEHIN: It's frozen. So those conditions are frozen. So we run MPACT coupled with CTF with fuel temperature either at tables or BISON. At a state point, we'll take those conditions, put them in Monte Carlo.

There are other programs that are looking at coupling Monte Carlo to CFD and other things. But for our purposes for applications, those are beyond the timeframe.

MEMBER MARCH-LEUBA: So MPACT and CF use the same TH.

MR. GEHIN: They use the same -- no, it's -- so, when you run the Monte Carlo calculation, you're not running a, at least for this application, not running a coupled neutronics thermal hydraulics.

MEMBER MARCH-LEUBA: Right.

MR. GEHIN: You're freezing the thermal hydraulics.

MEMBER MARCH-LEUBA: You run --

MR. GEHIN: You run MPACT, CTF --

MEMBER MARCH-LEUBA: Running, but it's fragment TH and put it into Monte Carlo.

MR. GEHIN: That's right.

MEMBER MARCH-LEUBA: Okay.

MR. GEHIN: So, like I said, there are programs looking at coupling Monte Carlo and TH, but that was beyond what we felt we could achieve in our program --

CHAIRMAN CORRADINI: From a safety

analysis standpoint, are you just -- no, let me ask the question differently.

If I were a vendor or an owner/operator, am I essentially identifying margin and then deciding what I can economically do with the margin? I mean --

MR. GEHIN: You can do that.

CHAIRMAN CORRADINI: -- this is not safety analysis I guess is what I'm kind of saying in a backward way.

MR. GEHIN: Yes, so this, yes, and so this can be used to quantify or to help quantify margin, particularly those associated with physics approximation.

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: So it won't --

MEMBER KIRCHNER: It's mainly benchmarking.

MR. GEHIN: It won't cover everything.

CHAIRMAN CORRADINI: Well, I didn't mean just this. I meant the whole shooting match, MPACT with this with --

MR. GEHIN: Yes, so it can be. Remember, some of our scope is operational challenges which aren't necessarily safety-related --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- and some are, like RIA and those areas. And so they won't cover absolutely everything when it comes to validating those models. But --

CHAIRMAN CORRADINI: So, yes, but I guess, so let me ask you. You brought it up. Let me just ask that. So, with the expected, I'm not sure if it will happen, with the expected new RIA rule, is this the only way to address the issue?

MR. GEHIN: We've been talking with EPRI and our, and vendors about the use of these tools to help inform that. I don't think there's any decision yet --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- on their point on how they're going to do it. But we're very interested to see our tools help on problems like that --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- if it's possible. But I can't say whether that's going to be the solution or not. Okay. All right. I think we're done with that.

Here's where I sort of compare and contrast what we've been working on versus what's available in the industry, so, again, whole-core, fully coupled, steady-state, transient thermal hydraulics, fuel performance with neutronics.

We removed many of the assumptions in standard codes, particularly the homogenization, dehomogenization, local lattice effects, cross section functionalization, averaging of thermal hydraulics, those sorts of things.

And it's been applied to UO2 concepts. Sensitivity analysis, as I'll go through in more detail, on the ATF can be used to investigate some of the ATF fuel concepts to determine whether more validation data is needed.

The table at the bottom goes through the different physics model in this capability, the industry practice, and the DOE code, in this case VERA, where the standard practice is 3D nodal diffusion with two energy groups informed by 2D fuel assembly lattice transport where we do direct 3D transport with detailed energy groups.

The power distributions, thermal hydraulics, fuel temperatures are typically done at nodal averages in a industry type calculation. We do all that fuel pin resolved. So you can just look where it says fuel pin resolved, fuel pin resolved, fuel pin resolved.

There is a cost for this. If you look at the bottom, target platform for the industry codes runs on workstations, relatively small systems.

Particularly the transport is computationally, more computationally intensive if you want to do it at this resolution. So our target system for that has been 1,000 compute cores, which is a departmental size cluster.

Many of those are available in the industry. We've been talking with -- or in DOE. We've been talking with our industry partners about, you know, we make these machines available. And as the value of our codes becomes apparent or they decide there's value, they can invest in machines like this. They're achievable at this level. So -- okay.

COBRA-TF whole-core thermal hydraulics, this is a subchannel code. This is a thermal hydraulics subcommittee I believe, so you're probably familiar with subchannel codes, very engineering --

CHAIRMAN CORRADINI: Don't give us a test.

MR. GEHIN: Okay. Engineering approach. CTF is a two-fluid, three-field representation. So it does single-phase and two-phase flow. For standard PWR operation, of course, we're primarily using single-phase flow with sub-cooled boiling.

But we've modeled some cases, if you look over on the lower right, main steam line break, coupling CTF and MPACT that definitely are multi-phase cases as well.

This code has been widely used and validated for various reasons. We're doing our own validation as well. I'll talk about that.

When we apply, what I mentioned earlier, when we apply this code, we apply it at what I would call a fuel rod subchannel, which is the, you know, the channel that's at the intersection of four fuel rods.

It's been subchannels typically applied at a, either that level at an assembly or assembly average conditions or quarter assembly average conditions. But for the full core we model all 50,000 or so sub-rod channels.

CHAIRMAN CORRADINI: Don't go back, but I should have asked. The neutronics codes that you talk about SHIFT and MPACT, are they now adopted into scale?

MR. GEHIN: No, they're separate from scale. There is -- I should take that back. MPACT is separate from scale. SHIFT is being incorporated into scale.

CHAIRMAN CORRADINI: And what makes the,

what's the decision to make it in or out? That's what I don't understand.

MR. GEHIN: To make it what?

CHAIRMAN CORRADINI: To decide if it's in or out?

MR. GEHIN: Really from a -- I mean, that's a decision that would be made by the scale team on --

CHAIRMAN CORRADINI: Oh, so it's really the scale team.

MR. GEHIN: It's available. It's fully available if there's use there. And so there's no issue there.

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: Okay. So I was talking about the rod channel resolution. Again, this resolution I mentioned is applied to every rod in the core. And you can see, for each quarter rod region then you get a variation there. And I'll come back to that.

And for some problems, that's not sufficient. For some of the problems that we're working on that's not sufficient. I'll talk about how we address that.

Of course, it's transient and steady-state. We use it, for example, coupled. If you look at reactivity insertion accident, we model it with that level of detail as well. And it does have cross flow model between channels also.

As I mentioned, CFD-informed models are under development. This four azimuthal region around the rod is okay for many cases. But for some problems that we would look at, like crud, that's not enough resolution if you want to resolve the crud layer where you -- if you've seen crud striping, it's in more detail than that.

In addition, the grid spacer models are usually represented as losses or approximate models that can be informed by CFD as well.

So the applications, PWR, BWR, steady-state, and transient, I mentioned the main steam line break problem. We are applying it to reactivity insertion accident as well.

We're not applying this right now to a LOCA. Although the code could be extended and applied to LOCA.

CHAIRMAN CORRADINI: So a lot of questions come to mind. So LOCA, is there something about the voiding process that then translates back to the BWR also that is the limit? I'm not sure I understand.

MR. GEHIN: You know, and I might have to ask for somebody to help with the answer to this. But we have not spent a lot of time validating this current code version for LOCA and applying it to LOCA to understand all of the issues for that application.

So I don't think from a fundamental point the code can't model LOCA. It's --

CHAIRMAN CORRADINI: You just haven't taken the time.

MR. GEHIN: Yes, maybe I'll ask Dave Pointer, who works on the thermal hydraulics for us, to see if I gave the right answer or not.

MR. POINTER: So I'm Dave Pointer from Oak Ridge National Lab. And Jess gave the right answer.

In the course of CASL, we've actually made some significant investments to improving the stability of the multi-phase analysis capability in CTF.

So, in theory, it can be applied to those problems where you do generate significant void in ways that we couldn't in the past. But we have not gone through the next step of beginning to validate those applications in CTF.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: Yes, and so, when we bring up discussion of LOCA, that question of validation always comes up. And it's on the list. If there's folks that are interested in applying these codes that way, we'd definitely be interested in looking at that.

CHAIRMAN CORRADINI: Okay. Thank you.

MR. GEHIN: So the capabilities here, again, sort of the bottom line trying to tie it back to ATF, is the CFD-informed rod-by-rod thermal hydraulics can be used to model ATF.

You know, if you look at the geometry, particularly the cylindrical geometry applicable, you may have to take into account surface conditions, things like that. But the capability, I believe, can be applied and extended.

I'm going to go through a few examples to show, to emphasize some of the things I was talking about. And the first one is CFD-informed subchannel modeling.

Some of the problems that we look at, this four azimuthal regions that you get with CTF is not sufficient in the models, you know, that used for heat transfer aren't sufficient. So what we've done is generated models, fuel assemblies, multiple grid spans in CFD and calculated detailed flow distributions.

When you get these flow distributions, you can use those to back out, if there's mapped work here, around the rod, you know, the heat transfer coefficient. And that's what this colored plot shows.

If you look along the axial, this is, you know, on the left-hand side, the axial position on the rod. And if you take the rod surface and roll it out into a 2D plot, you see this surface, which gives you a map of the detailed heat transfer coefficient around the rod and up the rod.

It's impacted. And you can see these different levels, of course, by the mixing vanes and those details.

So, once you have these heat transfer map, and it's generally done by a ratio of the actual heat transfer coefficient to, say, a Dittus-Boelter heat transfer coefficient that's used in CTF, you can input that into CTF and get an improved simulation of the details around the rod, as well as predicting the overall heat transfer.

MEMBER MARCH-LEUBA: So what we're seeing there, the horizontal lines are the spacers?

MR. GEHIN: Yes, these are the spacers.

MEMBER MARCH-LEUBA: And then what is that plume where you're pointing right now?

MR. GEHIN: This plume right here?

MEMBER MARCH-LEUBA: Yes.

MR. GEHIN: Yes, Dave, do you have an answer for that? I mean --

MR. POINTER: So the plume that you see there is actually an opening in the configuration of the spacer grid for that particular pin. This is the central pin in a 5x5 bundle.

MEMBER MARCH-LEUBA: So it's on a smoother symmetry of the --

MR. POINTER: It's an anomaly in the dimple and spring configuration in that particular --

MEMBER MARCH-LEUBA: Any properties much --

MR. POINTER: Yes.

MEMBER MARCH-LEUBA: -- it doesn't mix.

MR. GEHIN: Okay. Thanks, Dave. So we've applied this to a series of case. I won't go into the details.

But this chart here, this plot on the right-hand side gives the CTF temperature prediction. Solid lines are CTF, standard CTF. The dash lines are with these improved heat transfer coefficients. So we can a proved simulation. You can also see the error as you go rod by rod is a lot more uniform.

CHAIRMAN CORRADINI: So say that again, please. I'm sorry.

MR. GEHIN: Okay. So this plot gives a comparison of the difference between CTF and STAR. So STAR is the reference. CTF is, of course, where we've input these heat transfer coefficients and done a calculation of CTF temperature prediction. And --

CHAIRMAN CORRADINI: Okay. But I guess I should have asked my question more specifically. The Y axis is an error in degrees Kelvin?

MR. GEHIN: I believe that's the case --

CHAIRMAN CORRADINI: Okay. So now I'm going to ask the engineering question. Who cares?

MR. GEHIN: So, when we looked at --

CHAIRMAN CORRADINI: I don't mean to be --

MR. GEHIN: No, no, no, it's a good question because we have the -- when you look at the application of crud, crud is very sensitive to when you get at a boron deposition threshold of when boron deposits and when it doesn't deposit.

So, when we did our analysis looking at the homogenized crud, four regions per rod, we found that we did not accurately predict the crud deposition and we had to calibrate that model, because there were some regions that were right on the edge of this threshold where temperatures like this mattered.

Now, it may be for your problem this

doesn't --

CHAIRMAN CORRADINI: But your point is you're close to a threshold. Now I need to know the answer more carefully --

MR. GEHIN: Well, the other value to this is when you looked at modeling new grid spacers or incorporating grid spacer designs, certainly you're going to get data from experimental measurements. But you're not going to get this resolution of data where you're going to have to have a model in your --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- subchannel code to represent grid spacer.

So that's another application where maybe you're not looking totally at improved accuracy prediction, but you do need a model to represent the impacts of those grid spacers. And that certainly has an impact on crud, DNB, and other areas as well. So those are the areas where we've really been focused on this --

MEMBER MARCH-LEUBA: So basically that figure on the right says that when you use the same heat transfer coefficient in the STAR and CTF, you get the same temperature.

MR. GEHIN: Yes.

MEMBER MARCH-LEUBA: And if you use the wrong heat transfer coefficient, you get the wrong --

MR. GEHIN: I mean, it's not horrendously wrong, as Mike mentioned, but it does allow you to get a more uniformed prediction. If you look at the air variations, they're much smaller.

And so we think it's one of the keys for calculating crud. It may be important for DNB as well. Certainly, grid spacer mixing is an effect that we can capture also.

All right. CFD evaluation of DNB, so this is something we've been working on quite a bit on the hub program to be able to apply CFD directly to predict when DNB conditions would occur in a PWR with the idea of being able to supplement experimental data.

So, typically what's done in industry is they take a, say, 5x5 rod bundle, do DNB testing on that, and check things out, particularly when there are changing fuel designs like grid spacers.

We would like the ability to be able to inform them on their grid designs that may result in them having to do fewer DNB tests or find out things during the DNB test that would change their grid spacer designs.

So we've been incorporating multi-phase model development to DNB, combining this with more fundamental measurements on heat partitioning between liquid and vapor phases, you can see some of the physics that we've been looking at there, and then be able to put this into a code like STAR-CCM or NEK5000 to be able to run, basically mimicking what an experiment for electrical heated DNB test would look like where you slowly ramp up the power and then you detect when you actually have, you know, a temperature excursion indicating DNB.

We've been able to get data on this 5x5, bundled data --

CHAIRMAN CORRADINI: This is Westinghouse data?

MR. GEHIN: This is Westinghouse data.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: Proprietary data for mixing vanes and non-mixing vanes. I'm showing the non-mixing vane case here, which shows basically the predictions are within plus or minus 16 percent or better. So --

CHAIRMAN CORRADINI: I noticed there's no axes label. So --

MR. GEHIN: Well, sorry about that. But

this is a case, the value that we've had working directly with Westinghouse and some of the other industry organizations where we may be able to get access to data. But it is proprietary.

MEMBER MARCH-LEUBA: So the points, the sequence you're putting there are different flow pressure and power.

MR. GEHIN: Yes, I believe that's the case --

MEMBER MARCH-LEUBA: But the same spacer, right?

MR. GEHIN: Yes. So, you know, the vendors, of course, this is how they validated their, or developed their own DNB correlations with this type of data. And so they've given us some of that data. And then they've actually taken these capabilities and applying it themselves --

MEMBER MARCH-LEUBA: Right, but the value of this is on the computer you can have a different spacer and see how it changes.

MR. GEHIN: Right. And, you know, one of the challenge with using CFD for this is applying single-phase CFD, you know, you can only get so far in that, and then when you do your test and actually have two-phase, it may or may not perform --

MEMBER MARCH-LEUBA: By the condition, yes.

MR. GEHIN: Yes. And so we're trying to expand the application of CFD for these tests. At some point, maybe we can rely on it more. But we don't want to -- you know, what we want to really be able to do is try to better inform these expensive tests.

And so, of course, this is an area then for ATF fuels if you're changing things that would impact flow patterns to investigate impact on DNB might, at this state of maturity, might be able to inform where you think data is needed or if you're comfortable with where things are. Okay.

MEMBER MARCH-LEUBA: For ATF fuels, you just pick the CFD correlation, the DNB correlation to change.

MR. GEHIN: I'm not an expert in this area. In general --

(Simultaneous speaking.)

MR. GEHIN: -- experts on that side of the table. It's generally driven by the mixing vane, the geometry. There could be some surface condition effects. But I would not --

MEMBER MARCH-LEUBA: If the material works differently, the water level would be --

MR. GEHIN: Right. And then if you look at non-cylindrical geometry, of course, there's --

MEMBER MARCH-LEUBA: Sure.

MR. GEHIN: -- definitely applications.

MEMBER MARCH-LEUBA: But for anything that we are thinking in the near future, if you look from the outside, the pins look the same.

MR. GEHIN: They look basically the same. You're right. So that's why, if needed, this could be applied.

Transient capabilities, I'll talk about reactivity insertion accident. So this has been one of the target problems that we've had, control rod ejection for a PWR.

This is a capability where we've coupled neutronics, thermal hydraulics with fuel temperature table model to calculate, you know, the conditions in the core. This is a four-loop PWR core where there's a postulated control rod ejection worth $1.50, which is, you know, these things are always done conservatively.

And we can get detailed rod-by-rod power distributions. This figure here shows you that's, where the ejected control rod is you end up with a power pulse, if you can squint a little bit at that, and get an axial power shape.

So we get all those details for every rod. You can identify rods that you may want to look at, use those as conditions that would go into a fuel performance simulation as well.

We are looking at coupling and working on coupling BISON indirectly. But it's usable in the current state as I just mentioned. Of course, this is also something that can be applied to ATF fuels as well, and it's fully functional.

Okay. Coupling DOE codes with reactor systems codes, so as I mentioned, for our work we've been not relying on development of a DOE reactor systems code. That may come about at some point where we work on that. But in the timeframe we had, the vision was to couple with existing reactor systems codes.

So this provides a capability to analyze flow regimes which CTF has not been validated. And that's what I meant when we talked about the LOCA, that while the capability is there, it's not been validated.

And so we've been working with the NRC to couple, you know, particularly BISON with the NRC code system to look at LOCA. It's been a joint DOE/NRC effort.

TRACE and BISON, which have been coupled as a demonstration, one, you know, primary reason for doing this is to show that it can be done. It can be done in a relatively quick fashion that you can choose some of these codes that you want to couple. And, of course, TRACE is the NRC's safety analysis code.

The idea here is if this capability could buy a means to simulate ATF simulation for LOCA as a -- where other transients, TRACE has been widely applied to these transients. You've heard about the state of development of BISON. And so you can bring those two together.

MEMBER MARCH-LEUBA: Does it provide two-way coupling?

MR. GEHIN: It's two-way coupling.

MEMBER MARCH-LEUBA: So, but --

MR. GEHIN: This is a --

MEMBER MARCH-LEUBA: -- BISON provides the conductivity for TRACE --

MR. GEHIN: That's right.

CHAIRMAN CORRADINI: Can I just -- I'm sorry. I didn't mean to interrupt you.

MR. GEHIN: No, no.

CHAIRMAN CORRADINI: But I'm struggling to see -- I'm looking at your slides and looking at the time. I'm struggling to see how this affects -- this is all interesting. But I'm trying to make the bridge to ATF, and I don't see a clear bridge.

MR. GEHIN: Okay. So the idea, in this case, the idea on ATF, whether it's for NRC or somebody else, if you decide BISON is a good code for ATF --

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: -- you don't have to abandon your systems code, which you put a lot of time and effort in developing. You can use it with BISON as an example.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: So that's the idea.

MEMBER REMPE: So you've totally switched gears with this slide, right? You're not talking about any of your MPACT stuff with this.

MR. GEHIN: That's exactly right.

CHAIRMAN CORRADINI: That was about four slides ago.

MEMBER REMPE: Okay. Yes, well, I just wanted to make sure, because earlier I had asked, well, are you going to continue using PARCS in the

TRACE system. And I think even your last slide talked about MPACT and CTF, right. But this particular coupling did not use anything from your earlier stuff.

MR. GEHIN: No, no. And, you know, and so, yes, just to be clear, you know, PARCS is not a DOE-developed code. It's not in the --

MEMBER REMPE: Right.

MR. GEHIN: -- that I talked to you about --

CHAIRMAN CORRADINI: But that's okay.

MEMBER REMPE: That's okay. But --

MR. GEHIN: I'm just, I didn't know where you were coming from --

MEMBER REMPE: Right, I just was curious because of my earlier question about what the vision would be and stuff and --

MR. GEHIN: Oh, you know, LOCA simulation does not use neutronics. And so, you know, you get to the depleted point of the core, then you have a LOCA event, and you assume your SCRAM. You have the decay heat. And so this is, you know, it becomes a thermal hydraulics fuel performance.

MEMBER REMPE: But that says, for example, LOCA. And again, I'm back to ATWS-I. And again, this just was focused on doing a LOCA or a station blackout.

MR. GEHIN: Well, I knew LOCA, yes, and I knew LOCA would be a question that came up. And so I wanted to talk a little bit about what the thinking is there.

MEMBER REMPE: So --

MR. GEHIN: That's why I introduced this slide.

MEMBER REMPE: And on this analysis, are the results documented in one of the reports we were provided ahead of time?

MR. GEHIN: I don't believe we provided this. We can provide a report.

But I'll emphasize, this is a demonstration, primarily answering the question is can you take a DOE code that's been developed in the DOE system and couple it with, say in this case, an NRC code. You could consider doing the same thing with an industry code where the end user may want to keep their own systems code. Can you efficiently take an outside code and do that coupling? And so that was the primary purpose of this demonstration --

MEMBER REMPE: Okay.

MR. GEHIN: -- which was successful. And this figure down in the bottom is actually a movie, but I think this is a PDF. So --

MEMBER MARCH-LEUBA: Yes, it's a PDF.

MR. GEHIN: Yes. But that was the point of it. So, if you're not able to relatively easily couple these codes, then there's no reason why you would go beyond that point. So it's really to get past the first phase of can you do that.

MEMBER REMPE: And from -- again, we didn't see the results of it. But what was better because you did this? I mean, you've showed you can easily couple them. But did you get any results that you couldn't have obtained using their own tools?

MR. GEHIN: Well, the, again, the idea here is if you believe or if an end user would like to use BISON because they believe BISON is a good tool to model ATF, it would then provide those capabilities.

You would get the fidelity of -- in fact, we can circle back to that question. You get the fidelity of TRACE. You apply it to either a single rod model or however you want to apply it, and then apply BISON to use its ATF modeling capability is the vision --

MEMBER MARCH-LEUBA: It is a PowerPoint you can take on the --

MR. GEHIN: Oh, is it?

MEMBER MARCH-LEUBA: Yes.

MR. GEHIN: Oh, you're right. Yes. And, I mean, this just shows, this is like fully coupled. It's calculating temperatures. It's calculating void fractions and in a two-way sense just --

MEMBER MARCH-LEUBA: Order of magnitude to how many person-weeks or person-years or how long does it take to do this?

MR. GEHIN: As far as the coupling?

MEMBER MARCH-LEUBA: Yes.

MR. GEHIN: I mean, the initial coupling I think was done relatively quickly. I don't know if there's somebody, maybe Steve Bajorek --

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: Because, I mean, I can do it in FORTRAN, right?

MR. GEHIN: Yes.

DR. BAJOREK: This is Steve Bajorek, Office of Research. We started this work I believe in last October or November. They had the essentially coupling features done within a couple of days.

The very difficult thing is taking TRACE's adaptive mesh where we look at the fine mesh re-nodalization, which is moving on a component basis on the fly, and mapping that into a BISON code, which is a finite element mesh in 3D.

The reason we picked this is this is about the most difficult coupling exercise we could think of in trying to take something like TRACE and couple it over to the MOOSE --

MEMBER MARCH-LEUBA: But you're talking a week, a week of work.

DR. BAJOREK: A little bit longer than that to get everything done with that adaptive mesh --

MEMBER MARCH-LEUBA: But it's not ten years.

DR. BAJOREK: Not ten years, no.

MEMBER MARCH-LEUBA: Good.

DR. BAJOREK: No.

(Simultaneous speaking.)

MEMBER KIRCHNER: Go ahead.

CHAIRMAN CORRADINI: I want to be careful on time. But I'm going to ask, so now for ATF, this is interesting. But where is the ATF application? What am I missing?

MR. GEHIN: Okay. So, if you decide you want to use BISON as your performance code --

CHAIRMAN CORRADINI: But these are just demonstrators of using BISON in lieu of FRAPCON and FRAP-T.

MR. GEHIN: That's an -- yes, that's exactly right.

CHAIRMAN CORRADINI: Or in lieu of FAST.

MR. GEHIN: Yes, or if industry wanted to take RETRAN coupled with BISON, they --

CHAIRMAN CORRADINI: Okay, fine. I get it.

MR. GEHIN: It's a demonstration that you can do the coupling, because there were questions about that. And, you know --

CHAIRMAN CORRADINI: I know.

MR. GEHIN: -- can it be done? You know, you got a, and the legacy code and you got a new code. Can you do it?

CHAIRMAN CORRADINI: I got it.

MR. GEHIN: But you would have to buy in or, you know, decide BISON is a code that you would want to use, okay, and specifically focusing on the thermal hydraulics of LOCA.

DOE code applications for source terms is a question you asked. You know, the answer we had is we're not working on it beyond design basis accidents. But there are some things here that can provide inputs for source term.

So we can get, you know, high resolution reactor inventories. These have been well-validated. These can be used as inventories that provide, you know, or provide inputs to a code such as MELCOR, get detailed rod-by-rod. These can be averaged or however it needs to be. There are validation data from PIE and reactor operation.

We can, since we're using ORIGEN, we can provide the full detailed isotope set that's consistent with NRC applications for beyond design basis accidents.

BISON calculates fission gas release. This also is information that could be useful for beyond design basis accidents.

CHAIRMAN CORRADINI: But here I'm going to, what little I know I'm going to embarrass myself. It's not just the fission gas release. It's the coupling of that to a series of accident scenarios and the frequency and seeing if I'm going to change the alternative source --

MR. GEHIN: And so --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- that part we are not doing just to be clear. I wanted to be responsive to your --

CHAIRMAN CORRADINI: No, no, that's fine.

I appreciate that.

MR. GEHIN: Yes, and then again, for transient simulation, some of these, the transients that I talked about could be used as information informed beyond design basis accidents as well.

As addition, if you want to run a case at end of cycle, we can deplete out the end of cycle and provide all those initial boundary conditions that support beyond design basis accidents. Okay.

Let me move on to validation. So the validation approach involves single and coupled multi-physics. This chart here, when you look at applying a coupled system or a core simulation type code are the typical areas that you look at, critical experiments.

Monte Carlo is usually used as a key part of this for verifying these approximations, as well as being able to map between the geometry that your codes model versus what a critical experiment may be, for example.

Fuel rod PIEs and then operating power plant data are the sources of data that we have. And again, Monte Carlo supplements all of this. This is very typical and standard of what's done with existing codes.

Subchannel validation, if you look at CTF, I believe we've provided the assessment report for that. There's the identified phenomenon for validation. I won't go through the whole list here. You're very familiar with that.

We've got a set of available open experiments listed on the right for full channel and subchannel. And in the case of like DNB, we've gotten access to some proprietary data.

Again, this would all be supplemented if a vendor were to pick up this tool with the remainder of the proprietary data that they have.

Okay. VERA validation, on the plant level, for existing fuels, there's an assessment report for this. Again, this has been our emphasis and, of course, where all the operating data is. So we've applied it to a large number of PWR plants and operating cycles.

Typically, the comparisons are made for zero power physics tests. You've got criticality, rod worth, and then flux maps during power escalation, operational measurements, soluble boron, and flux maps, and then our operational transients, start-up, shutdown, or changes in power during operation such as maybe a load-follow event where we have data as well.

These plants and cycles listed here, I won't go into this detail. But they were chosen for nominal conditions and some of these operational occurrences like PCI and crud, which is why you'll see different plants listed.

MEMBER MARCH-LEUBA: You said this operational data proprietary?

MR. GEHIN: Most of it is, particularly the fuel data. There are -- some of the cycles for Watts Bar, the first five cycles we've been able to get released. But particularly when you get to the fuel data, that, the compositions and --

MEMBER MARCH-LEUBA: Oh, sure, the fuel data but --

MR. GEHIN: Yes.

MEMBER MARCH-LEUBA: The fuel data you can get it --

MR. GEHIN: Yes, so we've gotten this --

MEMBER MARCH-LEUBA: -- but I mean the plant measurements.

MR. GEHIN: Yes, so we've gotten those directly from the utilities. They're not public data usually. Some of the older cycles like I mentioned at Watts Bar TBA is released. And there's a public document, and it's been used by others for --

MEMBER MARCH-LEUBA: You have a DVD somewhere with it just in case.

MR. GEHIN: Yes. So a lot of, we've been able to get a lot of good data on this.

And there are different reactors, Westinghouse four-loops, 17x17, 16x16. But, of course, these are all zirconium UO2 fuels. So we've got a pretty good pedigree of how this code performs for operational plants that would support a good validation case.

Transient, the data there is not as widely or as much data for, if you look at reactivity insertion accidents for the coupled physics largely rely on the SPERT test. We use that for our validation case as well.

I believe you're probably familiar with SPERT, a PWR test reactor with a central rod that can be ejected to go through a power transient.

And here's an example of a case, generally good agreement. Again, we're modeling this in full detail with the DOE codes, resolved fuel geometries and thermal hydraulics with CTF with the fuel temperature table, so good validation data there.

Now, to the ATF assessments, we've got tables that are somewhat similar to what Steve had for

BISON. Across the top we have the different fuel types. And by U metal fuel, this means non-cylindrical geometry, just to clarify.

So we've got geometry, physics models, materials and nuclear data, validation, have we performed validation for this and is there design specific validation data available. And then I've got some notes below that you can refer to.

You can see, of course, for UO2 we have, all these are yeses. Coated clad yeses, when you get down to validation performed and validation data for the neutronics, we don't have that data. But we believe that applying a coating is well within the physics capability and prediction capability of the neutronics code because it's not a large impact.

Same is true for doped UO2 or fuel, it's not a large perturbation. And if necessary, you can perform sensitivity analysis to confirm that.

When you look at the FeCrAl or the iron-based clads, again the physics models and data are all applicable. We've not performed specific validation yet with the codes, although there is previous operational data with steel clads and, as well as data that could be generated through LTAs. Sensitivity studies could help inform that as well.

Yes, go ahead.

CHAIRMAN CORRADINI: Can you expect a difference, though? I'm -- it's the doped -- I'm sorry. I missed that you had the U3Si. But if I look down the row here about it, it's not the cladding so much as the fuel constituent, right?

MR. GEHIN: We think the cladding, and we can show this through sensitivity studies. It changed the absorption properties. But that's all within our --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: I think I'd be comfortable to say that's within our physics prediction.

CHAIRMAN CORRADINI: Okay, fine.

MR. GEHIN: You'd want to do a sensitivity study.

CHAIRMAN CORRADINI: Oh, no, that's fine.

MR. GEHIN: When you get to the fuel where you're changing fuel density and things like that, which I think is, you want to look at more carefully, we -- and again, where it says no here, we have not done the validation. The capabilities you see above this line in general are yes. But we've just not done --

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: -- the validation. And in most cases, we don't have the design-specific validation data.

Now, the one caveat on that, when you look at the non-cylindrical fuel geometry, we've not implemented that in the code. The physics models and the data are applicable. But it's not been implemented. So that's the state of where we are there.

Thermal hydraulic capability, I think as Jose mentioned, you know, for all the cylindrical fuel rods, pretty much the data, you know, or I'd say the geometry capabilities and the data is applicable. Of course, for fuel we put not applicable because that's within the, the cladding doesn't impact that.

We've prepared, we've performed validation for these cylindrical fuel types. And there's validation data generally available. And where it says no here, you know, you may be able to convince yourself that the current cylindrical fuel rod data is acceptable.

For the non-cylindrical geometry, you know, we've not implemented that. We've not looked at whether the thermal hydraulic models would change. The flow distributions would certainly be different if you go to that type of fuel. So that would have to be investigated. And we've not done validation on that --

CHAIRMAN CORRADINI: But again, I'm going to ask this --

MR. GEHIN: Yes.

CHAIRMAN CORRADINI: -- to make sure, though. And when we're thinking of this, I'm always thinking of thermal hydraulic coupling back to the fuels model.

MR. GEHIN: Yes.

CHAIRMAN CORRADINI: Okay.

MR. GEHIN: Yes. Okay. All right. So conclusion, so the higher-resolution, fully coupled capabilities are developed and are applicable to ATF. These are generally done at a higher resolution than currently available that can be used for, at a minimum for investigation of impacts and insertion of LTA and can be checked, you know, against higher fidelity methods.

You can actually reduce time, in our experience, in a capability like this you can reduce the time to perform investigations because the current industry methods take pre-generation of data. It has to be tabulated, put into a code. Whereas, if you can just directly simulate something, it's more computer time rather than the effort spent investigating challenges.

We have a significant validation for UO2 forms. Most of this could be leveraged for ATF. As I mentioned, the physics we have are applicable. The data is applicable. And there are sensitivity approaches or Monte Carlo that can be used to determine whether you need to do further, get further experimental data or not. It can be used by industry or NRC to support, you know, their current tools or be adopted.

The system code, a coupling allows for evaluation of broader transients. You know, as we discussed in some detail, we're not developing that part right now within this activity. There could be some future activities in DOE that could be applied there. But we've demonstrated that you can take the capabilities we have and fairly readily couple those with systems capability, which is, of course, important for safety.

And I believe that's it. So are there any questions?

CHAIRMAN CORRADINI: Do the members have any more questions? No? Okay.

So why don't we take a lunch break? And we'll come back here, reconvene at 1:15. Okay.

(Whereupon, the above-entitled matter went off the record at 12:16 p.m. and resumed at 1:14 p.m.)

CHAIRMAN CORRADINI: Chris, I think you're going to lead us off, right?

MR. STANEK: Yes. Just a few quick comments to start the afternoon session. In the afternoon session we will switch gears from accident-tolerant fuel to non-like water advanced reactors. Although you have heard this morning during the ATF presentations about some of the codes that we will discuss this afternoon, there are still other codes that haven't yet been introduced, and so as such we've generated another version of this table.

As was the case this morning and in the interest of time I won't talk about any of the details or any of the codes in this table, but hopefully it's a useful guide for you as we go through the afternoon presentations.

Also, as was the case this morning, one idea of this matrix is that it serves as a detailed agenda. So first this afternoon we'll hear from Tanju Sofu from Argonne National Laboratory, who will present neutronics code developments for non-LWRs.

Tanju will be followed by Rich Williamson from Idaho National Laboratory, who will present fuel performance. Rich will be followed by Elia Marzari from Argonne National Laboratory. He'll present thermal-hydraulics.

Then our final technical presentation of the day will again be from Tanju Sofu, who will give a presentation of mechanistic source terms for non-LWRs. If there are no questions for me, I'm happy to turn it over to Tanju.

CHAIRMAN CORRADINI: Go ahead.

MR. SOFU: Good afternoon. As the first technical presentation of the session today, I'm going to cover recently developed neutronics analysis capabilities for advanced non-water cooled reactor designs. After a brief background, only one page, on motivations for developments of these new advanced modeling and simulation capabilities I will introduce two neutronics analyses codes, PROTEUS suite and RATTLESNAKE, to address their validation of the verification basis and cover some example applications for SFRs, high-temperature gas code reactors and molten salt reactors.

DOE and NRC have supported development of numerous neutronics analysis capabilities throughout the past several decades, mainly to support deployment licensing and operation of water-cooled thermoreactor concepts.

The purpose of this presentation and presentations that will follow, is not to provide a comprehensive look at the entire spectrum of neutronics analysis capabilities, but rather focus on the recently developed capabilities that aim for design and analysis of advanced reactor concepts.

Legacy capabilities, as well as more modern Monte Carlo codes, can also support advanced reactor designs through a varying degree of accuracy. Therefore, the recent efforts under DOEs Advanced Modeling Simulation Program focused on providing high-order, deterministic neutron transport solutions to compensate for the limitation of these codes.

CHAIRMAN CORRADINI: This is an area that I'm not very familiar with. When you said legacy, what are you thinking of?

MR. SOFU: I'm thinking about existing codes that could include PARCS for NRC, Scale System from Oakridge, the 3-D for advanced reactors, sodium task reactors, and the spectrum of other capabilities that exist. That also includes Monte Carlo codes, MCMP, SERPENT, SHIFT we heard about this morning.

CHAIRMAN CORRADINI: So those are what you would term as legacy. That's what I was trying to get at. You made the comment ---

MR. SOFU: I think I kind of mix those, legacy as well as state of the art. I think in fact Monte Carlo codes often provide reference solutions for us to compare our results with.

CHAIRMAN CORRADINI: Okay.

MR. SOFU: It did not need to be ---

CHAIRMAN CORRADINI: No, I was just trying to understand what you were referring to. Okay.

MR. SOFU: So the unique capabilities we feel the PROTEUS Suite and RATTLESNAKE can offer include high-fidelity solutions for complex geometries, with strong heterogeneities bind with flux introductions for vigorous treatment of multi-physics phenomena and transient analyses with deforming mesh capability, which is an important aspect of fast reactor design.

In terms of impact, improved operational safety margins through high order and high fidelity modeling close-to-first principle solutions or benchmarking with, benchmarking of lower fidelity, lower order modeling approaches. Again, multi-level interface with matching levels of fidelity, and by that I mean providing ten by ten power distributions to match with CFD-type ten by ten analysis, subchannel analysis of entire reactor core and finally, enhance the impact of limited experiments to support reactor design and licensing.

PROTEUS is the first of the two neutronics codes I will cover today. It is a suite of cross-section generation capability, three different neutron transports solvers, and a general perturbation theory and sensitivity analysis capability all in one package. It also comes with unstructured, finite element meshing tools, or complex geometries, and cross-processing and visualization capabilities.

MC-squared-3, the cross-section, multi-group cross-section generation tool can be used for both fast and thermal spectrum reactors, including local heterogeneity effects in a way that homogenization of the units cell prior to the cross-section generation is not needed.

PROTEUS consists of two highly-scalable neutron transport solvers for complex geometries. Again, without any homogenization, these are solvers based on the method of discrete ordinates and method of characteristics. They're highly scalable in a way that they could scale to very large number of processors for efficient parallel computing.

PROTEUS also has a nodal neutron transport solver for simpler geometries for time-efficient solutions that does not require large computing platforms.

Finally, PERSENT is a capability used for perturbation and sensitivities analyses based on variational model transport methods. In fast reactor applications, it is also used to determine reactivity feedback coefficients.

The second code I will cover today to a lesser extent is RATTLESNAKE. RATTLESNAKE development was aimed at supporting DOE's TREAT reactor restart and feeds experiment modeling efforts, but its multi-scheme transport solution options, based on discrete ordinance and spherical harmonics methods lend themselves to a broader group of advanced reactor design, analysis and licensing.

As a MOOSE-based code, RATTLESNAKE can also enable multi-physics simulations by a coupling with other MOOSE-based thermal hydraulic codes such as PRONGHORN for pebble bed thermal hydraulics, SAM, which is systems analysis code as well as BISON. You'll hear about these capabilities in the next two presentations.

CHAIRMAN CORRADINI: You have mentioned now two or three times, is there something unique about some of these reactors, I think I know it for sodium, but is there something unique about the other reactor designs that you need the coupling characteristic? Because it would strike me this would make the use of it much more difficult.

MR. SOFU: One example would be pebble bed reactor that the multi-physics coupling could enable accessing the neutronics effects consistent with the temperatures of the solutions reactor core.

CHAIRMAN CORRADINI: And you'd need the coupling versus just simply, well, okay. I see your point. I'll stop there.

MEMBER REMPE: Could you elaborate exactly how you use these codes to support the TREAT restart? Was it something where you did some calculations and you provided them to someone from DOE, or how did these codes help you get the reactor restarted?

MR. SOFU: Yes, I think the TREAT restart effort went through a licensing process not with NRC but ---

MEMBER REMPE: The authorization was DOE.

MR. SOFU: Correct. And as part of that, I think RATTLESNAKE was used as one of the codes that supported the assessment of the reactor core, but also the RATTLESNAKE's ability to analyze a particular experiment where in the test channel, the test moved, there's a different type of fuel, could be accident-tolerant fuel and coupling the overall TREAT reactor core response with the experimental fuel pins tested in the channel, so-called power coupling factors and things like that is evaluated to a great extent in very great detail with RATTLESNAKE.

In the past, such a power coupling was done mostly based on intuition. There wasn't much of a technical basis. You would actually look at the temperature sensors, what you read input in the test loop and then try to correlate what was measured overall reactor response during a transient. RATTLESNAKE did provide a mechanistic basis for that.

CHAIRMAN CORRADINI: But for the re-licensing of TREAT, for the allowance for TREAT to go forward and restart.

MR. SOFU: Also for experiment modeling. You see, I think the mission of RATTLESNAKE to support TREAT operations and experiment design is not over.

CHAIRMAN CORRADINI: Oh, okay.

MR. SOFU: Its use is going to continue.

MEMBER REMPE: So because I have not ever been personally involved with an authorization to restart a reactor, did you just give them the RATTLESNAKE calculations, or did you say this is what we would have gotten with another code and this is what we got with RATTLESNAKE, and we believe RATTLESNAKE's better because of X, Y, and Z, DOE looked at both, I assume it was coming from DOE, looked at both of them?

MR. SOFU: Yes. I wonder if Jon Carmack is here, would be able to answer that specific question.

MR. CARMACK: I'm Jon Carmack, from the Idaho National Laboratory, sort of. The way I understand it, Joy, we have to have a code that we design the experiment packages in TREAT, but the code also has to be able to model the driver core. And so RATTLESNAKE is built on the MOOSE-BISON, or the MOOSE framework to model the core but also provide the coupling for experiment design. It's going to be used in the future.

I don't believe there's any historical code that was used to benchmark against, so they've been doing a bunch of calibration experiments in the reactor to correlate with that. Dan, you got input?

MR. FUNK: I'm Dan Funk, the former manager for modeling simulation programs in NE. Joy, I just want to make sure we clarify here, I don't believe that RATTLESNAKE was required in order to get, to obtain permission and authorization to start up TREAT. I want to make that clear. But it was useful in confirming what some of the calculations and conclusions and authorization basis was, but it was really pointed more towards the development work at that point.

The desire was to have tools that would enhance the use of TREAT as we projected would be needed, and so we're looking at it very critically, it's proceeding not as fast as maybe some would hope, but as much as funding will allow. So this is more forward-looking in some ways. The capabilities are there but I just wanted to clarify that so that we didn't give the wrong impression.

MEMBER REMPE: Thank you. This helps.

CHAIRMAN CORRADINI: So let me make sure I understand, because I'm --- So PROTEUS, I have to go back a slide, PROTEUS does the reactor physics and MCC-3 does the initial ---

MR. SOFU: Cross-section generation.

CHAIRMAN CORRADINI: Cross-section generation? And RATTLESNAKE is, at least to a first approximation, performs the equivalent function of

PROTEUS?

MR. SOFU: Correct.

CHAIRMAN CORRADINI: So, I'm sorry to sound economical, but why have two?

MR. SOFU: I think there are certain reasons why two, the NEAMS program supported development of these two capabilities.

CHAIRMAN CORRADING: But you're not ---

MR. SOFU: Historically, PROTEUS code was originally supported. The NEAMS program investment in the RATTLESNAKE development was mostly focused within the context of TREAT restart.

CHAIRMAN CORRADINI: Oh. Okay. I get it.

MR. SOFU: I think the RATTLESNAKE has proven clearly that the good capabilities to support, especially for thermal reactor analyses, HTGRs and ---

CHAIRMAN CORRADINI: I'm jumping, but I'll jump and ask the question. So if your industry council comes to you and says, what would you recommend we consider for our sodium fast reactor or our gas-cooled thermal reactor or my liquid-fueled MSR, you'd say either?

MR. SOFU: I would say for fast reactors I would advocate use of PROTEUS, for thermal reactors RATTLESNAKE. I think that's also consistent with Steve

Bajorek's vision of utilization of RATTLESNAKE to support pebble bed type concept analyses within NRC.

MEMBER KIRCHNER: And could you explain why one is better for one application and the other's preferable for the other? You're basically using transport methods, you're basically using, I would guess, in-depth trials for cross-sections.

MR. SOFU: That's an excellent question. In fact, I think you could probably do both with both codes. But the level of validation basis from PROTEUS is really strong, and I think those are my next few slides.

MEMBER KIRCHNER: Okay, fine.

CHAIRMAN CORRADINI: Thank you.

MR. SOFU: So in the next pages I'll talk about the verification and validation basis for these two codes. It's mostly for PROTEUS, because of its longer development history, but RATTLESNAKE also has a very strong V&V basis, and I have a slide on that.

So MC-square-3 and PROTEUS solvers have undergone rather extensive V&V process, and in the next few slides I included only the validation cases and only for advanced fast spectrum reactors. But these two codes have also been applied to numerous other thermal reactor V&V cases, including the TREATS experiments, RPI benchmark, OECD NEAs benchmarks and then ATR benchmark recently. In this slide, I'm showing the critical experiments conducted at Los Alamos zero-power reactor, ZPPR and EPR-II experiments. Those are all US-based legacy experiments.

The BFS experiment that you see, as well as CEFR startup tests are more recent, and these are leveraged through international collaborations.

BFS in particular is a Russian critical facility, pretty much the only one that is in existence today that can support fast-reactor design. It's located in IPP in Obninsk and used by KRA to support their PGSFR design, CEA to support their Astrid design and TerraPower for their traveling wave reactor design.

CEFR is China experimental fast reactor and analysis of its physics startup test is an ongoing IEA-coordinated research project. DOE and NRC are also participants in this effort.

The figure you see on the right shows ZPPR-15 tests of four measurements in comparison of results for your uranium-235 fission rates, and the bottom figure is for DFS 761 for uranium-238 fission reaction rates.

This is, this page provides a bit more in-depth look at the comparisons for one of the tests listed on previous page, zero-power reactor 6 and 7. The chart on the right shows reaction rates along with the radius of the core with two enrichment zones, and the peak reaction rates are at the core center. This is only for one of the load configurations and as shown in the chart, all the results are within the measurement uncertainties.

The table at the bottom shows eigenvalue predictions for four different load configurations, all within 80 pcm accuracy with experiment. This is considered fairly good.

MD-squared-3 PROTEUS and PERSENT have also been indirectly validated against integral tests performed at EBR-II nf ftf. The results of two such tests are shown in this and next page.

In this page, the comparisons of multi-physics analysis with data from EBR-2 inherent safety demonstration tests, chart 45 is shown. This test has been studied as a benchmark exercise in a recent IAEA-coordinated research project with participants from 12 countries, and the results show predictions by each participant with respect to test data.

As an unprotected, that means un-SCRAMed test, the predictions for time-dependent power relies heavily on accurate assessment of the complex reactivity feedback mechanisms following detailed depletion analysis over several core cycles.

Good agreement with test data, what's shown here is power, temperatures and flow rates, all indicate validity, however indirect, of neutronic assessments against data from a very rare integral test where numerous interconnected phenomena are at play all at once.

CHAIRMAN CORRADINI: This was just the loss of, the unprotected loss of ---

MR. SOFU: It's a station blackout of ---

CHAIRMAN CORRADINI: Unprotected station blackout, okay. But that's a loss of flow test for the SFR, correct? That's essentially.

MR. SOFU: Normally loss of flow implies you lose the primary pumps only. In that previous test, the intermediate pumps are also, so it is loss of flow plus loss of heat sink combined.

CHAIRMAN CORRADINI: I see. Okay.

MR. SOFU: The other tests that were used as an indirect validation basis for these codes have been, the FFTF passive safety demonstrations has so-called loss of flow without SCRAM test number 13. This test is a new benchmark exercise, is another IAA-coordinated research project starting this year with Argonne, PNNL, TerraPower, MIT and I believe NRC as U.S. participants.

Also as an unprotected or un-SCRAMed test, the predictions for time-dependent power relies heavily on accurate assessment of complex reactivity feedback mechanisms. In the FFTF case, it also includes the response of GEMS, gas expansion modules, as novel passive reactivity shutdown device used only in FFTF.

As this benchmark project is just starting, we are showing only the preliminary results in comparison to test data but already a reasonable agreement has been observed for power, temperatures and flow rates.

This space provides a summary of RATTLESNAKE's verification and validation basis with several TREAT validation and thermal reactor benchmark verification cases that have been either completed or ongoing. Strong TREAT emphasis reflects the developmental focus of RATTLESNAKE and highlights its strength as a capability to analyze the accidents with rapid reactivity changes.

I'll quickly go through ---

MEMBER MARCH-LEUBA: Are all of these benchmarks sodium, or is there any for gas-cooled reactors?

MR. SOFU: I think there's one gas-cooled reactor benchmark, HTR-10 benchmark, I had a slide but Steve asked me to put it in the background.

MEMBER MARCH-LEUBA: You show some bias?

MR. SOFU: It's actually, we need to be selective. I have to say that pretty much every slide that you will see in my presentation, also with Richard and Elia's presentations that will follow, each page could be a presentation of its own. You can only present, squeeze so much in short time.

MEMBER MARCH-LEUBA: While I have you interrupted, the PROTEUS calculation shows the coolant temperatures. So is PROTEUS a capital thermal-hydraulic and neutronic?

MR. SOFU: Correct. Essentially, and this is really not a fully-coupled case in a way that we use the electronics tools to evaluate the, start with a fresh core and deplete it to the point where the tests were performant to several cycles from fresh core, and then do a sensitivity analysis to evaluate reactivity feedback coefficients, and those reactivity feedback coefficients go into codes like SAM, you'll hear about, to determine the transient response of the whole primary and intermediate system, and that gives you the temperatures.

But temperatures are intimately connected to power in a way that if your reactivity feedback coefficients are not calculated right, then you have no chance of getting temperatures right or power right. So that type interconnected phenomena from integral tests is kind of a unique advantage here. There are no such tests outside EBR-II and FFTF.

There is very limited data coming from Monju and Phoenix but those are all SCRAM tests. I don't think this current climate, there probably won't be any other opportunity to unprotected tests, especially with advanced reactors. So that's all we have, and I think we have a good agreement, good handle on that.

MEMBER KIRCHNER: Just to follow up on Jose's question, is PROTEUS calculating the flow, the loop conditions, or is that a different code?

MR. SOFU: No, that's actually, that's SAM that you'll hear about later.

MEMBER KIRCHNER: Okay. So this is a combination of SAM and PROTEUS.

MR. SOFU: Correct. It's one-day coupling, in other words you evaluate reactivity feedback coefficients and core power distributions, and SAM uses that to analyze the transient.

MEMBER MARCH-LEUBA: By reactivity you mean the power reactivity feedback?

MR. SOFU: Correct. The reactivity feedback, I think it's worth showing this slide here, that net reactivity, what's shown in the top, consists of several components that could be the temperature coefficients for the fuel, fuel axial expansion, metallic fuel as counting unique properties that way. In fast reactors core can radially expand. The test spectrum is very sensitive to minor geometric changes.

MEMBER MARCH-LEUBA: That's why you need a thermal-hydraulic calculation, activity times 10.

MEMBER MARCH-LEUBA: I think what you're referring to is spatial kinetics, but ---

MR. SOFU: for EDR-II that was not necessary at all. It's a very small reactor. It's a mega-watt thermal. Spatial kinetics is not ---

MEMBER MARCH-LEUBA: I'll wait until that slide and then I'm asking.

MR. SOFU: So I'll quickly go through example application of these two codes to sodium fast reactors and molten salt reactors in HTGRs in next seven slides. Some of these examples also highlight the multi-physics use of these neutronics analysis capabilities.

Here, one example of PROTEUS code usage in combination with the NEK5000, Elia will cover that that later, was assessment of hot channel factors for SFRs. The traditional hot channel factor used in SFR core design are largely based on several decades old experimental efforts in support of EBR-II, FFTF and CRBR projects. Their validity for different fuel assembly designs of next-generation SFRs is questionable.

To address this particular need, coupled PROTEUS and NEK5000 calculations are used to reassess a select group of hot channel factors for AFT-100, which is a DOE design track, a fuel assembly designed with 91 fuel pins shown on the right.

In the coupling scheme, the pin power distributions shown on the left on a normalized scale, obtained with MC-squared and PROTEUS for individual fuel pins in each hexagonal ring are passed on to NEK5000 for thermal assessments.

A preliminary comparison of the legacy and newly calculated hot channel factors is provided in this table. Legacy values based on EBR-2 are in red font and newly-calculated indicated as SHARP in the table for the name of the multi-physics interface used for it are in green font.

CHAIRMAN CORRADINI: I don't think I understand. What is SHARP?

MR. SOFU: SHARP is essentially coupling interface between PROTEUS and NEK.

CHAIRMAN CORRADINI: So it's the combined calculation.

MR. SOFU: Correct. The top row shows the parameters for which the uncertainties are considered, and the first column shows the sub-list of hot channel factors reevaluated for AFR-100. As seen in the table, these preliminary results suggest significant reduction in select hot channel factors, with safety significance especially since the metallic fuel performance for fast reactors is often limited by peak cladding temperature.

You can see that in some cases, for example cladding interval temperature which is significant parameter of interest for us, the cladding thickness uncertainty is reduced from 1.03 to 1.018. The cladding thermal conductivity influenced is almost like a, cut down by a percentage that is small, from 1.09 to 1.04, and for fuel center line there's not much of a difference but it's not particularly important parameter for us.

It's important to note that even when a newly-evaluated hot channel factor is on the same order as the initially assumed value, it still provides a better justification for its use based on validated high-fidelity high-order multiphysics computation scheme. This technique is currently being leveraged to assess hot channel factors for DOE's new versatile test reactor project as a new NEUP IRP.

CHAIRMAN CORRADINI: So what, maybe you said and I missed it, what is the legacy code, legacy tool you're ---

MR. SOFU: It's not a tool, it's an experiment. It's the value used for ATR-2.

CHAIRMAN CORRADINI: Oh. But it was evaluated using experimental data?

MR. SOFU: I think mostly hydraulic tests and such and I'm not quite sure what else.

CHAIRMAN CORRADINI: So this is not, okay, I misunderstood. I thought this was a calculational comparison.

MR. SOFU: It is not. So international projects, we see a lot of that too. For example, when India designed their own reactors they often quote the values used in France or in the U.S., whether or not it is really applicable for their specific fuel assembly design. There's a lot of uncertainty going on in hot channel factors which influence core design significantly.

CHAIRMAN CORRADINI: Okay. But, trying to figure a way to ask this question. So if I turn to TerraPower, what would they use? If they wouldn't use the tool that you're offering.

MR. SOFU: I think, I really don't know what they use. I can't say. But I think generally accepted hot channel factors based on EBR-II operations are quoted here in red, and most of the time if you don't have any other way of evaluating this coefficient, you'd probably rely on that if your reactor has some similarities to EBR-II, same type of fuel assembly, same type of operating regime, coolant outlets, inlet/outlet temperatures and so on.

That's usually pretty much what everybody does, but TerraPower may have their own way of reevaluating this using their own techniques.

CHAIRMAN CORRADINI: So, let me push the point a little bit more. If I went and I looked at the PRISM submission and Super-PRISM, or S-PRISM to the NRC, what did they use? I'm trying to get a direct comparison as to what tool is being replaced by this calculational ---

MR. SOFU: I don't think there's any tool that this calculation replaces. Values are mostly legacy values everybody relies on. The PRISM, because of its strong similarity to EBR-II, my guess is that they would be using the red values that you see here.

CHAIRMAN CORRADINI: I'm sorry, Walt, I interrupted you. You were going to say something.

MEMBER KIRCHNER: Was PRISM met metallic? Is that the current concept?

MR. SOFU: Yes.

MEMBER KIRCHNER: Wasn't it, it was -- at one time, wasn't it?

CHAIRMAN CORRADINI: No, that was CRBR.

MR. SOFU: CRBR.

MEMBER KIRCHNER: Also FFTF.

MR. SOFU: Yeah, I think there would be greater similarity to FFTF, which one, PRISM? PRISM would be very similar to EBR-II.

Another example of MC-squared-3 PROTEUS tool kit used for SFR design is demonstration of its multi-scale modeling capability. The idea here is a select fuel assemblies from focal assembly or in addition to that, surrounding six fuel assemblies can be analyzed with pin-by-pin level of detail while the rest of the core can be modeled with homogenized fuel assemblies, which is the figure shown on the left.

We demonstrated this capability again for the AFR-100 design using PROTEUS discrete ordinance solver, achieving consistent solutions for the focal fuel assemble for the second and third cases shown at the bottom row.

Applicability of this approach, the configurations with strong flux ingredients is yet to be verified, but our ability to model only the focal assembly with pin-by-pin heterogeneity while the rest of the core is modeled homogeneously offers a significant reduction in computing resources and time.

CHAIRMAN CORRADINI: I'm sorry, you don't have to go back. I'm still back with, so I've got, I'm still struggling with EBR-II. So EBR-II essentially is actual data, and you're saying that most, because of the metal fuel concept, most would probably default to that if they didn't have a calculation. So the calculation is showing that the heat challenge factors are lower than what you'd actually assume or measure for EBR-II.

MR. SOFU: I would say properly measured, but at the beginning of this study, we studied existing hot channel factors and tried to find references for them, and references did not exist. So essentially those values are taken for granted, and we've been through a similar exercise for comparing hot channel factors for the joint design of PGSFR reactor with Korea. It was a big debating point. They would use one value and our consults would advocate using another value, and there was no strong basis for what value would apply the most.

In situations like that, you usually go with the higher hot channel factor because it's more conservative.

CHAIRMAN CORRADINI: Sure. Okay.

MR. SOFU: Another example is application of the codes to molten salt reactors for eigenvalue evaluation of commercial thermospectrum concept. The intent was here to use a commercial NSR design as a test that for our modeling and simulation capabilities. This case, both 2-D method of characteristics and 3-D method transport solution options were compared with Monte Carlo solutions. What I'm not presenting here, but we also did compare with the designer's own results, with good agreement.

Generally we do the comparisons with Monte Carlo as a reference solution, but in this case

PROTEUS offers sometimes a greater, more detailed flux solution of small mesh size for coupling with other analytical tools as needed, such as the CFT solver. It also gives you a better flux in regions with low flux.

These calculations were conducted for stationary view. Flowing fuel treatment of PROTEUS-NODAL solver was also demonstrated for the graphite moderated thermal NSR benchmark problem. Three cases were considered to evaluate the effect of delayed neutron precursor drift on neutronics. Reference case with stationary field, Case A, with slow-moving fuel with ten seconds transit in the core and five second outside the core and Case B with fast-moving fuel with one second in the core and .3 seconds outside the core.

Calculated eigenvalue suggests about 100 PCM impact on eigenvalue in each case with respect to previous case, due to decay of the first three four delayed neutron precursor groups outside the core.

The impact of the delayed neutron precursor drift on reactor kinetics will be greater during transience, and this analysis will be performed for the transient MSRE benchmark in FY19.

For high HTGRs, that's proof of principle. PROTEUS was used for both prismatic fuel assembly design shown on the left and whole-core image CRG simulation shown on the right. The accurate modeling of the large neutron streaming in the control hole channel, control channel, the large hole at the center of the left figure, when the control rod is withdrawn it is a significant challenge requiring high-fidelity, high-order transport solutions.

The whole core simulations on the right were for MHTGR core assessment of computational requirements and scalability of the solver. They looked at all rods out, operating rods in and all rods in cases. There was no data to compare with, so those were more like proof of principle calculations to demonstrate the ability to model complex geometries in different reactors.

Probably the more important pebble beds HTGR modeling capability comes from RATTLESNAKE, its utilization in combination with pebble bed tracking algorithm. Motivation for the high-resolution multi-physics simulation for pebble bed motion is to support direct transport calculation with pebble tracking. The scoot element method is used to provide time-dependent position of all pebbles for establishing an equilibrium course.

The results shown at the bottom are for a particle tracking transport with nine pebble model with respect to reference case with SERPENT, indicating good agreement, and the ultimate goal of this effort is to have the ability to track the burnup of individual pebbles as they move down the core during the cycle.

The figures shown on the right are for HTR-10 simulations, using RATTLESNAKE. The total, almost half a million tetrahedra, almost 80,000 node points ---

CHAIRMAN CORRADINI: So, I'm listening and the question keeps on coming back to me. So, I'm back to industry again. What would X Energy use if not this?

MR. SOFU: I had that discussion with Martin at a meeting at ORNL two weeks ago. They're interested in this capability but I believe they have their own methodology that they're pursuing. I'm not quite sure what it is, or based on what code. But the whole idea is understanding the depletion cycle as the pebble bed core starts moving down in a very gradual and slow manner is a challenge, is a significant challenge for them as well.

MEMBER REMPE: So I vaguely remember, was it South Africans, or someone did an experiment now with the real pebble bed reactor but just with some pebbles to try and validate that they did, were capable of tracking how the pebbles would go in, and it was for a core that didn't have control rods in like a THTR. Is that what you're, or is this just a proof of principle calculation?

MR. SOFU: It's a proof of principle calculation at this point. Another important point where we don't have a completion embedded into this capability quite yet in a way, we're able to understand the item value calculation, power distribution in pebble bed with particles moving down, but we're not able to deplete each pebble as they move down. That would be the next logical step.

MEMBER REMPE: What did the Germans use for the ABR?

MEMBER BALLINGER: The code that the South Africans were using was called VSOP.

MR. SOFU: That's correct.

MEMBER REMPE: But what did the Germans use for the ABR? Did they have a way of tracking this burnup on a pebble basis?

MR. SOFU: I'm looking for who can help us with that, but to my knowledge I'm not really sure.

MEMBER REMPE: I just was curious.

MEMBER BALLINGER: I think in Japan they tried to take VSOP and turn it into a colossal Monte Carlo code. I'm not sure they were successful at doing that.

MR. SOFU: Yes, if there's a way of finding out answers to those questions and getting back to ACRS I'll be happy to do that.

MEMBER BALLINGER: There were a couple of benchmarks on criticality that they had, and I forget now, I'm losing track of time. There were some benchmarks on pebble bed criticality height as he started adding pebbles to the, pebbles to the core.

MEMBER REMPE: So, out of curiosity, if you do have a chance to find out the answer you can send it to Weidong. That's the federal designated official.

MR. SOFU: Absolutely. I have one more slide here ---

CHAIRMAN CORRADINI: So I'm still back with, I can't get off of EBT-II. I'm trying to understand the penalty that I incur by taking these conservative hot channel factors versus a more refined approach, and then I have, the next question I have in my mind is, if those were assumed, and I think I asked you and you said you weren't sure, whether they were measured or they were assumed and those were considered assumed and conservative enough to proceed with operation.

Can I get away with that with uncertainty under the current situation or must I have this sort of precision? Because if I demand the sort of precision, I look for an experiment to validate it. And I'm ---

MR. SOFU: I think that would be a question for NRC, actually. But if I were to put regulator's hat, I would say I would feel more comfortable for a hot channel factor that has a sound basis as opposed to a value that is being used because everybody else using the same thing, and then you don't even know where it comes from.

And if that value is greater than assumed value, I don't care. That's still my preference. In other words, have others reestablish the set, high channel factor set and use that on a consistent basis even though it turns out to be more conservative than some number that everybody relies on.

MEMBER REMPE: So are these codes being used to support the design development for the BTR?

MR. SOFU: Well, I think I did mention that all of the NEUP projects this year, Chris' technical point of contact is to ask university support to use these tools to analyze VTR design to reevaluate hot channel practice for BTR.

CHAIRMAN CORRADINI: The core itself, or the experiment?

MR. SOFU: The core. Oh, it could be experiment as well. I am sorry, I didn't mean to rule that out.

CHAIRMAN CORRADINI: What was done, maybe that was, I'm still not there. What was done, or no, maybe I should ask it differently. On slide 9, when you were showing the unprotected station blackout or essentially loss of flow and loss of heat sink, there was a whole range of calculations. What were the other contributors using as their tool?

MR. SOFU: Oh. So ---

CHAIRMAN CORRADINI: I'm still struggling with trying to understand how this tool relates to other available tools and what the potential Applicant, whether it be for sodium in this case, sodium or gas, would choose to use as their depth of analysis?

MR. SOFU: I can see that this legend is kind of slow, but TerraPower was using SAS and SAS4A.

CHAIRMAN CORRADINI: Was using what? I'm sorry.

MR. SOFU: SAS and SAS4A. NRG, I don't know what they were using. KIT was using, I think that's important because KIT was using PARCS and TRACE.

CHAIRMAN CORRADINI: Oh, really.

MR. SOFU: Yes. I'm sure, KIT, no, PSI, I'm sorry. What is KIT? KIT is Germany. KIT was using SIMMER, PSI was using PARCS and TRACE, KAERI was using MARS-LMR, IRSN was using a code they called, I'm sorry, my mind is losing. CIA was using SANS, SANS4A Fukui was using their own JAEA Code.

CHAIRMAN CORRADINI: I guess where I was going with, the only thing I could remember was SAS. So, another way of saying it is PROTEUS in combination with SAM is the replacement for SAS.

MR. SOFU: For a lot of these participants, did get the reactivity to feed the coefficients they used for those codes from Argonne.

CHAIRMAN CORRADINI: Oh.

MR. SOFU: They did not do the neutronics part of it. Only a handful of them did. I think Fuqui did and PSI did, PSI used PARCS for that, so I think it turned out doing this benchmark was too much to bite for a lot of the participants so they, some of them, large number of them chose to only the system analysis, safety analysis, transient part of it.

CHAIRMAN CORRADINI: So from the standpoint of trying to understand, what goes through my mind it, they're using their legacy tools to do the analysis.

MR. SOFU: Correct. I think I'll just briefly mention this since I am running out of time, this was a multiphysics analysis of SFR core deformation. It's an interesting assessment because it uses coupled, fully coupled, PROTEUS, NEK5000 and DIABLO for structural mechanics calculations to understand how a fast reactor core would radially expand.

It is an important reactivity effect, in fact in the chart below you see that this is the highest contributor to net negative reactivity in this case, but typically that counts for a lot of the inherent safety features that we obtained.

The ability to make that prediction based on very detailed subassembly by subassembly representation of the entire core with neutronics, CFD level of thermal hydraulics and structural mechanics, is the first demonstration of having a complete mechanistic way of predicting this for new design.

MEMBER KIRCHNER: What would you venture the uncertainty is on that, and how does it scale?

MR. SOFU: There wasn't anything for us to compare with on this. It was more like a proof of principle type of demonstration. You know, an ideal application of this would be perhaps apply this to EBR-II and FFDF transients and analyze, reassess the core radial extension feedback and then put that back into the system analysis code to see if you're getting consistently code.

CHAIRMAN CORRADINI: Right. So this is an unfair question, but we're in the world of unfair. What is the person-months of effort necessary to do such an analysis?

MR. SOFU: Elia was involved with this project.

MR. MERZARI: Should I answer that?

MR. SOFU: I'm guessing maybe a year type of, maybe a little longer than a year. Go ahead.

MR. MERZARI: So this is the Elia Merzari from Argonne National Laboratory. It's a bit of an unfair question in the sense that this was a proof of concept. So the first time that you do something, it always takes longer. It took quite a bit to demonstrate. It took about six months to the calculations you see there, but I would envision that once we streamline the process, this could take no more than a few weeks. It wasn't done on millions of processors, it was done on 120 processors.

CHAIRMAN CORRADINI: So, modest amount compared to others.

MR. MERZARI: Yeah. And you saw something that you need to do a lot of work to find.

MEMBER KIRCHNER: Well, it's crucial to use it as a design tool, because you're going to hit a point where the size of the core isn't going to give you enough, your expansion versus your leakage, etc., isn't, it's going to limit the size of the module, essentially. And then you need to assess your uncertainty and your margin as you push that limit. I mean, that becomes a fundamental design challenge.

MR. MERZARI: Right. And I should mention that that calculation was a demonstration again. It was very little sensitivity, it was some sensitivity but not near as much as we need, and there are several sensitivities that go into a calculation like that, means a stage lost regularly through the core. There are several things that will need to be done for a to think of full design tool, but I agree with you.

CHAIRMAN CORRADINI: Would depletion be one of them?

MR. MERZARI: Certainly the rigid core expansion depends on fluence.

CHAIRMAN CORRADINI: Okay. And that also would have to have been done. Or needs to be done, I should say. Needs to be done.

MR. MERZARI: We need some calculations of different states, but you can assume this rate of fluence as an input to the calculation.

MR. SOFU: In radiation swelling of fuel assembly, the contribution to this expansion is captured with the DIABLO models. I think the importance of that particular application is there is no such comprehensive multiphysics way of evaluating the core radial expansion for a test reactor prior to this demonstration.

We have codes like NOUVEAU, you may remember, Mike, but they are generated during the IFR program very largely on empirical basis. But you get a code like that, assume applicability for a new design, is always going to be an open question.

CHAIRMAN CORRADINI: So I know we're running 15 minutes late but it's unfair, is the reason we didn't see RATTLESNAKE is because it's in the background slides but there are ---

MR. SOFU: No, I think largely I'm the one to blame for it because I'm more familiar with PROTEUS and I think the question about including RATTLESNAKE came in the late stages of preparing for this meeting, so I was able to leverage three or four slides from Markie Hart, I was grateful to give you what I have.

But we recognize its importance for NRC, especially for division, Steve Bajorek's vision to utilize that capability as a component of the MOOSE framework and for HTGR applications, so by no means is that an indication of its importance.

CHAIRMAN CORRADINI: Okay.

MR. SOFU: Thank you.

CHAIRMAN CORRADINI: On to fuels. We've used up about 20 minutes of your time, I'm sorry, Rich.

MR. WILLIAMSON: Okay.

CHAIRMAN CORRADINI: And we'll try to give it back to you, maybe.

MR. WILLIAMSON: I'm not sure I need the full time.

CHAIRMAN CORRADINI: Okay.

MR. WILLIAMSON: Okay, good afternoon. My name is Rich Williamson, I work and in fact I've always worked at the Idaho National Laboratory. My presentation is Fuel Performance Modeling for Advanced Reactors.

Here's the outline of what I brought to

present. I have a single slide to begin with. It gives background information including the objective of this particular presentation. I have a section of slides that are the BISON fuel performance code that essentially duplicate what you saw this morning in Steve's presentation. I left them in there intentionally so that the presentation was more complete, but we'll be able to skip over that section almost completely. There is one point I want to make out of those slides.

And then really the bulk of what I want to talk about is application of BISON to two fuel forms, TRISO and metallic fuel. So that'll be the bulk of what I have to talk about in summary, conclusions at the end.

As you know and as you've heard already this morning, DOE is developing modern fuel performance, modeling tools applicable to a wide variety of fuel and reactor types, operating conditions, geometries, and spatial scales. This capability has been developed for both advanced and traditional LWR concepts with LWR fuel receiving the greatest early emphasis, so that the plan has been to, from the beginning has been to look at both advanced and traditional fuel but to really demonstrate and learn by application first to LWR fuel.

As Steve pointed out, multi-scale modeling for us, the coupling device and the norm it provides, improve mechanistic material models and has delivered demonstrated results for UO2 fuel and we intend to follow that same path for advanced fuels.

The presentation objective is to provide a current status of DOE fuel codes for application to specific advanced reactor concepts as are identified in the table, which lists the key advanced reactor concepts against their fuel and coolant characteristics.

The key takeaway from this table, and I think it's simple, indicates that the DOE fuel performance codes BISON and MARMOT have demonstrated capabilities for metallic fuel, applicable to the SFR concept, and TRISO particle fuel applicable to the MHTGR and FHR concepts, but at this stage are not applicable to the MSR concept which employs a liquid fuel. So the focus then will be on metallic fuel and TRISO fuel as I mentioned previously.

This is the part we skip over. You heard about MOOSE, BISON, MARMOT, so you know about M.M. This is almost a duplicate of what you saw before, details about BISON and what makes BISON different.

CHAIRMAN CORRADINI: You're doing great.

MR. WILLIAMSON: I'm at slide 8 already. So, it slows down a bit in a minute. This slide has already been covered in some depth by Steve as well.

The only point I wanted to make is on this slide, concerning BISON documentation. I wanted to draw your attention to the link in the third line there that is a place you can go to get a current set of manuals. So although the code is, you have to have a license to get the source code, the manuals and documentation for the code are available, external documents, so anyone can go to that site and pick up those manuals.

The other point I wanted to make is it is an enormous headache to try to keep a source code and documentation and validation all in step at the same time and keep everything complete, so we're working and currently transitioning to a web-based documentation system that will combine the theory and user manuals and post more strict requirements on documentation of new code, but essentially much more the documentation will exist with the source code and build from the source code, so when you get the code you can build the documentation and that forces developers to keep things much more in lockstep.

Moving on to TRISO particle fuel. This slide is an effort to in a single slide cover the capabilities that are currently in BISON for TRISO particle fuel. I have a similar slide that I use for LWR fuel and a similar slide that you'll see in a minute on metal fuel, and the first point I wanted to make is this box on the left will always be the same.

The general capabilities in BISON, finite element based for a variety of different types of geometries, fully-coupled thermomechanics, species diffusion, these capabilities are the same for all these fuel types and so that's one of the, in my opinion, one of the real advantages to a code like BISON, because much of the fundamental capabilities that you need are there, and it's oftentimes more a matter of enhancing and adding capabilities to include in a fuel type.

MEMBER REMPE: Rich, I heard earlier today you took the PARFUME models and put them into BISON. Didn't PARFUME also have something about the silver attack on the silicon carbide for accident temperatures, so does the DOE approach say use BISON, but then if you need to do an accident, still go use PERFUME, or do you still have PERFUME that you guys are using at Idaho, or what's the story?

MR. WILLIAMSON: We still have PERFUME. To my knowledge it's no longer actively supported. The intent is to move away from PERFUME but there are capabilities that still exist in PERFUME that are not in BISON yet, and that's part of our current gap analysis. That's what we're working on now, too, to identify the gaps and put our development efforts into closing those gaps.

MEMBER REMPE: What would you use if you don't start, are you going to try to have an accident version, like go to MELCORE or something like that for accident analysis, or what's the plan? Or you haven't decided yet?

MR. WILLIAMSON: Yeah, I guess I would come down to haven't decided yet, although we don't plan, as with LWR fuel and ATF fuel that you heard this morning, there's no intent of going to severe melted fuel or anything like that.

CHAIRMAN CORRADINI: But I think that where Joy was going is if you take this to different DBAs and beyond-DBAs, you're going to need to do that to develop source terms. To develop source terms, you're going to need a release model. To have an release model, you're going to have to put it in a construct, so is the construct PERFUME? That's what I heard you kind of say.

MEMBER REMPE: And you said PERFUME's no longer supported so I think you got to go to MELCORE or something, I don't know.

MR. STANEK: I think a lot of this will be described in Tanju's last presentation. I'm not going to list source term that will go through for each of the reactor types, how one could generate a mechanism source term.

MEMBER BALLINGER: Can you do UCO as well?

MR. WILLIAMSON: No. Not today. We do UO2 only at this stage. The developments that you see here actually occurred early in BISON's life. This capability was available in like 2013 and there hasn't been a huge amount of effort in development since then.

MEMBER BALLINGER: Because I think that's what does in UCO.

MR. WILLIAMSON: Again, that's a gap. And you'll see when I come to the end of the triso section that is one of the areas of development for next fiscal year.

CHAIRMAN CORRADINI: So, Rich, maybe I misunderstood the cartoon. Is the colored cartoon in the middle the kernel or the compact?

MR. WILLIAMSON: In the middle is just the particle.

CHAIRMAN CORRADINI: So, excuse me for sounding holy god, you're going to nodalize that and then you got to get 1,000 to 10,000 of those in a compact and billions of them in a core, or are you developing some sort of empirical set of calculations that then would feed into some more macroscopic --- I guess I misunderstood.

MR. WILLIAMSON: I think I have a great answer to that coming.

CHAIRMAN CORRADINI: Okay.

MR. WILLIAMSON: So if I don't get to that then we'll come back to it, but I think I have that answer and I'll make sure to cover that.

So we talked about general capabilities. Fuel kernel is UO2 to date, and that's principally because UO2 is already a known quantity for us and so the UO2 model that we use for LWRs is essentially applicable to particle fuel although there are issues. For example, the CO production that is important for TRISO particle fuel had to be implemented or included for the TRISO capability.

Likewise, gap behavior, with TRISO particle fuel a gap can form between the inner, the porous pyrolytic carbon layer and the inner pyrolytic carbon layer and so you have to be able to handle a gap. We do gaps from the experience in the LWR world and so gap behavior is essentially there, we just have to worry about changing the fluid and including some capability to move mass across the gap.

So in essence, the newness of BISON for TRISO in material models for silicon carbide and pyrolytic carbon. We've included an irradiation creep model for silicon carbide and for pyrolytic carbon anisotropic irradiation-induced strain and irradiation creep.

And these models, Joy mentioned, come from PERFUME. Our actual source for these is mentioned at the bottom, but I think you'll find that's true. The same models that are in this source in 2004 were in PERFUME.

MEMBER BALLINGER: What are you defining as failure? Are you modeling failure?

MR. WILLIAMSON: You're getting to all the points that we don't do, and that's one of them.

MEMBER BALLINGER: Is that, the particle fuel is inherently probabilistic.

MR. WILLIAMSON: Understood.

MEMBER BALLINGER: Inherently

probabilistic.

MR. WILLIAMSON: Understood. And so, again, when you see my plans for even next year, that's one of them. The point I need to make again is this is development that has really lain dormant for a few years and now with increased interest in advanced reactors and TRISO fuel, has cranked back up and those are areas that we will address and have begun to address.

Now I have three examples, and I hope these lead to an answer to Mike's question. I have an example of an application device to a 1-D spherical particle, then a 2-D and a 3-D application. I'll start with the 1-D case.

It assumes spherically symmetric. And because it's spherically symmetric, it can be done in 1-D. So the mesh you saw was a three-dimensional mesh which is indeed complex. But if you assume it's one dimensional, as is done with PERFUME, then the problems run very quick, typically in under a second. And so with 1-D, if one assumes spherical symmetry, then one can run many of these particles and do statistical analysis, failure analysis in the same sense that it was done in PERFUME.

So this is a 1-D example. It involves the geometry you see here, so a UO2 kernel, porous paralytic carbon layer and then the typical three TRISO layers. What we've looked at as far as physics in this problem is thermomechanics plus cesium diffusion. We looked at a single fission product diffusion. There are no issues with adding other species to that, and then for this example, and this is just an example calculation, we show, what we looked at here was really three steps.

First an irradiation period that goes for two and a half years to a burnup of 12 percent as a step one. Then actually we moved from the core for 100 days in storage to decay, and then to simulate accident behavior, the particles essentially were just heated, furnace-heated to 1800 K for 220 hours to see the effect of an increased temperature.

MEMBER REMPE: This is ---

CHAIRMAN CORRADINI: This is an experiment?

MR. WILLIAMSON: This is a pure example.

MEMBER REMPE: This is where I'd think you'd want to have the silver. Don't they start having problems like 1600 C is when you start worrying about the silver?

MEMBER BALLINGER: Silver doesn't attack, it migrates through.

MEMBER REMPE: Right, okay, so then you have to worry about it ---

MEMBER BALLINGER: Cesium does a number on the ---

MEMBER REMPE: But doesn't it start migrating through at ---

MEMBER BALLINGER: Much lower temperature than that.

MEMBER REMPE: Yeah. So it seems like you're kind of missing something.

MR. WILLIAMSON: Yes. And I agree. I agree fully. We included cesium because we knew that cesium would move through the silicon carbide layer at those temperatures whereas it doesn't at operating temperatures. But yeah, point's well taken. Again, that species can be added to this calculation.

This, again, is just an example calculation to demonstrate capability, and there's lots of results to show. I just showed two. One's the tangential stress history for both the silicon carbide and pyrolytic carbon layers. I would just trace the red curve at the bottom which shows the silicon carbide layer, and it shows the expected behavior of that layer moving in a strong compression early in life because of the compression of the pyrolytic carbon layers but as the pressure builds in the particle that stress eventually goes into tension and then into significantly higher tension during the accident. So again, just a demonstration of capability.

The plot on the right shows the cesium concentration, these are radial profiles from the center of the particle out to the edge and two of the most curves show basically the cesium distribution after radiation and after storage, no change there, and then when raising the temperature much higher, then you start seeing the cesium diffuse out. That was the point we were trying to make here.

Again, this is in 1-D but run times of under a second permit rapid analysis if one wants to look at loss of particles.

The second example is now two dimensional, base spherical particles can occur during manufacturing as is shown in this micrograph. If one is okay looking at a single-faceted, aspherical particle, then this problem can be analyzed in 2-D axisymmetry. So it's a step up from 1-D, still computationally reasonably simple but it does permit one to look at a multidimensional type of effect.

So here we looked at the same example,

behavior as before, base irradiation followed by an accident, but now are comparing a spherical particle to a particle that has a facet, it has a flat spot on it. The two results that I chose to show are shown here. The red curve compared to the blue curve is the stress history in the outer silicon carbide layer, and you see the aspherical raising, after radiation, much higher stresses, much higher tensile stresses.

You see the same in this contour plot. This is at the end of the base irradiation and you see, for this example geometry that we picked, increases in the tensile stress in the order of a factor of four by having this facet there. So the multi-international effects are clearly important and can be addressed with BISON and 2-D reasonably efficiently. This problem ran in a few minutes, as I recall. Six minutes, using eight processors.

Moving now to the 3-D. Particles can show localized thinning of the silicon carbide layer due to soot inclusions or because of fission product interactions on that layer, which obviously will degrade the capability of the silicon carbide layer to handle the pressure of the particle.

So for this, again an example, we simply added random thinning to the silicon carbide layer as one might see here and simplify the case even more, just looked at asymmetry of this hole in this whole particle.

And the takeaway from this, as you can see, the stresses plotted here a region that is not thin compared to a thin region. You see significantly higher ensile stresses, significantly higher cesium fluxes in those regions. So certainly concerns that come up that can really only be addressed in 3-D. These cannot be done in 1-D.

CHAIRMAN CORRADINI: So maybe you're not done. I was going to ask the question, are you finished?

MR. WILLIAMSON: Yes.

CHAIRMAN CORRADINI: So, you went from 1-D to 2-D to 3-D, and the real manufacturing of the fuel you don't know where you are between spherical, asymmetric and a flaw, so what does one assume from the standpoint of prescribing the uncertainty range to do the original calculation before you even do the extant calc. I'm struggling here.

MR. WILLIAMSON: I am too. I really don't have an answer to that.

MEMBER KIRCHNER: You have to do it statistically, based on the post-production sampling of the kernels.

MR. WILLIAMSON: I think so.

MEMBER KIRCHNER: Your earlier picture already shows that most of them are not spherically symmetric. That's the experience from manufacturing.

MR. WILLIAMSON: Others probably know better than I do about that, you know, but that's ---

CHAIRMAN CORRADINI: Okay. So that would lead me to my next thing. Are, you have the AGR experiments. Was there pre-analysis so you knew the range of geometrical conditions of those compacts so you could then put that into a calculation, then see what you got post-test for the AGR, I can't remember which was which. I think AGR-1 was steady stage, R-2 was taken to failure, I don't remember. But is the, are the AGR experiments the place for validation of these sorts of analyses?

MR. WILLIAMSON: I think so.

CHAIRMAN CORRADINI: But they've yet to be looked at?

MR. WILLIAMSON: Correct. I'm about to show you what validation is done today. And it isn't a great deal. The only other point I wanted to make on this slide is now the run times have gone from a few minutes, so we went from under a second to a few minutes, now to a few hours on eight processors, and obviously that could be reduced some with more processors but now these are much more significant computations.

MEMBER BALLINGER: There were a whole bunch of benchmark runs, MPR 1, 2, 3 and all that. Are you aware of those?

MR. WILLIAMSON: I thought you were going to the benchmark, the IAEA benchmark.

MEMBER BALLINGER: Well, there's them too but there was a whole series of benchmark codes, benchmark runs in the early days that PERFUME was compared to as well along with others, and they didn't do too well, primarily because of the probabilistic nature of the failures. And so them had to do some stuff to make it work. But those, I don't see those listed. They're very well characterized.

MR. WILLIAMSON: Point well taken. We'll look at those. We haven't yet.

MR. STANEK: Rich, maybe this is a good point to point out something that Steve went through very quickly in his fuels presentation today, which was, it's analogous, which was he showed a 3-D image of a missing pellet surface, so that's a manufacturing flaw in UO2 pellet, but the 3-D code like BISON, you can do an analysis on manufacturing tolerances, what sort of tolerances can be, what size flaw leads to what size stress concentration is essentially the analysis that can be done, which would then inform the manufacturing tolerance which would then have an impact on your probabilistic failure assessment.

And so, this 1-, 2-, 3-D type of analysis, I think that's sort of where we're getting at too, is that yes, failures are probabilistic. Having a handle on how much of a flow one can accommodate in the fuel fabrication is something that can't be done with this type of pressure.

MR. WILLIAMSON: Okay. Moving on to V&V, particle fuel V&V efforts to date consist really of comparisons to an IAEA benchmark which is entitled CRP-6. Early 2000, I think, is when that happened. They, it really was an effort to compare codes on a series of problems rather than comparisons to experimental data.

So it's not full-on validation, but it's comparison to codes that are fully validated so it's a good first step.

This IAEA CRP-6 developed a set of fuel performance codes benchmarked in cases for both normal operation and operational transience. They ranged in complexity from a simple fuel kernel having a single elastic coating layer to realistic TRISO-coated particles under a variety of radiation conditions.

As indicated in the table on the left, BISON has been assessed against analytic solutions and other particle fuel coats for 13 cases from that benchmark. I think the total was 16, and at the time we did this work we did 13 of those 16.

Many comparisons can be made from that chart. I chose to make comparisons here to tangential stress, which is important for particle integrity. Comparisons of the tangential stress are shown in the table on the right, but the simplest cases, cases 1, 2, and 3, they all have analytic solutions and so BISON comparisons are excellent, as one would expect, to an analytical solution.

But the more complex cases shown in the bottom table, comparisons are made to a range of solutions attained by the fuel codes and the benchmark. Here the solutions are compared to the range, as you see from that table, the range of values that came out of the handful of codes that were involved in the benchmark.

About all we can say from this comparison is that the BISON solutions were always within the range of values computed by the other codes, but no deeper than that.

Continuing with the benchmark comparisons, results are shown here for three cases that have increased complexity. For these cases, rather than compare to all the codes, we chose to compare to three well-known, reasonably well-validated codes. Those are PERFUME from the U.S., STRESS the UK, and the ATLAS code which is the only of those codes that is finding element from France.

On the left, you see comparisons for Case 8, which was an effort to simulate the cyclic particle temperature experienced during multiple passes through a pebble bed reactor. You can see the passes, the effort to simulate that. Predicting the tangential stress in the inner pyrolytic carbon layer, which are the curves at the top, essentially overlaid for the four codes.

Then predictions of the tangential stress in the silicon carbide layer, which are the four curves at the bottom, nearly overlay. I want to note that these are what I consider excellent comparisons are really not unexpected, because this Case 8 of the benchmark carefully controlled everything about the calculation they compared. They controlled the geometry, even the material models, and so one would expect very good comparisons. And I point that out as we turn to Cases 10 and 11, where that wasn't the case.

For Cases 10 and 11, on the right, these were based on German fuel experiments. Here comparisons are made to the tangential stress at the inner silicon carbide wall, and you see substantial differences in calculations, particularly for Case 11 which are these four curves that go to higher burnup.

These variations have been attributed as part of the benchmark. Principally the differences in the fission gas release model, so for this case they didn't control the gas release and CO production models and so now you're starting to see the variations in codes because of the different models, selections of different models.

The BISON fell within the, with our inherent gas and CO production, this BISON is the red curve which is in kind of the middle of the pack.

MEMBER REMPE: Explain to me they didn't control the fission gas release model. It might be a function of temperature or something like that?

MR. WILLIAMSON: They didn't specify. So say for Case 8, they went to the point of specifying, this is the constitutive model, this is the equation you will use for irradiation creep of silicon carbide, for example. And so you would expect very good comparisons if you have constrained your benchmark to that detail.

But this Case 10 and 11, they constrained some of those details but they let the individual users then use whatever they have in their code for fission gas release and for CO production.

MEMBER REMPE: So then I would say that the Case 11 is more typical of what would happen if a licensee were to come in and say, this is what I believe will happen with my reactor for this particular event, and jeepers, man, there's a big variation, and don't they have to have data to validate any of these different models for that burnup?

MR. WILLIAMSON: I think so. But I ---

MEMBER REMPE: Something we'll have to, the regulator will have to testify knowing that there's so much variation there.

MR. WILLIAMSON: It's something that we will shortly learn more about as we move from these benchmarks into full-on validation where we look at what data are actually available and start making these detail corrections.

MEMBER BALLINGER: Did you separate out the fission gas release plus the CO production to see what contributed most to the stress? I suspect it's CO production.

MR. WILLIAMSON: And I would agree. So if you look at the, there's a paper that describes all this, and in there we compare the pressures and I don't remember if they were separated but I would agree, that's typical. I think that's because the CO is the bigger component out at those higher burnups.

CHAIRMAN CORRADINI: So I'd like us to get through your talk before we take a break, so are we on our way?

MR. WILLIAMSON: When is break?

CHAIRMAN CORRADINI: I'm going to declare break in 15 minutes. How we doing there?

MR. WILLIAMSON: I think easily.

CHAIRMAN CORRADINI: Okay, good.

MR. WILLIAMSON: I think. I hope so. Because I'm ready to wrap up TRISO just by saying if you want to read more detail about anything that I've talked about on TRISO so far, it's in this paper, this journal article, and then I want to quickly go through what our plans are with regard to development. Some of this has already come up.

We started now looking at PERFUME and BISON to develop this gap, capability gap analysis so that we know what's in PERFUME and what is needed in BISON. As Ron pointed out, UCO is an important fuel for particle fuel, and so that's certainly on our list as well as more mechanistic CO production. CO's a very important component, as has also been pointed out, and we have a very simplistic empirical model there.

Then particle failure probabilities have already been mentioned. We also, BISON with its discreet fracture capabilities, we're in a position to look readily at partial de-bonding between layers and actual silicon carbide fracture, and so we will begin experimenting with that.

MEMBER BALLINGER: Again, that silicon carbide fracture is also probabilistic, because the Weibull modulus is way different than for metal or something, and that Weibull modulus is a function of how you fabricate the particles. And so there's an uncertainty on the Weibull modulus which translates into a big difference in stress and fracture strength.

MR. WILLIAMSON: I can only agree. With regard to validation, talked a bit about that. Our next step that we started on is to look at the database. We need to better understand the database, review the NRC HTGR research plan to better understand the issues, and then during FY19 my intent is to develop a validation plan for TRISO fuel and begin to learn the high priority cases from that plan.

MEMBER REMPE: The only designer that's coming forward with a gas reactor right now is X Energy, is that true? Because AREVA said, we can't find a customer. They've kind of backed off. Is there anybody else out there that has a gas reactor? Because if that's the case my next question is, is it true that X Energy is using something in scale?

MR. STANEK: The answer to the first question is, in terms of gas reactors, I think you're correct. But there is an FHR vendor that's also using particle fuels.

MEMBER REMPE: That's true. Okay. And then I guess they are interested in the BISON suite, is that true? So you have some, I mean if it's true that X Energy's doing something else other than BISON, I'm just kind of wondering ---

MR. STANEK: Again, we ---

CHAIRMAN CORRADING: He's not going to answer that question.

MR. STANEK: Can't answer that question.

MEMBER REMPE: Yeah, okay.

CHAIRMAN CORRADINI: He's been instructed not to answer that question.

MR. WILLIAMSON: So I'm going to spend my last ten minutes on metallic fuel, and I think that is possible. I have less to say about metallic fuel. It's at a, there's a lot of capability there to do metallic fuel but very little validation to this point so not as much to talk about.

Here's the same slide that you saw for TRISO fuel. The general capabilities, as I pointed out, are the same for all these codes and in fact for the type of geometry here, for metallic fuel at least, the gap is essentially the same. One just needs to change the gap material from gas to sodium, in this case.

So much of the capability was in place to both the gap and the general capabilities. The real work has been in developing material models for metallic fuel. We're looking at both binary and tertiary UZr and UPuZr alloys, and you see the list of capabilities that have been placed in the code. Temperature dependent, temperature, species and porosity depending on connectivity, anisotropic swelling, thermal variation creep, thermal porosity-based fission gas release and zirconium diffusion models.

Cladding is different for these fuels, so models have been implemented for both HT-9 and 316 stainless in terms of temperature-dependent conductivities, thermal and radiation creep. For the HT-9 there's a failure model that has been implemented in BISON.

Coolant channel, again, borrows heavily from LWR work. In fact, essentially is the same model with sodium fuel fluid properties and sodium heat transfer correlations.

I have a single fairly simple example here. This is a pit from EBR-II. It's modeled assuming axisymmetry, so this is a 2-D-RZ calculation. Here we're looking at thermomechanics plus zirconium diffusion in the fuel alloy, all fully coupled. This is sodium bonded with sodium coolant channel.

And then for this problem to look at parametric behavior and understand fuel behavior better, the user looked at variations in fuel alloy composition and pin power.

And just two fairly simple results. Here's the temperature histories for different fuel compositions. You see expected behavior in that the fuel temperature rises gradually. That's mostly because of increasing porosity in the fuel until that reaches kind of a steady state and then the temperatures become steady. Similarly, the pressures as a function of different power rates show the expected behavior that higher powers mean higher pressures.

In regards to fuel metal validation, there's really quite a bit of older data out there from EBR-II and TREAT, and I think FFTF. We're digging into those databases to better understand what's available. Cases in progress are listed in the table at the bottom.

Scheduled for completion in FY18 are three cases from EBR-II and an transient case from TREAT. I have results from one of those cases, from X447. These are, I would still term these as preliminary because we've only seen them in the last few weeks and are still digesting them but this is a binary fuel at an average power of 30 kilowatts per meter for about a year. The multiple rods, these rods were taken out as Steve mentioned at various points in time to do PIE on them, in order to get these four data points. That's what had to be done, is a rod had to be removed and PIE had to be done to get the fission gas release.

CHAIRMAN CORRADINI: Just a quick question. Is the manufacturer, the way you make the metal fuel, going to change the properties one would then use in the calculation? Because my understanding is the way they made the EBR-II fuel is not the way TerraPower would make their current fuel.

MR. WILLIAMSON: Steve, you're going to have to help. Steve is a metal fuels guru, I'm not.

MR. HAYES: That's true.

CHAIRMAN CORRADINI: And you are?

MR. HAYES: Steve Hayes, from Idaho National Lab. The answer is, metal fuels historically has been manufactured in lots of different ways, and you're right, TerraPower proposes doing something a little bit different but one thing we've been fairly successful in showing over the years is metallic fuel performance is relatively insensitive to fabrication routes.

CHAIRMAN CORRADINI: So the property, I was trying to get at the property ---

MR. HAYES: I don't think he needs to modify many properties, or any, based on fabrication route.

CHAIRMAN CORRADINI: Okay. Thank you.

MR. WILLIAMSON: Thank you, Steve. Okay,

just drawing your attention to these three plots. Cladding hoop strain is a function of position, the sharp drop in both the measurements and in the calculation correspond to the top of the fuel slug.

Fission gas release is shown in the upper right, and then a comparison of the peak inter-clad temperature. This is a comparison between BISON and an estimate that was made by the experimenters. There was no measurements for this plot.

So what we can say at this point is we've done some very early validation of the metallic fuel capabilities. The first comparisons are very reasonable. There's significant work yet to be done.

Which brings me to the development and validation plans for metallic fuel. With regard to development, there's five bullets there. Our plans are to improve and/or find an alternate for the fuel swelling model. Early calculations have shown an issue with the radial swelling. Our current Zr diffusion models are applicable to tertiary but must be extended to the binary. We need to investigate lanthanide diffusion and fuel cooling and cladding interaction, sodium infiltration and cladding swelling.

There's, I guess what I'd like to leave the impression is there is a capability to do metal fuel but it's to the point where we can begin doing detailed assessments by comparison to data. We know there are areas of development that remain and we are focused on those. We're building the set of validation cases for FY19. I list three from EBR-II but there will be more than that.

That brings me to summary and conclusions. I think I'll just let you read those. I guess I, the top bullets are, I think, obvious as we walk through this, and the bottom opportunities for cooperation, certainly one is to implement fuel behavior models in vendor or NRC codes. I just wanted to point out that that effort has begun. As we learn more about material models or we use MARMOT to create proof of material models, we're very interested in cooperating, including those in NRC codes or vendor codes if there's interest. We have begun that effort and moving in that direction. Obviously there's the opportunity to use BISON by the industry or by NRC,

CHAIRMAN CORRADINI: Questions by the committee? Okay, let us take a break.

(Whereupon, the above-entitled matter went off the record at 2:56 p.m. and resumed at 3:13 p.m.)

CHAIRMAN CORRADINI: Okay, let's get back together, and I think now we'll turn to Elia.

MR. MERZARI: Yes Mr. Chairman, it's a pleasure to be here. It's actually an honor to be presenting, and I'm grateful for the opportunity.

CHAIRMAN CORRADINI: I'm not so sure about that.

MR. MERZARI: Can you hear me?

CHAIRMAN CORRADINI: We can hear you.

MR. MERZARI: Okay, thank you.

MEMBER REMPE: We're not sure we believe you.

MR. MERZARI: I'm sure, I know. In fact, I was sincerely not saying the word pleasure there, but let me ---

CHAIRMAN CORRADINI: But you went further and you said honored and --

MR. MERZARI: Yes, I know.

CHAIRMAN CORRADINI: -- now it's on the record.

MR. MERZARI: Yes that's right, it's on the record. So, in this presentation, I will cover the capabilities for non-light water reactors for three thermal hydraulic codes in development of DOE and it's a lot of material so believe me, I'm aware I have an accent, and I encourage you to stop me when I--when you can't understand what I'm saying but please, perhaps let's consider limiting the interruptions otherwise you'll never get to the end of this presentation but---

CHAIRMAN CORRADINI: I have a---

MR. MERZARI: --now that I've said that, you're going to interrupt me more, I'm sure.

CHAIRMAN CORRADINI: I have a--no, I was going to say we've dealt with the Spanish so we can deal with the Italian.

MR. MERZARI: Of course. Okay, sounds good. Okay, here are the codes I'm going to talk about: SAM is a component-based system code based on the MOOSE framework which you read about today, PRONGHORN is an engineering scale akin to the code, based again on the MOOSE framework, and NEK5000 is an open source competition free analytics code. For each code, I will briefly review the current capabilities and provide the validation status for each of the advanced reactor technologies of interest. So, due to the massive scale separation present in nuclear reactor flows, a more physical approach is often desirable.

Akin to what you saw this morning in Steve's presentation, a single-code approach is often insufficient as modeling scales several numbers apart requires different methods. This reason vests DOE as the full investment in the development of an integrated multi-scale suite of tools which spans scales starting from the plant level with SAM to engineering scales with PRONGHORN, and finally the finer scales with NEK5000. You will notice that there is some level of overlap between these codes which is introduced by design to facilitate coupling based on past experience. We recognize that most, if not all, safety analysis would be performed at the plant level, but the situation may arise when additional final scale modeling is needed.

I want to make a point. So, we are collaborating on all of these codes with industry partners, so I'll follow the orders from Chris not to mention specific vendors, but there is significant interest from the industry and so let's not also undersell that point, very significant interest. So, you will see--there is a very high probability you will see some of these codes in--if not in licensing applications, in commercial certifications. So, what I want to say here--in this presentation, we will--I will discuss the capabilities, validation status, and future plans.

We recognize that validation is a key

concern. The primary focus the recent year has been on the validation on liquid metal reactors and high temperature gas reactors, and these efforts are being expanded to cover additional reactor types. Again, we envision that the safety analysis will likely be conducted primarily with SAM, and potentially PRONGHORN for gas reactors, especially if 1-D shows approximations are sufficient. There are, however, several cases where these approximations may not be sufficient, and coupling to PRONGHORN or NEK5000 will be needed, or least desirable. Examples for this could be the pool monitoring in SFRs and the modeling of the core in fast spectrum molten salt reactors. So, the suite offers the flexi---

CHAIRMAN CORRADINI: Elia, I'm sorry, say that last part again please?

MR. MERZARI: So, what I'm saying is that you might need coupling to see if the--or post medium model for the modeling of--the pool modeling in--for the pool modeling in SFRs, for instance---

CHAIRMAN CORRADINI: Oh, okay.

MR. MERZARI: --where thermal stratification is important, and it's shown to be an important factor in several transients, or of the modeling of the core in fast spectrum molten salt reactors---

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: --where there are significant effects as I will show.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: The suite offers the flexibility to combine several approaches to reach the desired level of resolution and accuracy. Now, I'm going to dig a little bit more into SAM. SAM is a component-based system co-developed on the MOOSE framework. It uses a formulation particularly suited for advanced reactors in the liquid form, so, something where the MAC number is--oh I'm sorry, did I--where the MAC number is low. It may also have some applicability to gas reactors for components in conditions that do not require multi-phase or fully compressible solvers. Some offer significant improvements over the state of the art, the leverage, and the flexibility brought in using the MOOSE environment, including the use of coupling to other cores such as BISON, to model fuel performance during transients, and three major areas of improvement that I've listed here.

One is the modeling of large enclosures as I mentioned in--like large pools where thermal stratification may be an important phenomenon, the model--flexible modeling of the core where--going beyond the single channel approach, and improvements related to molten salt reactors such as the monitoring of fuel movement and delaying the precaution rift. For most of its development history, SAM has been focused on liquid metal reactors and the majority of these improvements, as well as its validation basis, pertain to this reactor type. SAM has been compared against several reactor transients for EBR-II and FFTF, and in general, they are shown to provide the same or better accuracies than SAS4A/SASSYS-1 for those tests. You also hear this sometimes called SAS, but it's actually--SAS4A is combined to SASSYS-1.

It should be noted that SAS has benefitted from decades of calibration for those same tests, so we were able to reproduce that history within SAM. For example, on the right-hand side of the slide, you may see a comparison between SAM results for two ETF-II experiments. It also beat the rejection tests, and in unprotected loss of flow. The PLOF represent the actual temperature of one subassembly. It is possible to notice that the behavior is very similar between SAM and SAS, and very close to the experiment. I will present a little more comprehensive table with an overview of the validation status of SAM for both fast reactors and other reactor types. Among the gaps identified for fast reactors is one of those that I guess I was listening to you before when Jose asked a question--

CHAIRMAN CORRADINI: Uh huh.

MR. MERZARI: --which is the lack of spatial kinetics capability, which may be required for some transients, in particular, for unprotected transients for very large reactors with significant homogeneity.

MEMBER REMPE: So just out of curiosity on the bottom plot, and I know nothing about the tests you're trying to match against, but it's kind of interesting SAM and SAS4A are just right on top of each other but none of them are--SAM isn't closer to the data, if I'm looking at that plot, right?

MR. MERZARI: But--okay, so I guess what I'm trying to---

MEMBER REMPE: Yes, it's like why are we going through this?

MR. MERZARI: I'm sorry, what's the question?

MEMBER REMPE: Why didn't it come any closer to the real data if you've got a model?

MR. MERZARI: I mean actually, they are essentially equivalent, that's the conclusion there, they're essentially equivalent.

MEMBER REMPE: The bottom plot.

MR. MERZARI: The bottom plot, yes. No, but they're essentially equivalent to each other. I'm not trying to say they're---

MEMBER REMPE: Supposed to be equivalent, but you didn't get any closer to the data, is why--what I'm trying to ask.

MR. MERZARI: Right, so the point here is trying to match SAS for this particular test, and on the fact that we have not mentioned exactly the data there, near the peak, these are largely due to very large uncertainties for the measurement in that particular--remember these are like--these are an unprotected loss of flow.

MR. BAJOREK: Elia, this is Steve Bajorek. I think part of the reason is when they ran this test, the thermocouples were biased low at these higher temperatures.

MR. MERZARI: Right.

MR. BAJOREK: So you had--even though you see good agreement between SAS and SAM and they're higher than the data, that's actually where they think they should be.

MR. MERZARI: Right.

MR. BAJOREK: It's at that high range---

MEMBER REMPE: Okay, that's why I was--that's the answer I wanted. You want to not match the data, is the answer, okay.

MR. BAJOREK: --there was a negative bias in measurement.

MR. MERZARI: I was trying to get to this.

MEMBER REMPE: Uh huh, I got it.

MR. MERZARI: Thank you, Steve. Okay, move on. One of the key advancements of SAM for us as far as the development of advanced modeling options for inlet plenum or delta pool, which is vulnerable to thermal stratification. Thermal stratification has been identified in several gap analyses as a key future development required for these reactor types. We have pursued multiple approaches in SAM, we are implementing and validating a traditional 0-D model--03--0-D mixing models, while also implementing more advanced multi-D options including system CFD coupling. The right approach will depend of course on the complexity of the transient, as shown in the figure on the top right. There will also be project--for loss of heat rejection, a simple 0-D model is often sufficient. We envision the coupling to CFD to be used primarily through foreman calibrated 0-D, 1-D, or in general use for the models. We have collaborated with several international institutions in this domain, as this remains an active area of research and development. This extends to evaluation as well. In fact, that's where we leverage most of these international collaborations, to obtain data we don't have. An example is the 1995 Monju turbine test, for which--which we used for our early assessment of CFD system code coupling.

Moving to gas reactor capabilities, SAM has current limited capability for gas reactors and this is not currently able to handle compressible flow in transients such as air and water ingress, which are typically the most challenging accidents to simulate for gas reactors. However, SAM can be used to simulate key components such as the reactor cavity cooling system. In fact--and Professor Corradini will be familiar with this--SAM simulations have shown a good degree of accuracy in simulating the behavior of RCCS systems, and were done in collaboration with the University of Wisconsin, Texas A&M, and the National Shutdown Test Facility at Argonne National Laboratory. You can see at the bottom right that SAM can reproduce the mass flow rate as a function of the rise of channel in the facility. You will also note that there is a significant scatter on that data and this is a function of the strong sensitivity the RCCS system has on ambient conditions. That is part of this work; we develop a novel model for the fitment of ambient conditions and the effect of ambient condition system analysis is published in a recent paper.

Moving on to MSRs, molten salt reactors pose unique challenges to system co-modeling, and several features are unique. These include the fact that the vast majority of the deposition is in the coolant, as well as the presence of a fuel circuit and the delayed neutron precursor drift. The validation basis for SAM is limited for this reactor type, as little data is currently available, but an important collaboration is ongoing with Louisiana State University for the simulation of MSRE. In the top right, you may see that SAM is able to reproduce these behavior for this reactor, and the reason--this is ongoing work, but these results have been published in a recent 2018 ENS transaction summary. Recently, we've added several MSR targeted features in SAM, including salt properties, delayed neutron precursor drift, generation and transport, and heat generation in the coolant as well as point kinetics and coupling for CFD for fast spectrum systems.

At the bottom right, you may see a demonstration of these features for--of the novel point kinetics capability in SAM that includes the delayed neutron precursor drift. This--again, this is just a demonstration with a very simple loss of flow transient in a simplified single-channel MSR loop model. One of the key gaps identified for SAM, and this you will see, it's recognized as an important challenge for MSRs is the lack of coupling for salt chemistry models and codes.

CHAIRMAN CORRADINI: Can we hold off there? So what is the coupling that's missing in the chemistry models?

MR. MERZARI: So, how you get properties in--as you increase the amount of fission gas material, fission products inside of the key.

CHAIRMAN CORRADINI: Oh, okay. I always thought eventually--oh no, you've got it up here, thaw and freeze during overcooling events.

MR. MERZARI: Yes, I didn't mention that because I'm going to emphasize that for FHRs.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: They're--it is a key

limitation for FHRs.

MEMBER KIRCHNER: That order, could you go back? I'm still pondering about putting in air and water mixtures into SAM, do you have to change your basic equation sets that you're solving?

MR. MERZARI: For which one, sir?

CHAIRMAN CORRADINI: Where are you looking Walt?

MEMBER KIRCHNER: Under SAM.

MR. MERZARI: Which slide?

MEMBER MARCH-LEUBA: He's talking about air and water injection. You see---

MEMBER REMPE: Air ingress.

MR. MERZARI: Oh okay, so for the air and water ingress? Okay, if you wanted to do that with SAM, you would need a multi-phase model or a way to track two phases.

MEMBER MARCH-LEUBA: Plus, you would have to add the chemistry, I mean, the sodium and water don't mix very well.

MEMBER KIRCHNER: No.

MR. MERZARI: No, no, I'm talking about--that's--the air and water ingress are for gas reactors. Those are the post-rated accidents typically for gas reactors.

MEMBER REMPE: That's not a coding capability is it?

MR. MERZARI: Yes, that's not a coding capability, we don't type that.

MEMBER MARCH-LEUBA: Yes.

MR. MERZARI: But to do that, we would need to track those. I don't think you would need necessarily an accurate chemistry model to do that, but for air and water ingress, you must be able to track two phases separately.

MEMBER MARCH-LEUBA: But---

MR. MERZARI: Well actually, I mean---

MEMBER MARCH-LEUBA: If you have hard graphite---

MR. MERZARI: Oh sure---

MEMBER MARCH-LEUBA: --and you have an air ingress---

MEMBER KIRCHNER: Or a water ingress?

MR. MERZARI: Yes, certainly there has to be--graphite interaction will require some material modeling for sure. So as mentioned, the next reactor type is the fluoride high temperature gas--high temperature reactor. This is the combined, essentially features of MSRs and gas reactors. The coolant is typically a molten salt while the fuel remains in solid form. The validation basis for this reactor type is again limited due to lack of available facilities, but several collaborations are ongoing with both vendors and universities. SAM presents some key attractive features for FHRs, including salt properties as well as salt thaw and freeze models, which are currently under development in our collaborations with the University of Wisconsin, and may be needed in the case of other cooling transients, as well as to model the start up. I know they have a nice group at the University of Wisconsin for natural circulation, I've seen some very interesting thermal-hydraulic effects there that would be fascinating to model with this. We note that SAM has also components targeted specifically to FHRs, such as flow diodes. As an example, on the right side you may see a demonstration of FHR simulation for the P-B FHR design of Berkeley, and this view states how the flow diode is used to reach the desired long term cooling state, so basically, to prevent the flow reversal.

And now to the fun part. In this table we summarized the validation status of SAM for fast reactors. The table represents, on the rows, the key capabilities and functions in SAM, while in the columns, we list a set of specific things we have identified as sources of validation data, both for ITs and SETs. The columns in green represent actual reactors, so it's the ultimate validation basis in a sense. Each cell is marked with a validation status letter. C stands for Complete, O for Ongoing, and P for planned. We note that a considerable amount of work has been done, but far more is needed and it is ongoing. We also note that for fast reactors were not nearly as comparable as--were nearly comparable to LWRs, a significant amount of data is available; we won't be as lucky in other reactor types. Any questions on this slide?

CHAIRMAN CORRADINI: So let me--maybe you said it quickly and I missed it, SAM is not a derivative of SAS4 and SASSYS, it's essentially a new formulation for--and then originally for sodium applications, but now single-phase system application?

MR. MERZARI: Right, right.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: So, the reason I guess I'm expecting a question there, why the switch, or why the change---

CHAIRMAN CORRADINI: Well I can guess, so I was going to hold off, I was going to go a different direction with my question, but you go ahead and answer that question, that sounds good.

MR. MERZARI: I think that's the first time today that that happened. So no, the reason is while certainly SAS has decades of experience with the modeling of liquid metal reactors, it has shown over the years it is pretty hard to modify and couple to other codes and difficult to maintain. So the idea there was to essentially replace at least one part of SAS--let us remind ourselves that SAS does much more than simple thermal hydraulics--and make it more flexible and usable in the longer term. Now, I don't want to make it sound as SAS and SAM are necessarily one is a replacement of the other; in fact, SAM and SAS can be used together. SAS has several models especially for severe accidents that are needed to model, for instance, in certain conditions the unprotected loss of flow. So you can use SAM for the thermal hydraulics and SAS for all those models that come in the fuel--in the transient fuel analysis.

In this table we summarize the validation status for SAM for FHRs and MSRs. A lot of nice work has been done here for these reactor types and actually you shouldn't consider this table nearly as complete; we need many more tests and these will need to happen in the future if these reactor types are to become viable. Again, we note the notable activity--the notable ongoing work on MSRE.

CHAIRMAN CORRADINI: But the similarity between all of these--well I know you're going to switch now to PRONGHORN--so the similarity between all of these is single-phase flow, normal operation, operational occurrences, and potentially certain selected design base assessments?

MR. MERZARI: Actually, the unprotected loss of flow show certainly DBAs, but also beyond design basis.

CHAIRMAN CORRADINI: But single-phase?

MR. MERZARI: Single-phase, yes.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: Well I mean in most of these designs--in most of these transients, there won't be a phase change for sodium, for instance.

CHAIRMAN CORRADINI: Well okay, but sodium boiling makes life more interesting and I would expect I'd see that in a beyond design basis accident because---

MR. MERZARI: You won't see it from metallic fuel. It's a strong statement, but typically in--when metallic fuel forms, you will not see sodium boil.

CHAIR CORRADINI: I know what you're saying.

MEMBER REMPE: So back to Walt's question about air ingress and water ingress, you've said well for the sodium reactors, I can go to beyond design basis accidents; aren't you going to beyond design basis accidents for gas reactors if you're going to do air ingress and water ingress events? And then, what are you are going to link to, BISON, that doesn't have a severe accident model for fuel?

MR. MERZARI: So okay, let me separate the question. So for--let me answer first the sodium part, so--and then the link to BISON. So right now, the only code that can really some of the severe accidents part is SAS4A, and the plan there is to implement some of those more--the long term plan is to implement some of the models into BISON and use some BISON to do those severe accident parts.

MEMBER REMPE: Okay.

MR. MERZARI: Regarding the gas reactors question, again, we are not planning to do water ingress and air ingress with SAM, we are not. So those are not part of the analysis at the moment. We may plan to do those with PRONGHORN, but right now the plans haven't firmed up for that.

CHAIRMAN CORRADINI: But the reason--I'm still back on sodium boiling--the reason I don't get it is because with the appropriate reactor design and feedback, I don't get high enough temperatures or enough power that will get me to the saturation conditions.

MR. MERZARI: Uh huh.

CHAIRMAN CORRADINI: But--okay.

MR. MERZARI: No but again, this is an aspect that the three tests showed in the 70s, and I think Tanju can perhaps answer this question better than me.

MR. SOFU: So you can certainly postulate accidents during which sodium could get to boiling temperature, but we feel modeling that particular type of transient is not within our immediate plans, because when sodium boiling starts, you have bigger worries than just reactivity feedback or fission. Those temperatures are essentially the trigger for severe accident conditions.

CHAIRMAN CORRADINI: Okay, that's fine. I figured.

MR. MERZARI: So that said, there are boiling models in SAS, so if that became a concern, that could be potentially transported to SAM, but that would require some development work. Those models are not there in SAM today.

CHAIRMAN CORRADINI: Okay, I understand where you're coming from.

MR. MERZARI: Okay, switching to PRONGHORN. PRONGHORN is MOOSE-based engineering lab analysis tool for advanced reactors. It targets primarily pebble bed gas reactors but it is extendable to other designs. So far everything that we've been doing is for pebble bed reactors. It features an isotropic porous media modeling formulation, as well as a more advanced formulation. In its enhanced formulation, it can combine porous media agents with other agents to generate a full model of the primary system in a significant advancement to what was previously done with these porous media codes for pebble beds. Moreover, distributing the existing models for pebble beds developed with NEK5000 can be implemented in a straightforward manner in PRONGHORN, and it can also couple to SAM to model on the FCCS and the overall system transient response. The validation basis so far is limited; PRONGHORN is a much more recent code than the other two codes I presented, but as shown in a recent white paper and shown here at the top right, PRONGHORN can reproduce while the pebble temperature is a function of axial and radial positions in the SANA experiments, which is a classic validation data set from Germany for pebble beds.

CHAIRMAN CORRADINI: So is--I want to make sure I understand. Two questions; one is what is it about the physics with PRONGHORN that you've chosen to use it instead of SAM where you, in your initial slides, you used the terminology "applicable DOE engineering-scale code," whereas SAM is useful in the SFR, PRONGHORN is the choice of your interest, what's the physics of it do you make the switch?

MR. MERZARI: So the--it's not as much of the physics as a metro scale resolution, so here we're solving more scales because we are actually modeling three dimensionally, the old code, if it were porous media.

CHAIRMAN CORRADINI: Oh, as where SAM is a one dimensional---

MR. MERZARI: It's essentially one dimensional.

CHAIR CORRADINI: It's a sodium RELAP for quantify--I know that would make you upset.

MR. MERZARI: It's a sodium/salt RELAP. I'm okay with that definition.

CHAIRMAN CORRADINI: Okay, so it's three

dimensional because of the pebbles?

MR. MERZARI: Because of the pebbles, and--okay of course you could model, for instance, an FHR with SAM, and instead of modeling 3-D through the pebbles, you could replace it with a channel model.

CHAIRMAN CORRADINI: Okay, I see. All right.

MR. MERZARI: But if you want to add more detail, especially for the neutronics, perhaps a porous media model is more effective. What also SAM is missing is some of the multi-phase tracking capabilities that we kind of need for gas reactors for some of the transients and the compressible models.

CHAIRMAN CORRADINI: So is it a coupling between PRONGHORN and the other tool that Tanju was speaking of, the RATTLESNAKE?

MR. MERZARI: Yes, that's available.

CHAIRMAN CORRADINI: But that is the logical connection?

MR. MERZARI: Yes, that's the logical connection.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: So those two tools are both based on the MOOSE framework and they can be coupled.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: And they will be used for a full analysis of these pebble. So--and perhaps this answers also your question Mike--so this is the advanced formulation in PRONGHORN--I'm showing an equation, I know--and it's basically a multi-phase approach in which the pebble is essentially 3-D; there's another phase but it is stationary, and this allows you--there is a fundamental two-phase capability in PRONGHORN that can be used, for instance, you can think of the operations regions that have no pebbles, or the phase goes to zero, so it's very easy to combine multiple regions with this, and it can also, this fundamental capability, be used to track some from an interphase, perhaps to here. So you can see that the fundamental--the physics in PRONGHORN is probably more suitable to track some of the scenarios like air ingress and water ingress.

CHAIRMAN CORRADINI: But when you say water ingress, you mean steam? That's what I immediately took to be the case; or are you talking liquid water?

MR. MERZARI: For water ingress, I think what typically is assumed is not steam, it's liquid.

CHAIRMAN CORRADINI: Really?

MR. MERZARI: No, I'm sorry, steam, steam, yes.

MEMBER REMPE: It's supposed to be steam.

MR. MERZARI: Yes.

CHAIRMAN CORRADINI: Yes, that's what I thought.

MEMBER REMPE: Even if you---

CHAIRMAN CORRADINI: So it's a mixture of compositions in a gas phase? Okay, fine.

MR. MERZARI: Yes, but there is still an interphase and you still need to track it.

CHAIRMAN CORRADINI: Right, well a mixing.

MR. MERZARI: Yes, yes.

CHAIRMAN CORRADINI: I understand, okay.

MR. MERZARI: Okay sorry, do you want me to--

CHAIRMAN CORRADINI: I'm good, no, no, no, you're doing fine.

MR. MERZARI: Thank you, good. Okay, so we present here the validation status of PRONGHORN in a manner similar to what was done for SAM, you will note the limited validation basis, which so far has been completed only for the SANA test. Additional simulations and benchmarking are ongoing. We note that there is a potential issue here; some of these data sets are not available.

MEMBER REMPE: Yet.

MR. MERZARI: Yet. Finally, and hopefully I'm not--how much time do I have?

CHAIRMAN CORRADINI: You have about 15 minutes.

MR. MERZARI: Okay, that's pretty much on time. Okay so finally, we introduce NEK5000, a state of the art, open source computational fluid analytics code that features both incompressible and compressible fluid formulations. Thanks partly to being open source, NEK5000 is easy to integrate and it features a MOOSE interface, which is part of the rationale to go toward an open source specific code. NEK5000 covers a range of resolutions from direct numerical simulation to large eddy simulation, to Reynolds-averaged Navier-Stokes, and finally porous media formulations. What sets it apart from the codes is that it has a very state of the art capability which allows it to run very large calculations on supercomputers as well as models calculations in small clusters and even laptops.

CHAIRMAN CORRADINI: So I want to take you back to the slide that you had, but you said it originally where you showed SAM in terms of length scales, PRONGHORN, and NEK5000, and there was overlap;

and you said the overlap was good for what?

MR. MERZARI: To couple to different codes. So I'll give you an example. So, let's take a pebble bed for instance, you want to model the pebble bed with a porous media approach---

CHAIRMAN CORRADINI: Right.

MR. MERZARI: --okay? You kind of want to move away from the interface between the porous media and the CFD codes. You don't want the interface between the CFD codes and the porous media to be right at the end of the pebble beds; why, because typically that leads to some instabilities. So if you are able to extend the PRONGHORN calculation a little bit more in the open region, the coupling becomes much more sound. So you couple essentially in the CFD region rather than at the interface, because that interface tends to be unstable very often.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: Does that make sense to you?

CHAIRMAN CORRADINI: I think so. I was going to go a different direction; my thought was why have PRONGHORN at all if NEK5000 can do porous media calculations?

MR. MERZARI: So you can do porous media calculations with commercial software even, you don't even need NEK5000 really for that. The rationale there is that you really want something optimized, especially if you plan to couple with neutronics, and having a well optimized, well established code to run that particular portion does buy you something. Actually, if you want a code modeling tool for pebble beds, I think that's the right strategy, to include a specific code that is optimized for that.

CHAIRMAN CORRADINI: So I'm going to ask, another similarity, which I'm sure you're not going to like. So, is NEK5000 just a better fluent?

MR. MERZARI: I'll take that; better is good.

CHAIRMAN CORRADINI: I used the word better so you would agree with me. But it's similar to, it's essentially---

MR. MERZARI: Yes, but---

CHAIRMAN CORRADINI: --it's uninitiated.

MR. MERZARI: Yes, but you see--yes okay, I'll take that, but we have access to the source code.

CHAIRMAN CORRADINI: Okay, fine.

MR. MERZARI: And that matters, it's not--it's just not---

CHAIRMAN CORRADINI: I'm not disagreeing, but in terms of similarity, there is a--that's an appropriate analog.

MR. MERZARI: It's an appropriate analog, I like the word better in there but it---

MR. SOFU: I think I would add that, I think that you--with NEK5000, you would get reference solutions that you can get validation for--RANS-based approach code---

CHAIRMAN CORRADINI: Sure.

MR. SOFU: --from commercial code. Order of accuracy, level of--order of the solutions is going to be significantly better.

MR. MERZARI: Right, that's why you used the word better, so I---

CHAIRMAN CORRADINI: So that he wouldn't argue with me.

MR. MERZARI: So on the better part, the code is ranked first in several CEA and EA blind benchmarks--I mean, the blind is important--on CFD applications to reactor safety. This includes the T-junction benchmark, which is listed there, which was a model in thermal striping. Another notable test is the simulation at the MAX facility, shown at the top right, illustrating how NEK5000 can reproduce the measurable velocity of two jets impinging on a structure, again for applications in thermal striping.

The primary working validation basis for NEK5000 is--has been focused on fast reactors. As mentioned in the previous slide, there has been a significant validation work performed for thermal striping, including for sodium data sets, such as the PLAJEST test from GE. Thermal striping is one of the limiting conditions for liquid metal reactors, as the core outlet temperature may have significant variations between assemblies and structures; it may be subject to significant thermal fatigue.

Additionally, I have performed extensive validation tests for wire wrapped bundles, both for legacy tests, and including PIV---recent PIV experiments done at Texas A&M. Again, we envision NEK5000 and CFD in general to be used primarily to inform and calibrate SAM for safety analysis purposes; but NEK5000 may also be used for component level modeling, and as mentioned previously, we expect that its coupling to SAM is going to play an important role in the simulation of thermal stratification in the upper plenum.

Moving to gas reactors, while not as extensive as for liquid metal reactors, NEK5000 has received significant validation for gas reactors as well. We have two ongoing activities here I'm just going to briefly mention; the simulation of the upper plenum tests, and the simulation of pebble bed tests at Texas A&M. On the top right of the slide you may see a NEK5000 simulation of jets of different Reynolds numbers in the upper plenum mock-up of Texas A&M, and the bottom right, you may see a NEK5000 simulation of the flow through a random pebble test. This test is being conducted right now, we'll have soon comparison tests, so this is ongoing work. We envision that NEK5000 will be primarily used to inform PRONGHORN, and help define distributive resistant models for pebble flows; for example, to provide closure models for pressure drop in transfer and distributive resistance. It mostly will be coupled to PRONGHORN and SAM to simulate the upper plenum in a coupled fashion if needed. The chair has disappeared. Okay, well I'll go on.

MEMBER REMPE: You can go ahead.

MR. MERZARI: Okay. In the next two slides I'll summarize quickly, applications for FHRs and MSRs. In the interest of brevity, I do not dwell long here. In general, NEK5000 will be used to inform SAM and PRONGHORN. A good example in the case--is the case of twisted tube heat exchangers. Available correlations do not often provide good match in experiments in the region of interest due to the fact that typically it exhibits changes for molten salt at very high Prandtl and very low Reynolds, and there's very little data in that region. You can see the figure on the top right is the correlation, for instance, provides--over estimates the loosened number by over a factor of two in those--for that test, while NEK5000 is relatively close to the experimental data.

Again, you can see the Reynolds numbers included are very low, but these are actually some of the Reynolds numbers that are being targeted by these designs, and so nothing was changing in the NEK5000 model there. We could match the--we could match very well the correlation in the region in the validity of the correlation, but outside of the region of validity of the correlation, the correlation fails miserably while the same NEK model gets essentially the right answer for this particular test. A possible exception to the rule of using CFD models to conform with SAM or PRONGHORN is the modeling of the code in fast spectrum molten salt reactors, which is illustrated in this figure at the top.

In fact, in molten salt reactors there may be re-circulation regions and these may cause significant local peaking. The reason for that is that you have very high Prandtl; the fusion doesn't quite account for any effect in the heat removal, and you deposit all the heat in a region where no velocity--where this no velocity and suddenly you have local idle position, where there is no means for the heat to escape. So, of course you could take care of that while removing the--by removing the re-circulation region, but in a real reactor that might be actually quite a challenge.

I will now present a summary table concerning the validation basis for NEK5000. NEK5000 is fairly mature--is a fairly mature code for this class of reactors, and is considered by validation as being done. As you see, there's quite a few C's there, and all required features have been implemented. Nonetheless, some validation work still needs to be done for these reactor types. The picture is far less rosy when we get to FHRs and MSRs, as the NEK5000 validation basis is far more limited. Significant work has been done, however, for pebble bed reactors, and there's a lot of work--a lot more work to be done, and we have an--we mentioned an ongoing activity for MSRs.

CHAIR CORRADINI: Is it the fluid properties that make--I mean, since NEK5000 is a--I don't want to say standard but we'll say an open source commercial tool, is it the fluid properties that make it in a situation where you have to continue to do validation?

MR. MERZARI: Well the conditions are relatively different, first of all, and so the---

CHAIR CORRADINI: Right, I knew that. I was going to say for the MSR I got it, because you're essentially producing the heat within and that causes the feedback you've got to check, but I'd assume that for these two it would be primarily the material or the fluid properties.

MR. MERZARI: The fluid properties is relatively--it's the geometry, the complexity, and certainly due to the geometry boundary conditions, and in the case of FHRs in particular, the salt and thermals, which we don't have and we will need to validate for some of these transients. But, let me also point out the fact that FHRs and MSRs have very low Reynolds numbers---

CHAIR CORRADINI: Right.

MR. MERZARI: --and that poses some challenges. So for instance, using standard RANS models in those conditions is questionable at best.

CHAIR CORRADINI: But what--if I were the regulator, I would just say well get rid of the turbulence completely, and let me look at essentially a laminar calculation as a bound.

MR. MERZARI: Well--but, the laminar calculation, I'm not sure it's a bound.

CHAIRMAN CORRADINI: But, what Reynolds numbers are we talking about? We're talking about thousands, or at the least---

MR. MERZARI: Sometimes hundreds, sometimes hundreds and it's---

CHAIRMAN CORRADINI: But I'm definitely laminar.

MR. MERZARI: Well, I mean, that's the thing, you might be laminar if you consider a single channel, but the moment that you add more complex geometry, you might end up with instabilities and the flow not actually being stationary.

CHAIRMAN CORRADINI: Okay.

MR. MERZARI: And that is definitely questionable. I mean, there's no such thing as a truly laminar flow, that is completely stable unless you're talking about a fully developed nice pipe with the flow well characterized.

MR. SOFU: And with that kind of a heat, if you just focus on flow, the Reynolds number, you also have to consider the buoyancy effect--

MR. MERZARI: Right.

MR. SOFU: --associated with a tremendous heat flux coming from very, very hot surfaces.

MR. MERZARI: That's right. So with that, I conclude. Actually, I think I bought you back five minutes. The DOE is developing a modern, thermal hydraulic, multi-scale suite applicable to a variety of reactor designs. In fact, while emphasis to date has been mostly for sodium and gas reactors, substantial capability exists for other reactor contents, such as MSRs and FHRs. I've shown some basic capabilities to simulate advanced reactor LDEs, including an unprotected loss of flow, and more is available in the reports and papers I've sent you and I remain at your disposal for further questions. I realize I haven't covered all that I--all the possible--I mean, there's a lot material here and I cannot possibly cover the full status of these codes, but I'm available for further questions, and I hope I conveyed to you the right picture, which is in my opinion, that these codes have received significant interest from the industry, there is a lot--there is significant capability there, there is remarkable progress, and there is definitely potential. Of course, a lot more work needs to be done, especially when it comes to validation. Thank you very much.

CHAIRMAN CORRADINI: Questions by the committee? On to the world of source term. Everybody wake up.

MEMBER BLEY: While you're waiting for it Chris, I asked the question at the wrong time this morning. We didn't have--well, being that we were looking at micro structures, but now as we've got molten fuel and liquids and aerosols being generated, the chemistry's got to become extremely important. How is the modeling of the chemistry in this section of the work you guys have done?

MR. STANEK: So, I think the best answer to that is that's a topic for the next time we meet.

MEMBER BLEY: Do you have an actinide chemist who's working with you on this stuff, or is that for the future?

MR. STANEK: Based on our interactions with colleagues in the NRC and some of the vendors, we now believe we have our arms around what the needs are in modeling and simulation--

MEMBER BLEY: Uh huh.

MR. STANEK: --of chemistry. We're working with the Advanced Reactor Technology Program to hone in on what our strategy will be going forward, so it's still notional at this point, but yes, we have engaged the radio chemists and the right modeling and simulation people to develop a needed capability which frankly doesn't---

MEMBER BLEY: But that's off in the future, so the stuff we're looking at now is without that except as it shows up in some kind of correlations that get picked up somewhere?

MR. STANEK: That's correct.

MEMBER BLEY: Yes. Okay, thank you.

CHAIRMAN CORRADINI: Tanju? If it's a green you're good.

MR. SOFU: The last technical presentation of the afternoon, so--and I'll just jump right into it. The formal source term definition in the U.S Regulations is provided in Part 50.2, if you read there; and then this source definition is closely linked with the LWR source term requirements in Part 50.67. The first reference there, TID-14844, makes a prescriptive assumption for release of all--100 percent noble gases, half of halogens, and one percent of the remaining solids to the containment, assuming a LOCA leading to a core melt as the bonding event. The other reference there you see, 1465, also assumes a LOCA core melt, but it specifies unique EWR/PWR releases in-vessel, ex-vessel, accounting for the engineering safety features along with the uncertainty analysis; and finally, the SECY-93-092 sets the stage for regulatory expectations for mechanistic source term evaluations for advanced reactors. And I think the rationale for a mechanistic sourced term assessment is that because the source term requirements will significantly differ for those reactors mainly because there is no single bonding event like LOCA determining the source term. In fact, for some concepts like those that rely on TRISO fuel, very small releases can be anticipated even during AOOs and DBAs, and sometimes during normal operation from defective fuel particles; there's certainly a circulating activity in the coolant expected.

CHAIRMAN CORRADINI: So the reason though that you--you don't have to go back to the slide before--but the reason you identified that, this is for LWRs?

MR. SOFU: Correct.

CHAIRMAN CORRADINI: So there's no construct except from a process standpoint for non-LWRs?

MR. SOFU: Correct.

CHAIRMAN CORRADINI: Okay.

MR. SOFU: So I'm trying to draw a contrast as to why we would need a more mechanistic sourced term approach for advanced reactors.

CHAIRMAN CORRADINI: Okay. The reason I asked the question like that is that the background documents you gave us, I interpreted as more process discussions than tool discussions.

MR. SOFU: Absolutely, yes.

MEMBER REMPE: So this isn't really for you, this is for the folks sitting around the table here, but it sounds like from your first bullet when I was looking at this last night, I was thinking about if we had a new regulatory system and you had top level regulatory criteria, it sounds to me that your experience is also suggesting that you shouldn't just use the--for top level regulatory criteria, 10 CFR 100, you should also do--use the regulatory criteria for normal operation; and so when we talked about that a few weeks ago or a month ago, it sounds like there might be a gap in what we heard about because they might need to consider the regulatory criteria for normal operating releases and AOOs; is that kind of what you're thinking too?

MR. SOFU: I agree, that's correct, and I think the--this licensing modernization project---

MEMBER REMPE: That's where I'm coming from.

MR. SOFU: --the NRC is evaluating based on DOE and NEI initiative sort of sets the stage for that discussion.

MEMBER REMPE: Yes, but are they--in the discussion we had they did not have all of like, the 10 CFR 20 and 50 releases--thank you--or criteria.

CHAIRMAN CORRADINI: I don't--I guess, I don't appreciate what you're asking, I apologize.

MEMBER REMPE: When Former Commissioner Apostolakis and Karl Fleming were here a few weeks ago and we talked about that, they did not have all of the normal operating regulatory criteria in there and they--and George, when I brought that up actually said yes, you're right, this is--basically even if we design to these top level regulatory criteria that we've identified, it may not meet all the regulatory requirements. And so I'm just kind of emphasizing that because of the guy sitting over there to the left and doing his letter.

MEMBER BLEY: You're wrong.

MEMBER REMPE: I'm wrong?

MEMBER BLEY: Yes.

MEMBER REMPE: Well, years ago---

MEMBER BLEY: I'm not doing a letter.

MEMBER REMPE: Oh, okay. Well if you ever do---

MEMBER BLEY: Not today.

MEMBER REMPE: --okay, if you ever do a letter on that topic, okay, I just wanted to emphasize that point. Again, this is off topic, but it's something I wanted to emphasize. Thank you.

CHAIR CORRADINI: Sure.

MR. SOFU: So the bottom line is that for advanced reactor types, you will need to focus on a broader spectrum of accidents, not just local-type bonding events, because there could be releases that are frequent but very small, versus infrequent but sizably large, but the risk factor will be comparable. Also, accidents that could lead to early releases versus delayed releases could have implications on radionuclide discharge content as well as the emergency response implications, and we need to worry not only about the fuel in the reactor core but we need to concern--probably consider the field and storage for liquid metal coolant systems. Coolant covered gas clean up systems could malfunction, they could just immediately bypass the reactor pool but that could be right inside the containment, and any failure of that system could be sourced inside the containment. And for molten salt reactors--not that I know much about it, but I'm assuming some chemical processing systems may or may not be inside the containment--their malfunction could also lead to significant releases.

So the--on top of all that source term assessment, but also probably the mechanistic approach to considering a broader spectrum of accidents for advanced reactor concepts will also be needed to support PRA in Level 2 and Level 3, as well as emergency planning on reduction requests. So there are plenty of reasons to do this mechanistically looking at a broader spectrum of accidents. What I provide here is a kind of--a proposed mechanistic source term definition, and the general approach I present in the next speech is largely based on this particular definition.

CHAIRMAN CORRADINI: But what I--I've looked at your slides ahead of time. What I see is process, so it's mainly a process discussion?

MR. SOFU: Right.

CHAIRMAN CORRADINI: Okay, okay.

MR. SOFU: Here's the approach. The first step is an inventory assessment; and then you need to understand the release pathways depending on what you're considering as the source. We need to model the phenomena in volt and release pathways, we need to evaluate specific scenarios, not just bonding events, and of course, last step is the regulator will take a look and say we agree or don't agree. So the inventory step, there can be significant differences for each reactor type, but even sometimes for each design. For a traveling wave reactor that targets an ultra-high burn-up fuel, for example, versus for a heat pipe based micro-reactor with very, very low burn-up, an inventory will be significantly different, even with the same type of metallic fuel, for example.

For the release pathways shown here at the second step, I have example diagrams for them for SFRs and MHTGRs in coming pages. For modeling and scenario evaluation, approaches that could be utilized can rely on NRC and the recently developed DOE capabilities you've heard this afternoon. That's something that we've performed in trial mechanistic source term calculations for SFRs and MHTGRs. That's the release pathway diagram for a liquid metal reactor in general. We've done a trial calculation based on this diagram for NSFR under the DOE program. The green color shows primary barriers for release of radioactivity, and obviously in this case we are focusing on fuel in the core. We consider the fuel matrix itself as a barrier because depending on the accident sequence, it could hold the solid fission products within the fuel and then they're not--other than small chunks that could get into coolant channels--may be stayed in the matrix. And also depending on the accident scenario, for example, a very long loss of heat sinks type of accident versus a very rapid transient overpower, what radionuclides are released at what rate will differ significantly.

So I'm showing--the first step is retention of the fuel, and then once you lose the integrity of the cladding, depending on the accident, you will have fission gas immediately released to the coolant, but some particulates and even molten fuel could get released if this a rapid transient leading to fuel melting. There's a complex phenomena absorption, condensation, dissolution, retention in the fuel, but probably more a more important unknown, which I will highlight later on is along with the fission gas release, some of the solid chunk fuels could be scrubbed to the cover gas space with the bubbles. And if the cover gas space between the sodium pool and the cover gas interface, there would be vaporization, condensation, re-vaporization, and some vapors could nucleate on, and--or condense on the particles. Typically, there would be a design leakage rate from cover gas space to the containment space, and then a similar phenomena takes place inside the containment, and then leakage from the containment. Those are sort of release pathways for a typical accident--multiple-failure accident that could lead to a large-scale fuel failures in NSFR.

An approach--the mechanistic source term approach for liquid metal cooled reactors is therefore it will involve first, inventory analysis, and then transient scenario modeling. We need to understand in-pin radionuclide distribution before the failure or at the time of the failure; radionuclides released from the failed fuel, some of those released chunks of molten fuel could be carried through the bubbles--fission gas bubbles--to the cover gas space, and some of them could be retained inside the liquid metal pool and released to the cover gas space at the surface, the free surface. We need to analyze the cover gas region for radionuclide tracking, containment region, and finally the off-site dispersion analysis. So, these are the capabilities that could be leveraged to perform--to implement such an approach.

An inventory analysis could be done with ORIGEN, or in a radionuclide group basis using REBUS, for fast spectrum reactors. Transient scenario modeling could be done with SAS4A traditionally, but we can also leverage our newest capabilities, SAM and PERSENT to help with this process. Interim radionuclide distribution are typically handled with the fuel behavior codes, if you have such capabilities in legacy codes, like METAL and SAS4A, but BISON, if Rich gets his way, we'll be ready to provide such capability in a short few months. Rich is shaking his head. And for radionuclides released from the fuel, we do not have a currently existing capability but we're developing a module to do that type of job coupled with SAS4A and SAM within the context of some international collaborations; I have a slide on that.

And then for--really, once we know what gets to the cover gas space, what goes to the environment, then those implications could all can be taken care of on the NRC codes like MELCOR. CONTAIN-LMR used to do a specific sodium-fire type of modeling for liquid metal coolant and sodium coolant, but I think with DOE support, CONTAIN-LMR capabilities are now incorporated into MELCOR so we won't even need that.

MEMBER REMPE: Yes, it's--is it--it's not NRC supported anymore is it?

MR. SOFU: CONTAIN-LMR, probably not, yes.

MEMBER REMPE: So--but again, you're saying now we're going to put it in MELCOR?

MR. SOFU: It is already in MELCOR.

MEMBER REMPE: So--yes, okay.

MR. SOFU: So, as you see that I don't have green boxes showing a radionuclide bubble transport and liquid-metal radionuclide release; those are identified as gaps. We did perform---

MEMBER REMPE: I'm sorry, if you're still on, go ahead.

MR. SOFU: We did perform a trial calculation to find out what the status of theses codes for a simple application. We again focused on AFR-100 design, and performed the trial calculation. The report is publicly available; there's a link here that you can access. You can see the two scenarios, one is a protected loss of plus, loss of flow, plus in the sense that plus is very degraded decay integral capacity, otherwise you won't get fuel failures with those accidents; and the other one was an unprotected control rod withdrawal leading to a quick rise in the fuel temperatures and leading to fuel melting.

So the consequences of these two accidents--duration and consequences are quite different. What we found out at the end--what we are missing is, as I highlighted before, a pool bypass for bubble transport, and fuel release fractions, which is the radionuclide release module that I mentioned in the previous slide. Professor Corradini?

CHAIRMAN CORRADINI: No, I was just going say I do these as--well, you said examples but, one would have to know the--estimate the likelihood of these scenarios coupled with what would be the release and look for the--I don't want to have to say the worst combination--but the limiting combinations. So, these are just examples; there could be a wide range.

MR. SOFU: Examples, and I think the sub-bullet here that I included based on Richard Lee's comment on my slides, these sequences---

CHAIRMAN CORRADINI: He had a comment? I'm shocked.

MR. SOFU: He did send a comment. So these sequences are typically, normally for a design selected based on a--using PRA.

CHAIRMAN CORRADINI: Okay, that's okay.

MR. SOFU: But we really didn't do PRA in this case.

CHAIRMAN CORRADINI: I was looking at your slide four and I guess my interpreting of slide four as you were walking down the path is you'd have to look at the ensemble of things that could go wrong and their ultimate result and look at that--what are the dominant ones that you then would have to look is. Okay, because that's what they did for the BWR and the PWR to result in 1465.

MR. SOFU: Absolutely. Definitely.

CHAIRMAN CORRADINI: Okay.

MR. SOFU: I think you're absolutely right about that.

MEMBER REMPE: Your trial calculation, did it include using MELCOR or CONTAIN or something?

MR. SOFU: Yes. Trial calculation, I did--I believe it did use CONTAIN--I'm sorry--MELCOR.

MEMBER REMPE: Okay. And it used BISON or some other -- it used, like, all these other codes that was on this slide earlier?

MR. SOFU: Trial calculation used, I believe ORIGEN, SAS4A. This module is developed as part of that trial calculation and MELCOR. So, for these missing steps, we just assume, whatever released from the field somehow reached to the cover gas.

So, that would be a very conservative

approach, because I think you would have significant retention of some radionuclides in the sodium coolant that we didn't take advantage of.

MEMBER REMPE: Was it a linked calculation, where you -- or did you just get output and put it to the next --

MR. SOFU: Pretty much, those were sequential calculations. You would get the results from one analysis and then, perform assessments with the other codes.

So, these were -- and I think, at some point, when you reach to this particular step, it more like a spreadsheet type calculation, goes into -- connects to MELCOR and input, MELCOR input deck.

MEMBER REMPE: At this point, is this a better approach than just trying to put some models and have a sodium reactor MELCOR? I mean, what's the benefit?

MR. SOFU: This question has come up during our discussions with NRC and also Sandia. My suggestion is trying to develop all these capabilities somehow capture in MELCOR would be reinventing the NEAMS program all over again.

It would be, in theory -- and I think one suggestion, I don't remember, I think, who came to

Argonne with, I think it was Randy. Yes. So, Randy's suggestion was, can we have surrogate models that capture the behavior of a particular reactor type, based on running these models and understanding their consequences?

That's certainly a possibility, but it would be far from being mechanistic or general enough that every time you change your reactor design or have a different reactor type, molten salt, so that you need to continue developing surrogate models within MELCOR to achieve that goal.

MEMBER REMPE: I'm just remembering the old days, the RELAP and things like that, and people said, can't we get the important things, because you need to do multiple sequences and --

MR. SOFU: Yes. But for light water reactors, MELCOR actually does extend to scenario of elevation phase. It has those capabilities. But they're really very LOCA and light water reactor hardwired approaches.

MEMBER REMPE: I thought they actually -- I don't know if they've done anything for the sodium reactor, but for the gas reactor, they did and try and do something with PARFUME a few years ago, for the --

MR. SOFU: Okay.

MEMBER REMPE: -- NGNP stuff and so, I thought they had tried to do that already. And --

MR. SOFU: Yes.

MEMBER REMPE: -- again, you've got something that's actually interacting, instead of this sequential thing, which might --

MR. SOFU: Right.

MEMBER REMPE: -- be more expensive to run. I don't know, it's just a thought.

MR. SOFU: I think my takeaway from this particular slide is the MELCOR has well proven radionuclide tracking capabilities, within cover gas and containment space.

If somehow, provide that link, what radionuclides are reaching to that interface, cover gas and containment space, MELCOR would be the best tool to understand the consequences of accidents.

And we have the capabilities to feed that information into MELCOR. I understand strong desire to do everything with one code, but I would -- my personal thought is that this would be too big of an effort.

MEMBER REMPE: Okay.

MR. SOFU: All right. So, this trial MST calculations, mechanistic source term calculations for liquid metal reactors found a lot of attraction.

We've used that capability in our collaboration with GE-Hitachi, as an art program funded project as part of their PRA modernization effort. We repeated that for TerraPower's TWR design and also for KAERI's PGSFR design.

We recently received a voucher from DOE to work with Fauske and Associates, as well as Westinghouse, to apply this capability to a lead-cooled fast reactor concept. And that also supporting the development of this radionuclide release module from oxide fuel.

And finally, we have two recent awards, NEUP awards to University of Wisconsin and New Mexico, to do tests with sodium and liquid lead, to assess radionuclide retention characteristics of those coolants, that will provide really useful information, useful data, for radionuclide release module.

MEMBER REMPE: Why the oxide fuel thing with Fauske and Associates? My understanding is, the sodium fast reactors are all going with metal. Is there a vendor or a design also staying in oxide?

MR. SOFU: This is a lead-cooled reactor.

MEMBER REMPE: Oh, it's a lead, okay.

MR. SOFU: They are focusing on oxide fuel initially. I think, eventually, they want to have nitrite fuel, but --

MEMBER REMPE: Okay.

MEMBER KIRCHNER: So, you probably can't answer my question. What are you seeing in terms of results?

Getting down to the bottom line, someone, someplace, has to make a decision on emergency planning zones. They're not going to be able to look at the infinite number of combinations of scenarios.

So, are you finding some commonality in your work that would suggest that you're seeing versus the EPA protective action guidelines or what's the practice in LWR industry? Are you finding some scaling, based on --

MR. SOFU: Yes. So --

MEMBER KIRCHNER: -- technology and choices and power level, obviously, is a big factor?

MR. SOFU: Correct. So, what we are seeing that, first, we need to push the envelope of those accidents for liquid metal applications to a point where we need to have some fuel failures.

It's hard to get to that point with a lot of those concepts, because they're inherent in passive safety characteristics, passive direct gain characteristics. So, we have to --

MEMBER KIRCHNER: That has not been demonstrated, that a postulate --

MR. SOFU: Postulated.

MEMBER KIRCHNER: -- filling in?

MR. SOFU: Correct.

CHAIRMAN CORRADINI: The postulate being, what, Walt?

MEMBER KIRCHNER: That these reactors do not --

MR. SOFU: But --

MEMBER KIRCHNER: -- the fuel rod.

MR. SOFU: Correct. But we have two unprotected tests coming from EBR-II and FFTF that demonstrates inherent safety principles and using capabilities validated with these tests, for similar designs.

We have fairly good confidence of inherent and passive response of EBR-II and FFTF designs. So, that is one that these designers are taking advantage of.

So, just to jump to your question, however, oftentimes, when we analyze, really, above and beyond the spectrum of accidents, we probably would normally fall under the residual risk category of events, but we nevertheless have to go there, because you need to have fuel failures to do the source term assessment.

Generally, retention in fuel, retention in sodium, cover gas, and containment space is sufficient to minimize the dose concerns well below the regulatory limits. So, that could probably support reduction of those emergency planning zones, consistent with that measurement.

But again, in my approach that I said, let me just jump there, the regulatory review is the final step that we're, of course, we don't want to short-change.

It all boils down to how NRC would receive these calculations. These trial calculations are, essentially, studies that inform the design, not necessarily intended to support the license application.

From here on, I will go really fairly quickly, because I'm going to repeat a similar pathway for HTGRs. And this pathway, release pathway analysis, was prepared as part of NGNP project. As you see, at the core of it is a TRISO fuel, much, much, much larger than what it is.

But also, it's part of a graphite block and what's shown here is the helium pressure boundary and, finally, around it, surrounding it, is another barrier, is reactor building.

And several phenomenon are highlighted here, steam-induced vaporization, circulating activity inside the -- from defective TRISO particles. Plate-out, lift-off, wash-off.

And if you have a breach, you can have either the helium leaks or helium breaks, that could lead to release of this high pressure through venting to the environment.

So, multiple barriers for HTGRs, at the center is the TRISO fuel, with multiple layers. And then, fuel compacts and fuel elements, the graphite block is another barrier. And helium pressure boundary, as long as you maintain it intact, circulating activity is not necessarily a concern.

Finally, the reactor building, which is not a traditional containment structure for modular HTGRs, because if you do lose the pressure in the helium pressure system, then I think it vents the helium first, outside to the environment.

But once that initial puff is released, you have the ability to seal this reactor building, to retain the fission products, following that initial phase of an accident.

So, during normal operation, relatively low inventory of fission products inside the helium pressure boundary is expected from defective fuel elements.

And limiting event is considered to be the loss of helium pressure boundary integrity, leading to a slow or sudden pressure loss and larger delayed release of fission products from the fuel at elevated temperatures, if, indeed, temperatures get elevated.

As indicated earlier, a lot of the statistical analysis really don't just assume, based on tests performed, I think they just assume at a certain temperature, certain failure rates.

So, those releases from failed fuels at certain temperatures is based on those correlations. It doesn't have a lot of BISON modeling there, I believe.

So, the functional containment concept introduced in NRC's Reg Guide 1.232 and in the criterial of MHTGR 16, it allows taking credit for coated fuel particles as the primary barrier. Therefore, the reactor building is not leak-tight and therefore, it's not a conventional containment structure.

And here's the MST Approach, very similar steps. Inventory analysis, transient scenario modeling, fuel response to scenario studied, radionuclide release rates from the fuel, and then, the helium pressure boundary radionuclide release, reactor building analysis, and offsite dispersion analysis.

Codes are more or less the same. Again, inventory analysis could be done with well-established capabilities in ORIGEN. And in NGNP project, I believe RELAP was used as the scenario, transient scenario modeling. But capabilities of PRONGHORN could be leveraged to make that assessment.

Certainly, BISON and, definitely, PARFUME models will give us the fuel response, as well as radionuclide release rates from the fuel at elevated temperatures. I put this here, I think a lot of that release rates is going to be coming from test data.

CHAIRMAN CORRADINI: I was going to ask about that line, because I thought, I'm going to pick on Rich, what I thought Rich said was that BISON is not in a position to do that line.

That there would have to be something, PARFUME, modified PARFUME, PARFUME in MELCOR, something. Am I misremembering?

MR. WILLIAMSON: So, if I understood what you just said correctly --

CHAIRMAN CORRADINI: The line that says

radionuclide release rates from fuel, under, I'll call it, beyond design-basis conditions, I thought BISON wasn't in that position, yet.

MR. SOFU: Not yet.

CHAIRMAN CORRADINI: At all.

MR. WILLIAMSON: Well, yes, I guess I'm hesitating a little bit because we certainly, for a given particle, can -- in fact, the prong that I showed that had a cesium release, we certainly can and have already demonstrated the capability to predict release from an individual particle for a specific species.

So, we're in a position to do that, to do that for a host of radionuclides. Statistically, we haven't done that yet.

CHAIRMAN CORRADINI: Okay. But -- can you go back?

MR. SOFU: Sure.

CHAIRMAN CORRADINI: So, well, okay. So, let me ask the question a little differently. So, that middle line is not just from the fuel, but everything that kind of got dusted up in operating the reactor inside the primary system, as well as what would be released from the fuel, yes?

Because if I have any sort of transient response that I have to blow down, I have to know any sort of material that got accumulated from its operation. And that's not in any of these, as I understand it.

MR. SOFU: As a scenario modeling?

CHAIRMAN CORRADINI: But that's the flow, that's not the fission product deposition that was there because of --

MEMBER REMPE: Lift-off.

CHAIRMAN CORRADINI: -- because of lift-off. Dust, I've got a gas reactor --

MR. SOFU: Oh, yes, I see --

CHAIRMAN CORRADINI: -- with a bunch --

MR. SOFU: -- what you mean, yes.

CHAIRMAN CORRADINI: -- of dust. And now, I punch a hole in the gas reactor and the dust comes out. So, I have to know, what are the radionuclides in the dust. That's what I guess I'm getting at.

MR. SOFU: I kind of take comfort in the fact that these calculations were performed for the modular HTGR as part the NGNP project. There are --

CHAIRMAN CORRADINI: Yes, but --

MR. SOFU: -- two reports here.

CHAIRMAN CORRADINI: But you showed me these two reports, but these are the ones that I thought were more process than calculational. Am I misremembering which ones we were sent?

MEMBER REMPE: No, you're correct. They did peer -- or they had an expert panel on the gas reactor one, to evaluate where the uncertainties were. And it wasn't a calculation.

MR. SOFU: No, no, I mean, obviously, this wasn't a kind of license application in that sense, but --

CHAIRMAN CORRADINI: No, no, I understand.

MR. SOFU: But it --

CHAIRMAN CORRADINI: But I --

MR. SOFU: -- did identify --

CHAIRMAN CORRADINI: -- didn't disagree with the process --

MR. SOFU: Yes.

CHAIRMAN CORRADINI: -- all I guess I was getting at was, is that there are pieces in your listing here that go beyond what --

MR. SOFU: Yes.

CHAIRMAN CORRADINI: -- the red names are.

MR. SOFU: I agree with you --

CHAIRMAN CORRADINI: Okay.

MR. SOFU: -- the steps could be rearranged and expanded, it's just essentially -- the purpose of me drafting this, I apologize if it doesn't fit your vision, but, essentially, leverage some codes that could fulfill certain roles, identify the codes, most of them.

CHAIRMAN CORRADINI: No, no, it's fine, I'm not worried about that, I was just trying to make my point. So, if you went to, let's pick on somebody, if you went to X Energy --

MR. SOFU: Yes.

CHAIRMAN CORRADINI: -- what are -- forget about what the codes are, do they have the same process path? In other words, how are they going to make their case, if they were to come into the regulator?

MR. SOFU: So, I'm assuming, in their case, the limiting scenario would be losing the helium pressure. And at that point, they will have a circulating activity already and that could be released to environment directly, because they may not have a containment structure that will hold that pressure.

So, with that accident, I think you will immediately have some dose consequences of, offsite dose consequences associated with helium puff, with circulating activity reaching to the environment. Detectors will sound and --

CHAIRMAN CORRADINI: Right, but --

MR. SOFU: -- you'll have to --

CHAIRMAN CORRADINI: -- you're going much further than I am, so that's good. So, now, let me push the point. Has the industry shared with you guys their approach to any of this?

MR. SOFU: No.

CHAIRMAN CORRADINI: Okay.

MR. SOFU: Those are sort of DOE proposals, based on some trial calculations are done for SFRs, and what NGNP did for MHTGRs.

MEMBER BALLINGER: But you had to previously -- the blue TRISO fuel QA, in order for you to claim that that's the primary barrier and that you don't need a conventional containment, you have to have previously -- you have to demonstrate that your coated particles meet a certain QA spec --

MR. SOFU: Correct.

MEMBER BALLINGER: -- ahead of time.

MR. SOFU: Correct.

MEMBER BALLINGER: So, that is up top.

MEMBER KIRCHNER: It would seem to me, pragmatically, for the case of the HTGR, which is rather unique, because you're going to have this problem of blowing down the primary system and the planned buildings for the structure can't withstand that.

CHAIRMAN CORRADINI: Well, they --

MEMBER KIRCHNER: So, they're going to vent.

CHAIRMAN CORRADINI: They could, but they're --

MEMBER KIRCHNER: They could, but --

CHAIRMAN CORRADINI: -- they've designed --

MEMBER KIRCHNER: -- the cost is --

CHAIRMAN CORRADINI: -- it not to.

MEMBER KIRCHNER: No, the cost would be prohibitive. So, or it could be prohibitive. So, the approach currently is to vent. So, it seems to me, yes, you could do all this detailed analysis to try and calculate what the circulating inventory is and what the plate-out is and so on.

Pragmatically, wouldn't you just define a tech spec for what you can withstand in terms of that circulating and deposited inventory?

CHAIRMAN CORRADINI: And demand --

MEMBER KIRCHNER: Ensure that the fuel is manufactured so that you, based on your analysis, with your detail models, you're not going to have a problem. And then, from that, figure out what the offsite dose is. And then, that's going to tell you what your EPZ diameter is, right?

CHAIRMAN CORRADINI: So, your point is, work the problem backwards?

MEMBER KIRCHNER: Work the problem backwards, yes.

MEMBER REMPE: You need to consider a spectrum.

MEMBER KIRCHNER: And I would think the same with the LMR scenarios as well. Otherwise, to go from alpha to omega, from the very beginning with every single transient that you have in your PRA space, even if the codes are running very efficient, it's an enormous undertaking.

MEMBER REMPE: But don't you have --

MEMBER KIRCHNER: I think one is underestimating where you should put the effort and where mechanistic approaches are most valuable.

My own biases, that your codes for the detailed analysis, at a smaller component level, are probably much better V&V'ed than MELCOR, at the very macroscopic level, where you're actually then worried about release.

So, I would divide the labor in a way that I would bound what I start with in estimating the releases. And then, I would inform the design of the reactors with your detailed modeling capability, to convince yourself you have adequate margin.

MR. SOFU: That is --

MEMBER BALLINGER: And hope --

MEMBER KIRCHNER: Not to get there.

MEMBER BALLINGER: And hope that the QA requirements don't strangle you.

MEMBER KIRCHNER: Well, that may be unique to the particle fuel.

MR. SOFU: I agree, that could certainly be an approach, a valid one as well. But normally, we don't necessarily analyze every single sequence. But what you do, in LMR case for example, I analyze the accidents, which you need to analyze to understand their consequences.

MEMBER KIRCHNER: Sure.

MR. SOFU: You would very quickly identify the bounding ones for which you would then proceed to --

MEMBER KIRCHNER: Proceed further.

MR. SOFU: -- source code evaluation.

MEMBER KIRCHNER: Okay.

MR. SOFU: You have to look at the spectrum for Chapter 15 purposes anyway. And in Chapter 15, if you run into sequences where, with uncertainties included, you will expect some fairly sizable fuel failures. That's the one to look at, not necessarily the whole spectrum.

MEMBER REMPE: Because, in your vision, Walt, what about air ingress and water ingress --

MEMBER KIRCHNER: Well, that's another --

MEMBER REMPE: -- events?

MEMBER KIRCHNER: -- class that they would have to analyze --

MEMBER REMPE: Yes, you've got --

MEMBER KIRCHNER: -- for HTGR.

MEMBER REMPE: -- to be able to --

MR. SOFU: Absolutely.

MEMBER REMPE: -- rule it out and I --

MR. SOFU: Absolutely.

MEMBER KIRCHNER: Yes, that's --

MEMBER REMPE: -- yes.

MEMBER KIRCHNER: The initial puff may not be the more demanding problem for the HTGR.

MR. SOFU: So, I hope you recognize that, with these questions, you're putting me in a spot where I'm trying to find solutions for a specific reactor type or specific company.

Those are just initial puff shows a pathway and code capabilities that could support a real application. I would have loved to be part of a project like that, but this isn't my role under Shane's program.

And finally, for molten salt reactors, we don't have a diagram similar, a pathway phenomena diagram for MSRs. They also come with a greater variety of design choices.

They could have solid fuel, they could have dissolved fuel, they could be fast spectrum, they could be thermal spectrum. So, it is anticipated that the functional containment concept can also apply to MSRs with dissolved fuel, as well as the TRISO fuel.

So, owing to high fission product retention capacity of molten salt, source term may be less of a concern from fuel dissolved in the coolant.

That's kind of counterintuitive to folks who are not really immediately familiar with the technology, because they consider that, well, if you're worried about core melt, then here you are, you have already molten fuel. But I think the fission product retention capacity of the salts is significant.

More of a concern could come from effluence of the salt chemical processing system, maybe. And also, maybe the tritium generated in the core, which is a kind of very elusive species, as we all know.

I kind of drafted this proposed mechanistic source term approach for MSRs, not that I know much about it, but I think I can safely say that, what's immediately missing for such a source term assessment would be molten salt chemistry modeling, for which, even under NEAMS sphere, we don't have a whole lot to offer, other than plans, currently. And also, radionuclide release rates from salts, to the cover gas space and such.

But still, we can leverage scenario evaluation phase of it, because like SAM and Nek, and these two codes are being already utilized to some molten salt vendors, adopted as part of their design process.

And again, another takeaway from my presentation is just dependable reliance on use of radionuclide tracking capabilities of MELCOR and offsite dispersion analysis with codes like RASCAL and WinMACCS.

Those are just samples, there are alternatives available, but they would do the job under it.

That's my conclusions. I know that I'm running out of time, let me see if -- the takeaway from this slide, perhaps, there are some gaps in our trial calculations identified.

One of them is, radionuclide release rates from the failed fuel and this bubble transport of some solid and liquid phases to the cover gas space. And chemistry modeling and retention in molten salt for molten salt concepts and FHRs.

And we do believe that the emerging DOE ModSim capabilities you've heard today in codes like SAM, BISON, PRONGHORN, and Nek5000, in combination with the radionuclide tracking capabilities of MELCOR, can be leveraged to remove the empiricism embedded in traditional codes, MAP, MELCOR, for advanced reactors.

CHAIRMAN CORRADINI: Okay.

MEMBER REMPE: So, as you rethink this or as you continue to think along this, like, this last bullet talking about you're going to support a Level 2/3 PRA --

MR. SOFU: Yes.

MEMBER REMPE: -- you've got to do uncertainties. And so, if you do this sequential thing, that's going to be really a pain to deal with, if the codes aren't linked, with, like, MELCOR.

MR. SOFU: Correct. But I think, as I answered to Walter, Dr. Kirchner, that you don't necessarily follow the full source term assessments text for every single accident in your PRA tree.

You identify the bounding events and then, follow the path, complete the source term assessments for the rest of them, I think.

For concepts like LMRs, that's an easier ordeal, because not all accidents will lead to fuel failures and you don't need to do source term assessment for cases where you don't have a fail failures.

For an HTGR, this would be a bigger task to tackle, because you may actually have statistical releases from gazillions of TRISO particles. Even for DBAs, and sometimes AOOs, I mean --

MEMBER KIRCHNER: Even original startup.

MR. SOFU: Exactly.

MEMBER KIRCHNER: You always have --

MR. SOFU: That's true. So, for that, I think it's -- you're right, that's a bigger challenge to do the whole sequence for every single thing you can think of for an HTGR.

But nevertheless, for HTGR, during NGNP project, DOE's approach was complete reliance on mechanistic source term assessments for AOOs, DBAs, and BDBAs.

MEMBER REMPE: It's just something to think about, and I'm not sure what you'd do for the molten salt one.

MR. SOFU: Yes. Correct.

CHAIRMAN CORRADINI: Other questions? Okay. Chris, you're our cleanup.

MR. STANEK: Okay. Well, let me start by thanking everyone for their attention today, their feedback, engagement. That feedback and engagement, for us, is extremely useful, as we continue to slowly evaluate our code development priorities.

Let me maybe start by making an off-the-cuff observation from the day, which is that I think today was semi-painful, but perhaps necessarily so, as a first step, in terms of what we hope is an ongoing discussion.

But we thought it was necessary to provide a 30,000-foot view of all of the codes that are under development. And so, our approach today was really to present a pure informational meeting, at least that's how we interpreted the guidance, maybe inaccurately so, but that's how we went about today.

And so, what that meant was that we presented the DOE codes in something like a vacuum. We didn't talk about how they compared to other codes, how they might interface with other codes, and we didn't talk about how users are using the codes or might be using the codes.

And I don't want to be presumptuous, but I'm probably not being presumptuous, because one of Chairman Corradini's first questions, but my assumption is that our approach has left you wanting some of those examples.

And so, now that we have all this sufficient, let's say, background information on the table, I think hopefully we've successfully made you conversant in DOE codes, that the code names now, when we say them or someone else says them, that you understand what those codes are and what they can and can't do.

Now, with that background information and now that we've gotten through that, as an idea, if there was to be a next briefing, perhaps it would be valuable to focus on some examples, let's call them use cases, of where the codes are being used or potentially being used.

My thought here is that the timing of such a next meeting, again, I'm being presumptuous, but the timing might be opportune. We're, especially in the advanced reactor part of this, we are working closely with vendors who are having their own conversations with the NRC, and so, they don't want us to be out in front of their conversations with the NRC.

But as they begin to talk to the regulator, we can more naturally have conversations using very specific examples that I think all of us are somewhat frustrated up here that we're not able to talk about in great detail, but perhaps going forward, we can begin to do that.

In terms of a summary, a prepared summary, all we wanted to do was to very quickly ascribe a notional maturity to the codes you saw today. This is what we interpreted as the formal request from the ACRS.

And the maturity level of each code was discussed in some detail in the previous presentations, but here, we refer back to those tables we started the day with, where we've tried to distill the information that was presented in the presentations that you heard, to give you a sense of a notional or a relative maturity level of each of these codes for a specific application.

And so, here, this is a non-rigorous way of doing it, but hopefully, in an attempt to distill it to a meaningful sort of way, something that leaves you with a sense of where at least we think things are.

And so, where we've color-coded the code name in green, that means that a relatively mature capability exists. It doesn't mean a complete capability, and the validation might be limited, but we think those codes are applicable at this time for those specific applications.

Where the code names are in yellow, there, we have a basic capability, but there's some key models that require additional development.

And finally, for codes that are in red, the code is still conceptual or in its initial formative phases.

So, what you can see from the ATF set of codes, by and large, we feel that the codes that are being developed are fairly mature and applicable to accident tolerant fuel.

This is my last slide, but for non-LWR reactors, the DOE codes are, let's say, reasonably less mature. Reasonably meaning that we haven't spent as much time working on them.

I think we're accelerating our maturity level quickly, but compared to the maturity level for the accident tolerant fuel, for the advanced reactors, as you heard today, we have capabilities that are applicable to each of the advanced reactor designs.

In each of those areas, we have interested industry members, but we are well aware of the necessary development that needs to happen and we're working hard on that.

And you also heard, in the previous presentations, mention of a chemistry code that we're -- that's an urgent need that we are rapidly addressing in real-time.

So, that was just intended to be a quick snapshot of everything that you heard during the day and, hopefully, sort of bubbles this up to a level that is somehow digestible.

And I think any of us are happy to answer any further questions. But in the case there are none, again, I thank the ACRS for the opportunity today to present this, and again, the feedback received is, for us, extremely valuable. Thank you.

CHAIRMAN CORRADINI: Good. Well, thank you. I think, we're going to go around, so here's the process. We want to have public comments, first and foremost. And then, we want to go around the table.

But I'm going to start off by thanking Shane and all the myriad contractors that went through this, because we started this by a phone call after I got asked by the Chairman, so how are those DOE codes, are they ready for prime time? My response was, we'll check it out.

So, I want to thank all of you for all the effort you've put in, it was quite a lot.

Okay. So, why don't we first ask if there are comments from the audience here, while we get the outer phone line open.

MR. BROWN: Bridge open.

CHAIRMAN CORRADINI: Oh, the bridge is open? Well, why don't we -- if the bridge is open, let's take the public comments from the phone first, if I could do that. So, hold on, everyone.

Is anybody out on the line that wants to make a comment, please?

MR. WHITT: Jeff Whitt is on from Framatome, just to make a brief comment, just express our support. We've had an opportunity to work with both CASL and NEAMS in the development of the codes and support it.

And I know that was a question that was asked early this morning, there is an interest and a desire for using of these tools for future design and confirmatory work against license codes.

And I would say, generally, I would not discount the future use of DOE codes in licensing, where that seems to be the right, applicable approach for some of the advanced fuels or some of the other advanced concepts.

So, we are appreciative of DOE coming and making this presentation and letting us listen in and be a part of it. So, we just want to express our support and thank you.

CHAIRMAN CORRADINI: All right. Thank you. Are there any other comments on the phone line? Okay. Hearing none, could you close, put it on mute, please? Close the line? Everett, you had a comment?

MR. REDMOND: Sure, thank you. Everett Redmond, Nuclear Energy Institute. I also chair the NEAMS Industry Council. Just wanted to give a little bit of an overview there.

The Industry Council is comprised of the chairs of the three technology working groups, molten salt, high-temperature gas, and fast reactors, as well as representatives from EPRI and some relationship to CASL.

I want to thank also everybody here for their interactions today and thank DOE for the work putting together the presentations. There was a lot of conversation about interacting and understanding who's doing what with what codes.

Obviously, as Chris said, that's more for the developers to outline that, but there will be some interactions in the next few months, in terms of with staff from some of the developers.

But one thing I would highlight is that NEAMS has done some training sessions in the past, with some folks in industry, Molten Salt Reactor Working Group, for example.

So, you're getting a lot of interest from the industry in these codes. Exactly how much they ultimately get used is up to the developers, but there is great interest, I want to emphasize, on the part of the community out there. Thank you.

CHAIRMAN CORRADINI: Thank you.

MR. LEE: Richard Lee from Research. Since my name was invoked in his view, I wanted to tell you the comments I get. First is that I said the NRC source term releases to the containment and to the environment.

So, when we do severe accident analysis or source term, I do not use the FRAP code, because there has no role whatsoever in my analysis. Okay? So, I don't see why it should be linked to BISON whatsoever, because it is not talking about steady state or has anything to do with AOO or anything. So, that's one thing.

And then, if you see the two sequence that was cited, and my comment is that you really need to have the PRA to tell us these are the risk significant sequence.

And the same way we did when NRR asked us to synthesize the high burnup fuel and the MOX fuel, okay? Dana Powers went and looked at all the sequence of PWR and BWR, to make sure we capture all the risk significant sequence, before we synthesize analysis and produce a revision to the NUREG-1465.

CHAIRMAN CORRADINI: Thank you. Other comments? Okay. Let's go around the table. So, I have two questions for the Committee. One is, are there any lasting comments they want to make from today's presentations?

And also, I'd like to take notes as to, since this is an information meeting and we're clearly going to need to have others, what direction would you propose that we go for our next Subcommittee meeting, which will also be information?

Because as Chris said, we really got a lot of information in a relatively short amount of time from a whole range of tools that DOE's developed for both ATF and for advanced reactors. So, I'm look at you, Ron.

So, question one is, any other comments about today. Question two is, and now what?

MEMBER BALLINGER: I'm sure everybody's going --

CHAIRMAN CORRADINI: Green light.

(Laughter.)

MEMBER BALLINGER: I'm sure everybody's going to say this, but I appreciate the update on things. I'm familiar with some of these things, but having it all in one place is a good idea. I'm heartened to see that you've now expanded the animal groups to include snakes, range animals, and now, fish.

(Laughter.)

MEMBER BALLINGER: I'm not sure what else you can do, maybe some insects or something.

CHAIRMAN CORRADINI: Don't challenge him.

(Laughter.)

MEMBER BALLINGER: But with respect to going forward, I think the idea of picking some really important, what you consider important, of the concepts, the ones that are the most likely to, with divine intervention, I suppose, be going forward and do some examples, like has been suggested.

MEMBER BLEY: Yes, sir, I do have a few comments. First, same thing, it was a great day. It's one of the better meetings I've sat through, I enjoyed it, and the discussions. It's kind of wonderful to extend the state of the art and examine these interesting phenomena.

Bottom line, for me, at the top is, I've just heard bits and pieces about this whole program and these large computer code developments, with some worry. I gained some confidence today in hearing how they're being used and still retaining the need for data and experiments, that's helpful.

On the goal of this whole business, early today, Chris pointed out that in response to Congressional direction, which I guess is -- we don't have any Fukushimas here, DOE issued this report on the program back to Congress in 2015.

Early in that report, you say, with respect to the goals, kind of two parts. One is, they can tolerate loss of active coolant in the reactor core for considerably longer time.

Indeed, if that ends up being true, that would help us a lot, in the area of risk. I haven't heard anything yet that hints at that and most of the work hasn't been up at that end of the problem.

The kinds of things that contribute to risk, though, you need minutes to hours to do anything about. So, I haven't heard things that make me think you're going to buy that kind of time.

The other part is, while improving, you want to do that while you're improving fuel performance during normal operations, operational transience, as well as design-basis accidents and beyond-design-basis.

Everything except beyond-design-basis, it sounds like that's coming together pretty well. I haven't heard much that makes me think you're covering the beyond-design-basis events yet.

And on the mechanistic source terms, I guess I'll just harp a little, and it seems like you're on the right track here, getting the chemistry as right as you can in that area, allowing for uncertainties, because there are strange reactions going on very fast, with daughter products that come and go, it's going to be pretty messy.

So, being able to account for uncertainties in that chemistry is going to be important, if people are going to really buy into this and think it's convincing.

Tanju said something I like to hear from people working this area, is, every time he said something, it was depending on the accident scenario, barriers may or may not be useful. And that's crucial and too often, people don't recognize that. But I guess that's what mechanistic source term is all about.

I hope folks consider that there might be other simplifications beyond what Walt suggested earlier, that might be helpful.

In other areas, we found that you can collapse many of the PRA scenarios into classes that look the same for what's coming next. And in this area, I hope that's possible. Usually, there are simplifications like that, there can be. You have to test those. But that's kind of the whole gamut.

Where we go next, anything you bring will be interesting to me, but I think examples would be useful. And I just picked up the papers you pointed us to and I look forward to looking at those. So, thanks a lot for today.

CHAIRMAN CORRADINI: Matt?

MEMBER SUNSERI: So, I can't express this anymore eloquently than Dennis did, so I'll just leave it as, I found that the strategy that you developed is a lot more developed, or farther along than I had anticipated and the progress you're making on maturing these codes is -- my confidence level is well raised also.

So, I'll just leave it at that. I thought all the presentations were well done and the presenters were well prepared.

And since I'm the operational guy here at the table and this is kind of outside my area of expertise, I'll leave it to those more qualified than me to judge where we should go next. Thank you.

MEMBER REMPE: So, I'd like to add my thanks for coming here and discussing it. It helps. I guess, I'm back to the question I raised at the beginning of the day.

Yes, I understand you're enthusiastic about your research and you believe you're going the right way, but I -- no one has yet, I mean, I've heard, oh, they're going to be coming in, and that will be interesting to see, but no one is yet willing, in the ATF program, to come in and say, I want to use one of these for qualifying the fuel.

So, I'd like to see something like that. And I actually think there's a lot to be learned from such a thing like that.

And I understand, industry says, well, I can do it cheaper if I use my own code, but maybe they ought to be encouraged with some funding to do that and get some confidence that these codes are better, if that's -- we've spent a lot of years developing these codes, so let's use it.

And so, again, it's beyond ACRS making such recommendations, but it sure seems like that that's an important thing to do.

With respect to NRC and the next step, I actually think it would be good to have a Subcommittee meeting where we hear from the staff, not only the folks that are doing the accident tolerant fuel or the advanced reactors, but also research, see some actual comparisons to see, are these codes really better?

Again, when we asked about that earlier, I believe we were told by the person from INL, well, my job isn't to look if it's better, just it matches the data, but I don't know if it's better than FAST is. And so, I think we need to have some folks do that, to get some confidence, too. And I guess I'll leave it at that.

MEMBER MARCH-LEUBA: I thought that was Mike's job.

(Laughter.)

MEMBER MARCH-LEUBA: Okay. Yes, well, I'm very impressed by the DOE team. I think you guys have done a fantastic job over the years, and today of course. And I'm especially impressed by the tools that we have seen. I mean, something like MPACT, it's a dream calculation. I mean, I see it and I love it.

However, I'm concerned about the complexity of the new tools and the user base that -- the DOE team has been working on this for the last 12 years and you know how to use it. But those tools are not for you, are for everybody else.

And I suspect that the large vendors may be able to take advantage of it, but I'm worried about the small companies, which are the ones that really need these tools.

The ones that are going to design the new reactors, how are they going to be able to do something like this, especially if it takes 10,000 cores to run the calculation like this? I can't -- wait until we are through and then -- I think that the process is, we talk now.

MR. SOFU: I think, the 2,000 -- when you are trying to develop capabilities that doesn't exist elsewhere, it automatically pushes you to a particular domain of complexity that you're trying to do things that doesn't exist. If you repeat existing capability, then you're not really adding any value.

But it's interesting that a lot of what we developed under NEAMS program is adopted earlier by small companies, as opposed to large ones that already have their developed capabilities. They're not interested in that. So, it's the other way around. I just wanted to make mention of that.

MEMBER MARCH-LEUBA: So, for the future, I'd like to see, I mean, if you know of examples where companies already taking advantage of this or have plans for doing it, it would be fantastic if we could have some of those examples, instead of going into the nitty details of how you calculate the power on node 27.

And in that line, what I would like to see is a plan of application of these methods for ATF. Obviously, we haven't done it, but go through how would I resolve the accident tolerant fuel with this method? What would I do that would be useful and that would save me money on the testing?

CHAIRMAN CORRADINI: Walt?

MEMBER KIRCHNER: Thank you all for the presentations. For me, it's very enjoyable. I started my career at Los Alamos doing advanced code development, so it's, for someone like myself, it's interesting to see how much progress has been made. So, I congratulate you on that.

Since the slide is up, I would suggest, you've heard some thoughts already on source term, I think this is a difficult problem, from end to end, to do the source term estimates.

So, I would have in my back pocket or my thinking or my strategy, whatever you want to call it, a way to bound these problems. Dennis spoke eloquently to certain aspects of this. The chemistry challenges can't be underestimated, especially for some of the more advanced concepts.

So, I would have concern there and I would want to have Plan B, because you're not going to have the level of maturity in the PAR space that we have in the LWR, backed up by all their experience. Certainly, not early on. And so, I guess, a caution there, is what I would put out. And thank you, again, for the presentation.

As to the future, yes, I'd be interested in hearing more. I think, hearing more attacking specific problems may be useful. And I know that perhaps involves vendors, then, and actual designs, but that's probably where the rubber hits the road, in terms of applying these codes. And with that, thank you.

CHAIRMAN CORRADINI: So, I'll thank everybody, but you've been thanked enough. So, let's just move on from there. I guess, what took me by surprise today was Chris's starting comment, which the industry advisory group didn't want to let us know who are potential adopters.

So, that -- because one of my first questions is, okay, who are your users? So, I've got to come back to that question. So, if it's still of the belief that there is a potential set of users that don't want to be identified, I would think the next step, for me, would be user needs.

I'd like to hear from industry, what are the user needs? So, Everett said he's got his advisory group, if they don't want to say, I'll use BISON, I want to hear from them, I think I want to hear from them, what do they need in a tool that gets them to the end game?

And then, if we were to talk about it that way, I would flip it and go to the NRC and say, if they're the users, what do they need to get it to the end game? That kind of goes a little bit with what I think Jose was after, which is plan for application of ATF.

I think the one thing that Walt mentioned, and Dennis mentioned, which is, simpler is better. Somehow, I would like to work the problem backwards, what is the simplest way to identify the limiting source term?

And if you can do that, that simplifies all the preliminary analysis and gets me to that source term, rather than complexity. Because these are very interesting tools, but they're complicated. And I'm wondering if the industry is hesitating because they view them as complicated, or maybe they're not familiar with them and, therefore, that's -- so, I think, for me, the next step would be to try to hear what the users need. Not necessarily who the users are, because I sense you're not going to be allowed to trot them out in front of us to write down and certify, but at least to hear what they need. What are they looking for in a tool that they can use for their safety analysis?

I guess, that's where I would like to go in the future. So, maybe we can find a way to marry that together with another Subcommittee meeting. I would think, since this one took four months, the next one might take a few months. So, why don't we start talking about, between -- I originally called Tom and Tom called Chris and Chris called, and so, we can talk about it and see where we go from there, okay?

MR. STANEK: Sounds good.

CHAIRMAN CORRADINI: I don't have anything else. Any other members have anything else? Otherwise, we're adjourned. Thank you very much.

(Whereupon, the above-entitled matter went off the record at 5:12 p.m.)

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Overview and Introduction to ATF Session

August 21, 2018

DOE Briefing to ACRS:

Advanced Computer Models for Reactor Safety Applications

Overview

- **Scope of briefing:** The following presentations will describe adequacy and maturity of recently developed DOE modeling and simulation tools for application to ATF (morning) and non-LWR reactors (afternoon).
  - Although many other codes exist, some of which address similar phenomena as DOE codes and some which that may interface with DOE codes, discussion pertaining to non-DOE codes is beyond the scope of today's presentations.
  - In order to provide a comprehensive overview, description of each capability under development is necessarily kept brief.

- **Deployment:** Vision is for DOE to make its codes available to NRC and US companies, from which they may create proprietary versions of the codes using data they generate.

- **Software quality and validation:** DOE code development efforts place high level of importance on software quality assurance and validation.
  - All codes adhere to strict SQA principles.
  - DOE performing sufficient validation for there to be confidence in code use. Additional validation required by users for specific applications.

Outline of ATF Presentations

	Doped-UO_2	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U_3Si_2	Non-cylindrical metallic fuel
Fuels	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON
T-H	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD
Neutronics	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT

Outline of ATF Presentations

	Doped-UO_2	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U_3Si_2	Non-cylindrical metallic fuel
Fuels	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON	MARMOT BISON
T-H	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD
Neutronics	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT

1. Steve Hayes — Fuels

2. Jess Gehin — T-H, Neutronics

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Fuel Performance Modeling for Accident Tolerant Fuels

August 21, 2018

DOE Briefing to ACRS:

Advanced Modeling & Simulation Tools for Accident Tolerant Fuels

Outline of Presentation

- Accident Tolerant Fuels — Development and Testing Background
- Multiscale, Mechanistic Modeling of Nuclear Fuels
- The **Bison** Fuel Performance Code
  - Overview
  - Verification
  - Validation
- Model Enhancements for Accident Tolerant Fuels
  - Doped UO_2 Fuel
  - Cr-Coated Zirconium Cladding
  - FeCrAl Cladding
  - SiC Cladding
  - U_3Si_2 Fuel
  - Non-cylindrical Metallic Fuel
- Validation for Accident Tolerant Fuels
- Summary and Conclusions

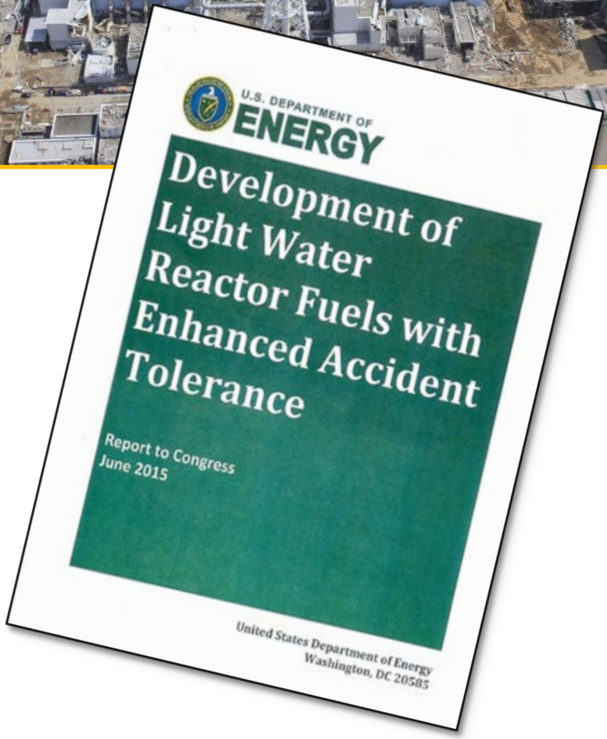
Accident Tolerant Fuels

—

Development and Testing

Congressional Direction and Development Plan on ATF

Following the accident at Fukushima, Congress directed the Department of Energy to begin developing fuels with enhanced accident tolerance that can be used in existing light water reactors.


U.S. DEPARTMENT OF ENERGY

Development of Light Water Reactor Fuels with Enhanced Accident Tolerance

Report to Congress
June 2015

United States Department of Energy
Washington, DC 20585

The Development Plan:

- Defines the general attributes of accident tolerant fuels
- Lays out an aggressive 10-year schedule starting in 2012
- Establishes the goal of inserting lead fuel rods/assemblies in an operating commercial light water reactor by 2022

Industry-led Development of ATF Concepts

- **Framatome**
  - Cr-coated M5 cladding
  - Doped UO_2 for improved thermal conductivity and performance

- **General Electric**
  - Iron-based cladding
  - ODS variants for improved strength

GE imagination at work

- **Westinghouse**
  - Cr-coated Zirlo cladding
  - SiC cladding
  - Alternative fuels with improved thermal conductivity and high density

DOE does not currently have a formal relationship with Lightbridge

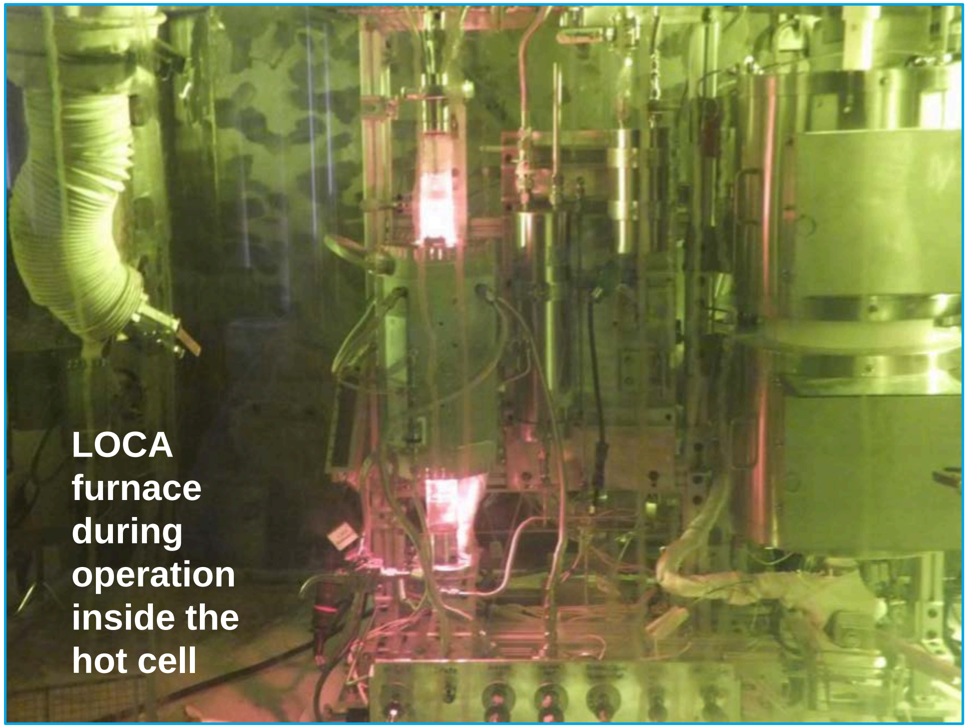
DOE Irradiation Testing Program to Support ATF

Halden testing must be redirected

Test Series	ATF-1	ATF-2	ATF-3	ATF-H-x	CM-ATF-x	ATF-y
Test Reactor	ATR	ATR	TREAT	Halden	Commercial Reactors	TREAT
Test Type	Drop-in	Loop	Static/Loop	Loop	LTR/LTA	Loop
Test Strategy	Scoping Many Compositions	Prototypic Cladding and Integral Fuel Concepts	Focused	Focused	Mature concepts	Mature concepts
	Nominal conditions	Nominal conditions	Off-normal conditions	Nominal conditions	Nominal conditions	Off-normal conditions
Fuel	UO_2*, U_3Si_2	Promising concepts	Rodlets conditioned in ATF-1 and ATF-2 irradiations	Promising concepts	Promising near-term concepts	Rods conditioned in LTR/LTA irradiations
Cladding	Zr w/coatings, Fe-based alloys, advanced alloys, SiC					
Key Features	Fuel and fuel-cladding interactions	PWR conditions	Integral testing	BWR conditions	Prototypic testing	Integral testing
Timeframe	FY15 – FY20+	FY18 – FY22+	FY19 – FY25+	FY19 – FY22+	FY19 – ?	FY22 – ?

Loss-of-Coolant-Accident Test Facility (ORNL)

- Internally pressurized, irradiated fuel rods
- Flowing steam environment
- Heating rate of 5° C/sec
- Temperature up to 1200° C
- Capable of water quench



LOCA furnace during operation inside the hot cell

Post-burst Zircaloy-4 tubes after LOCA sequence to 1200∘C with internal pressurization.

Plans for Lead Test Rods/Assemblies in Commercial Reactors

FY18

- GE: initiate testing of FeCrAl cladding (Hatch)
- Westinghouse: establish LFR fabrication line for U_3Si_2 fuel (INL)
- Framatome: perform pool-side exams of chromia-doped UO_2 fuel (LaSalle)

FY19

- GE: initiate LTA testing of IronClad and ARMOR fueled rods (Clinton)
- Westinghouse: initiate LTR testing of Cr-coated Zirlo and U_3Si_2 fuel (Byron)
- Framatome: initiate testing of Cr-coated M5 cladding (Vogtle)

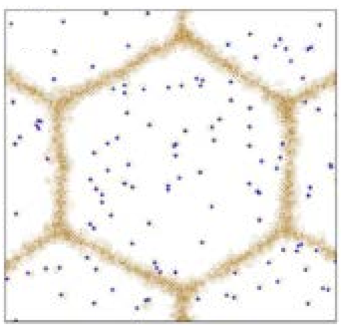
DOE's Approach

Multiscale, Mechanistic Modeling of Nuclear Fuels

Multiscale, Mechanistic Modeling of Nuclear Fuels

- **Objective:** Use hierarchical, multiscale modeling for improved, mechanistic, and increasingly predictive models of fuel performance
- Mechanistic fuel behavior models: 1) minimize form errors, 2) provide insight were experimental data is sparse, and 3) may require less (or different) experimental data for validation

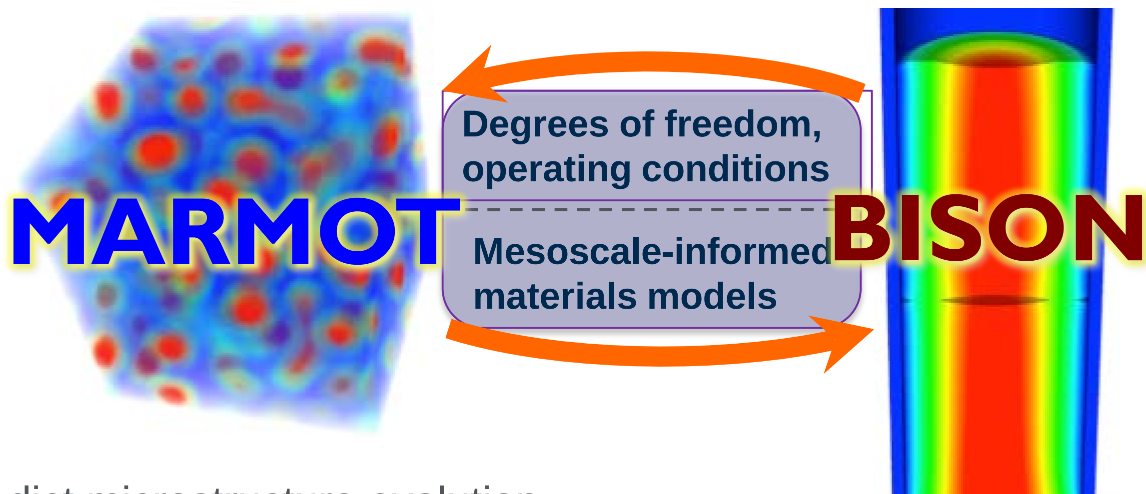
Atomistic simulations



Atomistically-informed parameters

Meso-scale models

Fuel performance models



- Identify important mechanisms
- Determine material parameter values

- Predict microstructure evolution
- Determine effect of evolution on material properties and fuel behaviors

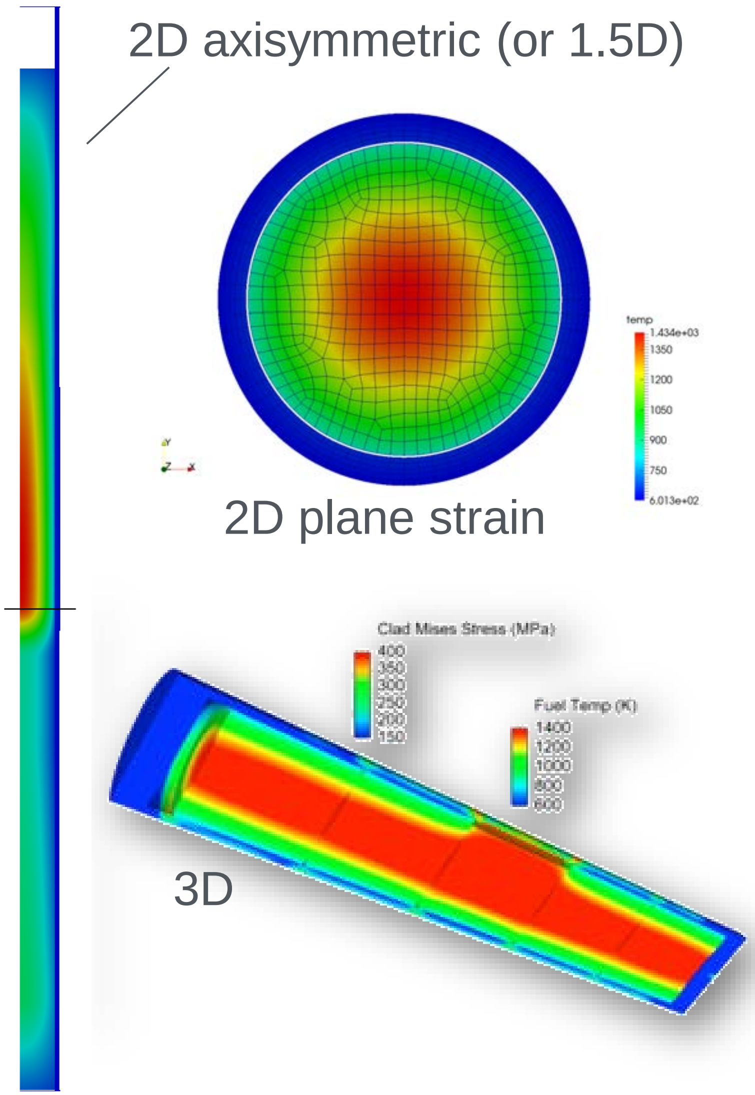
- Predict fuel performance and failure probability

The Bison Fuel Performance Code

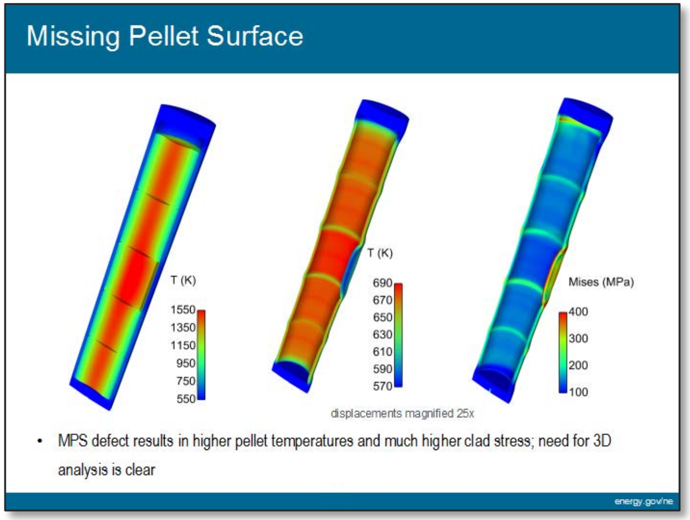
1) Overview
2) Verification
3) Validation

BISON Fuel Performance Code

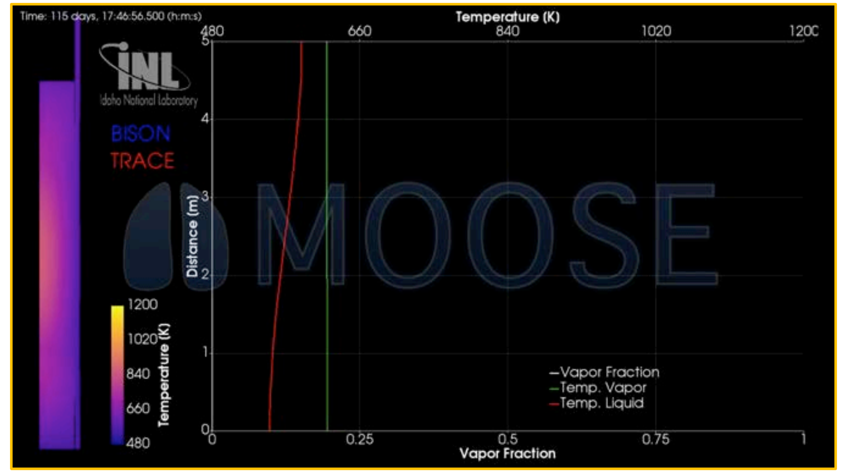
- Finite element-based engineering scale fuel performance code
- Solves the fully-coupled thermomechanics and species diffusion equations in 1D, 2D axisymmetric or plane-strain, or full 3D
- Applicable to both steady-state and transient operations
- Used for LWR, ATF, TRISO, and metallic fuels
- Readily couples to lower length-scale material models
- Designed for efficient use on parallel computers
- Includes LOCA and RIA accident capability
- Development follows NQA-1 process



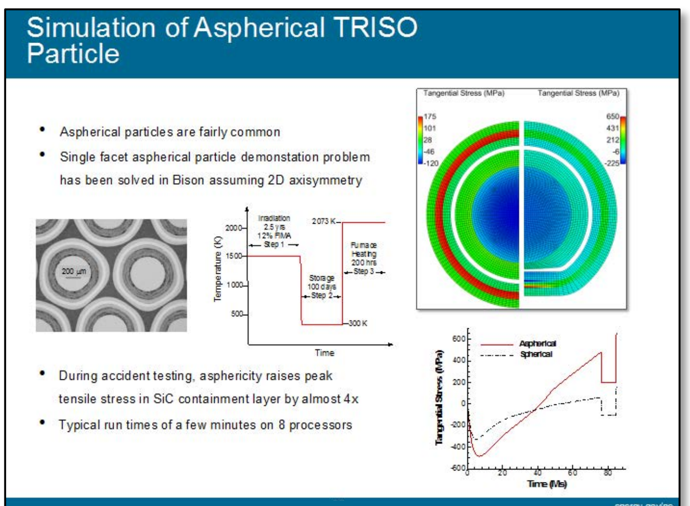
What Makes **Bison** Different?



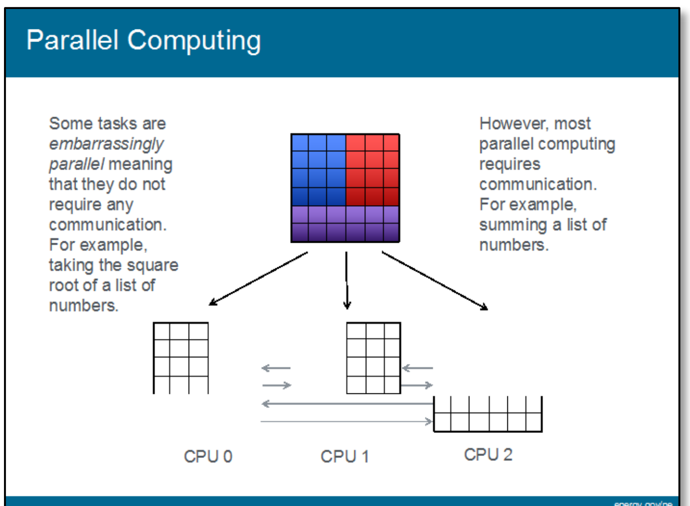
3D/Arbitrary Geometry



Coupling



Fuel Types



Parallel Computing

Bison Code Verification

- MOOSE/**Bison** is supported by >2000 unit and regression tests
- All new code must be supported by verification testing; all tests must pass prior to code merge
- Regularly audited per NQA-1 standards
- Documentation:
  - All tests distributed with source code
  - Code verification process described in journal article

Current view: top level
Test: BISON Test Coverage
Date: 2018-02-07 10:09:49
Legend: Rating: low: < 70 % medium: >= 70 % high: >= 80 %

	Hit	Total	Coverage
Lines:	18111	20668	87.6 %
Functions:	2005	2134	94.0 %

Directory	Line Coverage		Functions	
src	91.7 %	11 / 12	100.0 %	3 / 3
src/actions	88.2 %	903 / 1024	98.1 %	102 / 104
src/auxkernels	83.3 %	992 / 1191	94.6 %	158 / 167
src/auxkernels/tensor_mechanics	87.0 %	40 / 46	100.0 %	5 / 5
src/base	93.5 %	275 / 294	60.0 %	9 / 15
src/bcs	78.3 %	492 / 628	85.5 %	71 / 83
src/bcs/coolant	84.7 %	726 / 857	85.5 %	71 / 83
src/functions	91.9 %	813 / 885	98.2 %	54 / 55
src/ics	99.2 %	130 / 131	100.0 %	5 / 5
src/kernels	80.7 %	630 / 781	87.2 %	136 / 156
src/materials	87.7 %	8268 / 9424	96.2 %	733 / 762
src/materials/tensor_mechanics	91.4 %	2665 / 2915	96.1 %	367 / 382
src/mesh	86.5 %	558 / 645	77.1 %	27 / 35
src/parser	100.0 %	60 / 60	100.0 %	3 / 3
src/postprocessors	91.5 %	668 / 730	94.4 %	151 / 160
src/userobject	83.4 %	818 / 981	94.4 %	101 / 107
src/utils	100.0 %	21 / 21	100.0 %	3 / 3
src/vectorpostprocessors	95.3 %	41 / 43	100.0 %	6 / 6

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ELSEVIER

Verification of the BISON fuel performance code

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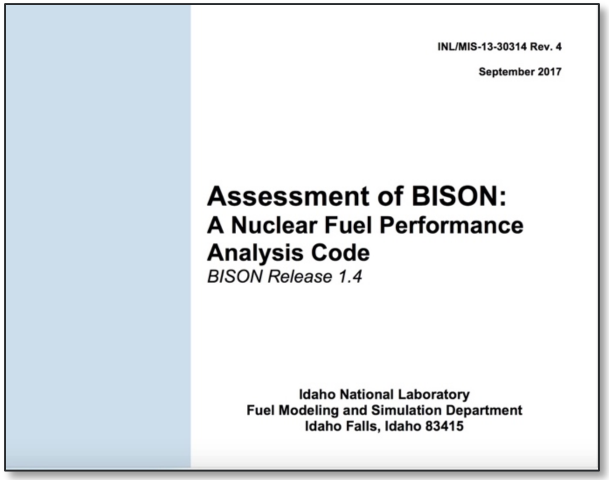
ABSTRACT

Complex multiphysics simulations such as those used in nuclear fuel performance analysis are composed of many submodels used to describe specific phenomena. These phenomena include, for example, mechanical material constitutive behavior, heat transfer across a gas gap, and mechanical contact. These submodels work in concert to simulate real-world events, like the behavior of a fuel rod in a reactor. If a simulation tool is able to represent real-world behavior, the tool is said to be validated. While much

Bison LWR Validation Status – 1/2

- Current assessment status
  - ~**75** integral, normal operation and ramp fuel rod experiments
  - **47** LOCA cases (43 burst tests, 4 integral rods)
  - **19** RIA cases
  - Some vendors have performed additional validation w/proprietary data
- Documentation:
  - Assessment report updated annually and distributed with code updates
  - Accessible online
    - User Manual
    - Theory Manual
    - Assessment Report



INL/MIS-13-30314 Rev. 4

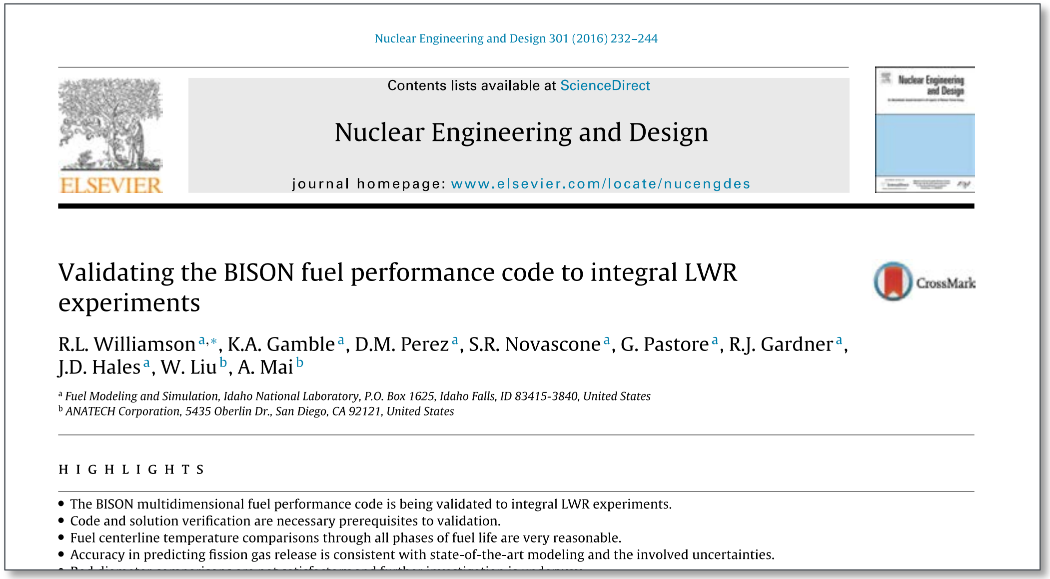
September 2017

Assessment of BISON: A Nuclear Fuel Performance Analysis Code

BISON Release 1.4

Idaho National Laboratory
Fuel Modeling and Simulation Department
Idaho Falls, Idaho 83415

https://bison.inl.gov/SiteAssets/BISON_assessment1.4.pdf



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ELSEVIER

Validating the BISON fuel performance code to integral LWR experiments

R.L. Williamson[a,*], K.A. Gamble[a], D.M. Perez[a], S.R. Novascone[a], G. Pastore[a], R.J. Gardner[a], J.D. Hales[a], W. Liu[b], A. Mai[b]

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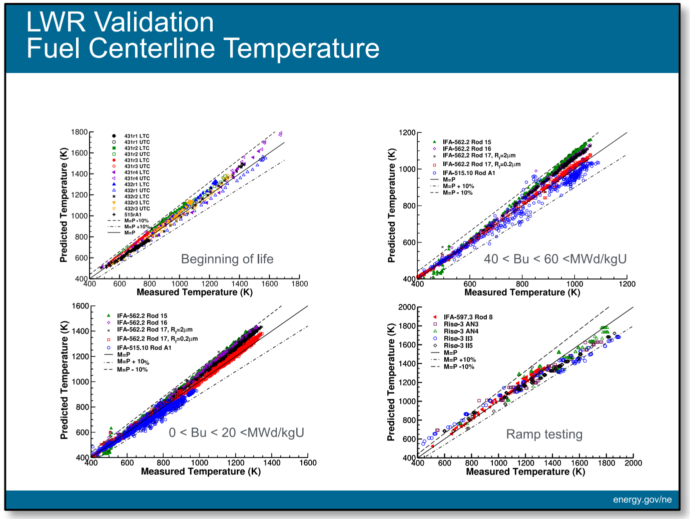
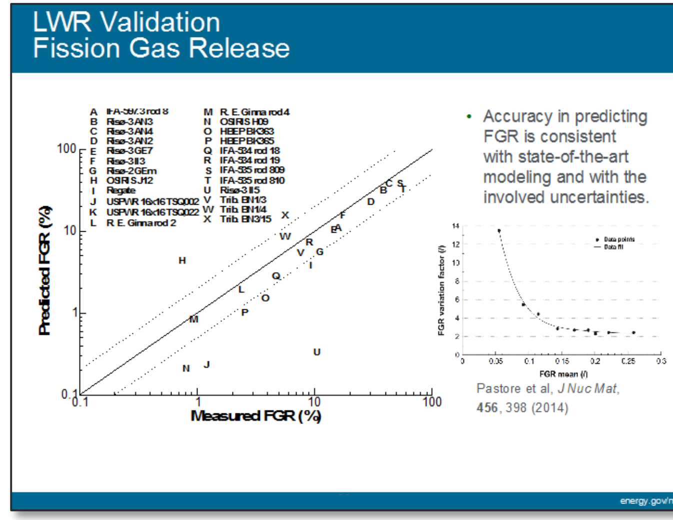
HIGHLIGHTS

- The BISON multidimensional fuel performance code is being validated to integral LWR experiments.
- Code and solution verification are necessary prerequisites to validation.
- Fuel centerline temperature comparisons through all phases of fuel life are very reasonable.
- Accuracy in predicting fission gas release is consistent with state-of-the-art modeling and the involved uncertainties.

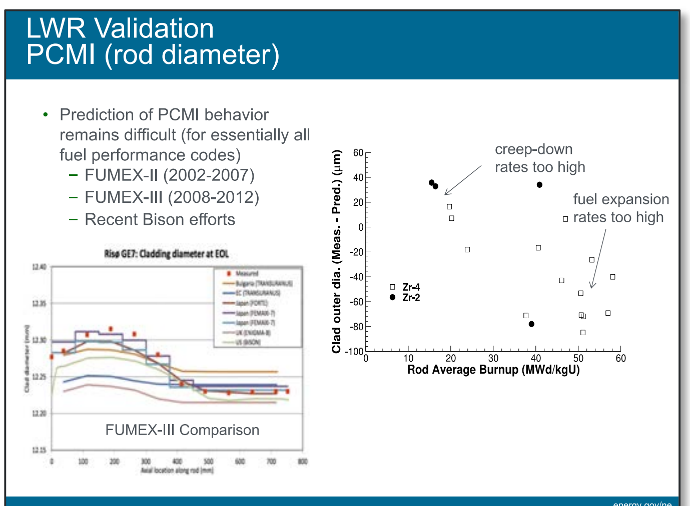
Bison LWR Validation Status – 2/2



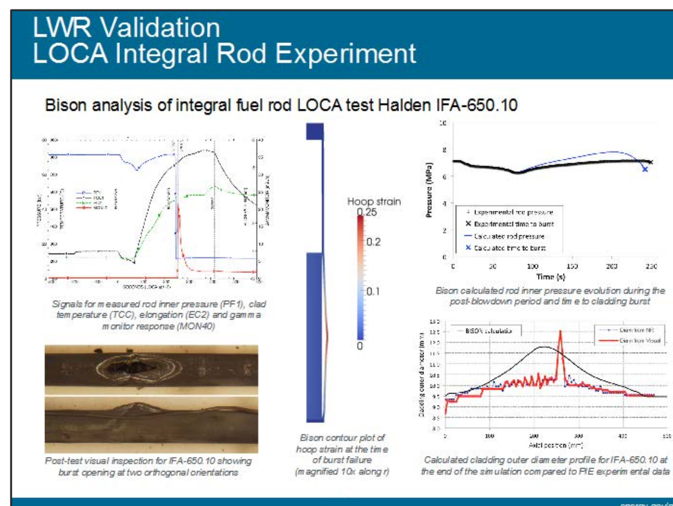
Fuel Temperature



Fission Gas Release



PCMI



LOCA

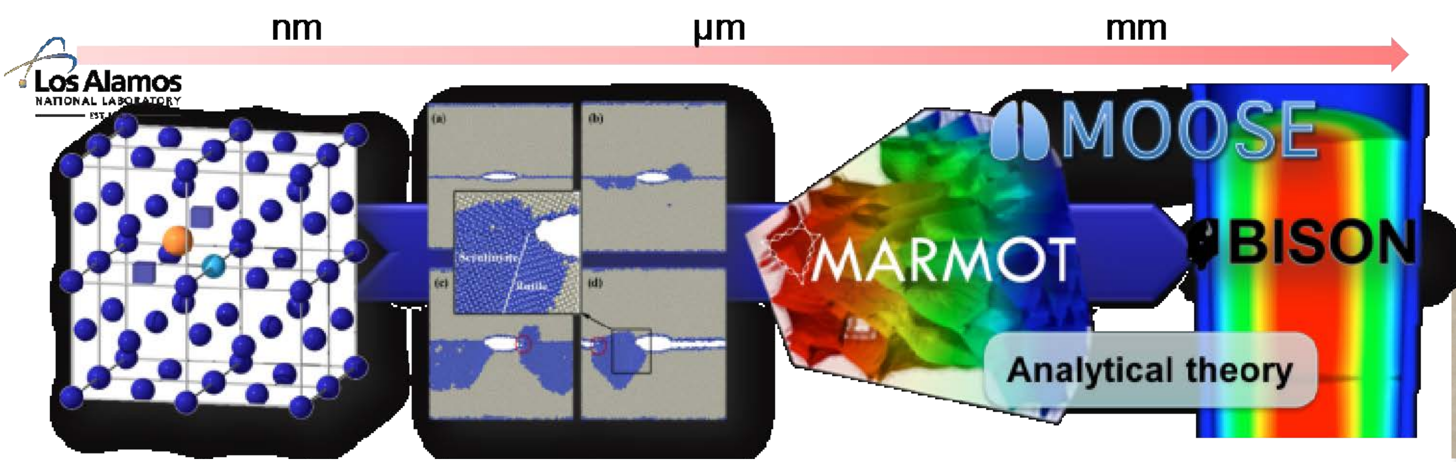
Model Enhancements for ATF

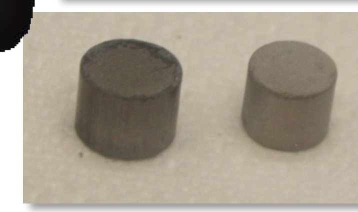
Model Enhancements for ATF

- **Bison** is a state-of-the-art fuel performance code
  - Increasingly incorporates new and improved mechanistic models for fuel behaviors
  - Exceptionally well **verified** using modern methods
  - Extensively **validated** for current LWR fuels
- **Bison** is a sound platform on which to implement enhancements to simulate Accident Tolerant Fuels
- DOE "High Impact Problem" (HIP) on ATF
  - $3M/year for 3 years (FY2015-2017)
  - ATF modeling continues in mainline DOE programs
  - Close relationship with DOE (ATF laboratory and industry teams) testing programs generating new performance data to be used for validation

Approach to Developing ATF Performance Code

1) Introduce basic ATF properties/models in **Bison** to establish simulation capability
2) Introduce mechanistic models into **Bison** from lower length-scale (LLS) activities as they become available
3) Use sensitivity analyses on ATF material properties/behavior models to prioritize LLS mechanistic modeling activities
4) On-going assessment/validation





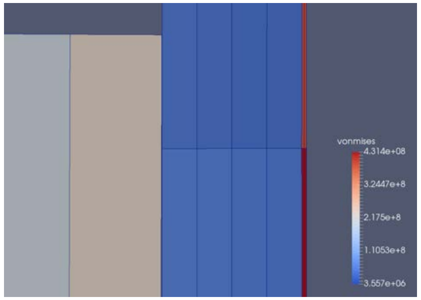
Phase thermodynamics
Defect/gas thermo. & Kinetics
Interfacial properties (potential)
→ Conductivity
Bubble formation
Phase evolution
→ Heat transport
Swelling/gas release

Heat of mixing
Migration barrier
→ Precipitation
→ Hardening

ATF High Impact Problem (HIP) Highlights

Coated Claddings

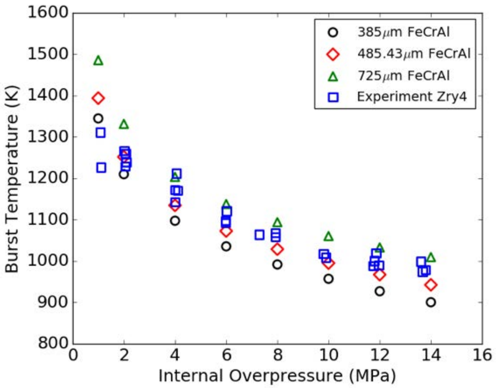
Capability established in BISON to model coatings, and several case studies examined.



FeCrAl

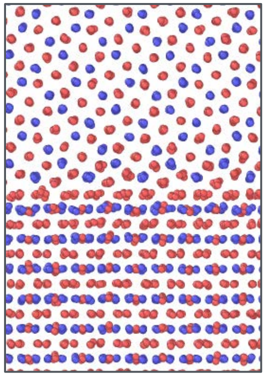
Advanced mechanical models being developed based upon cluster dynamics-informed crystal plasticity models.

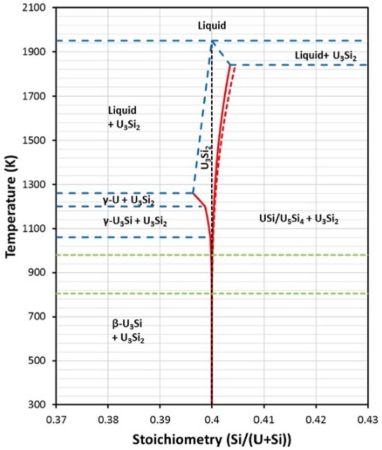
Burst model developed and implemented in BISON



U_3Si_2

Non-stoichiometry, fission gas release, swelling, thermal conductivity

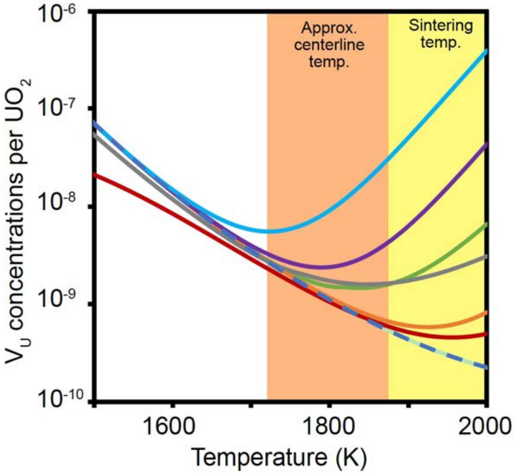




Doped-UO_2

Detailed description of dopant solution mechanism.

Impact of dopant on fission gas behavior.



Overview/Status of ATF Models in Bison

	"Complete" Set of Models	Evaluation: Base Irradiation	Evaluation: Accidents	Activities Planned for FY19
Doped UO_2 Fuel	Yes for FGR, No for creep	Yes	Yes	Improved FG diffusivity for FGR
Cr-coated Cladding	Yes, but no irradiation effects	No	No	Investigate mechanical effects of coating
FeCrAl Cladding	Yes	Yes	Yes	Support user needs
SiC/SiC Cladding	In progress	No	No	Complete evaluation of models
U_3Si_2 Fuel	Yes	Yes	Yes	Support user needs
Metallic Fuel	Yes	Yes	No	Support user needs

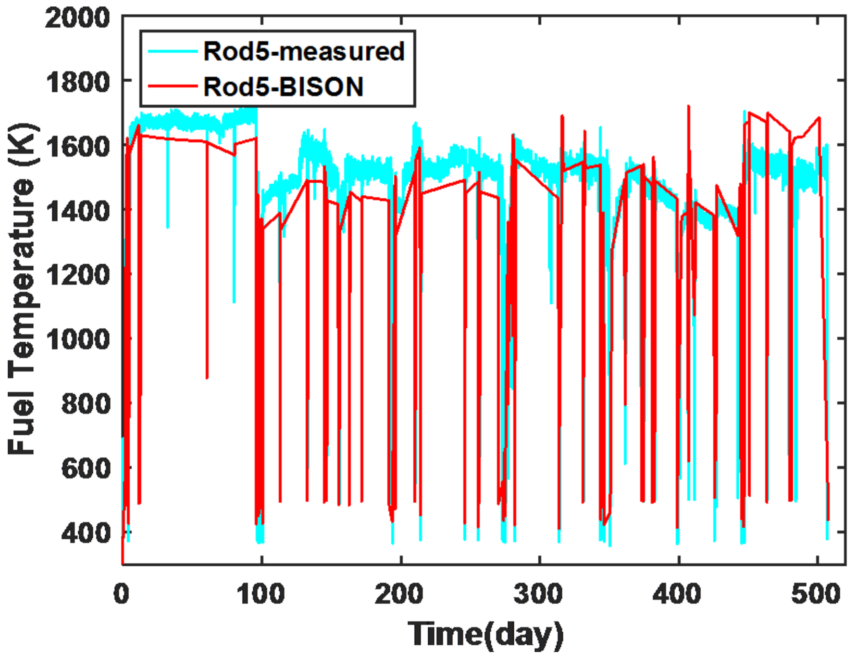
Cr_2O_3 Doped UO_2 Fuel: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes (UO_2)	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes (UO_2)	Yes	Yes	Yes	Yes
Basic mechanical properties	No (UO_2)	Yes	No	Yes	Yes
Creep	No (UO_2)	Yes	No	Yes	Yes
Swelling	No (UO_2)	Yes	No	Yes	Yes
Fission gas release	Yes	Yes	Yes	Yes	Yes

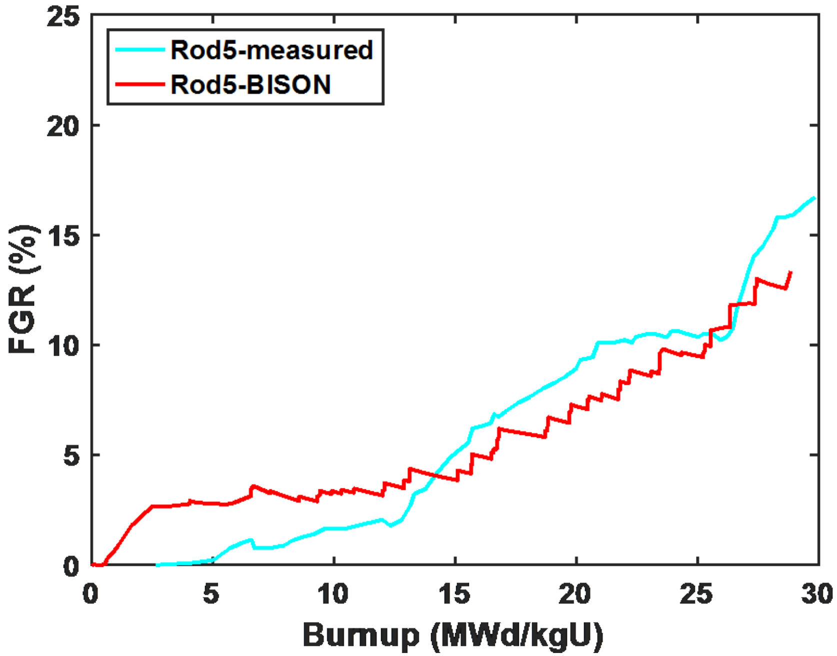
Cr_2O_3 Doped UO_2 Model Results

Bison Simulation of Halden IFA-677 Rod 5

Fuel centerline temperature



Fission gas release



	Rod 1	Rod 5
Fuel	UO_2+Add.	UO_2+Add.
Cr_2O_3 content (ppm)	900	500
Average grain diameter (μm)	56	45

Chromium-coated Cladding: Model Summary

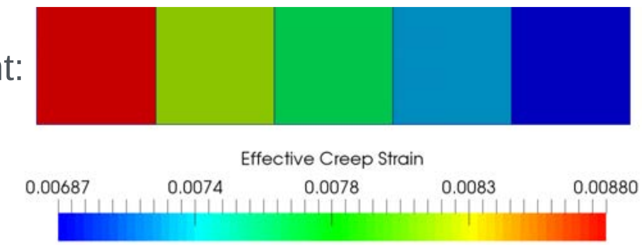
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Basic mechanical properties	Yes	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Oxidation	Yes	Yes	No	Yes	Yes

Note that no models incorporate irradiation effects. Cr-coated claddings under irradiation in ATF-2 (ATR).

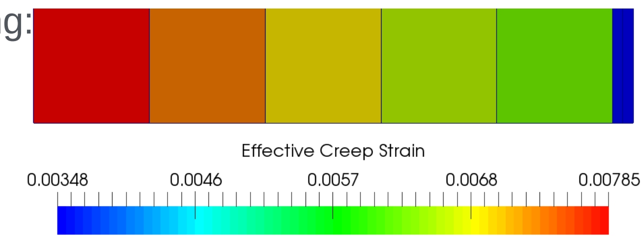
Cladding Coating Mechanical Behavior

- Objective: Compare the mechanical response of coated vs. non-coated Zircaloy cladding
- Cladding-only model with representative LWR temperature, pressure
- Chromium coating, 0.02 mm thick
  - No creep model led to unrealistically high stresses
- FeCrAl coating 0.02 mm and 0.04 mm thick
- A FeCrAl coating of 0.02 mm carries 1/10th of the load in the hoop direction

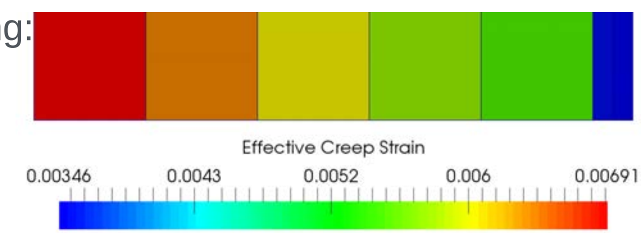
No coating:
Displacement:
3.74e-2 mm



0.02 mm coating:
Displacement:
3.10e-2 mm



0.04 mm coating:
Displacement:
2.69e-2 mm



Opportunity for use as a tool for optimization

FeCrAl Cladding: Model Summary

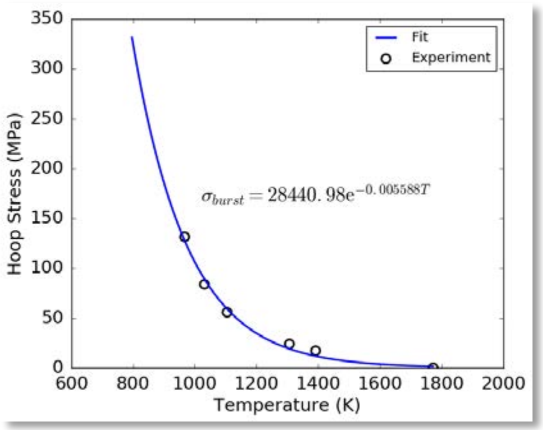
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Basic mechanical properties	Yes	Yes	In progress	Yes	Yes
Thermal Creep	Yes	Yes	In progress	Yes	Yes
Irradiation Creep	Yes	No*	No	Yes	Yes
Oxidation	Yes	Yes	No	Yes	Yes
Burst	Yes	Yes	No	Yes	Yes

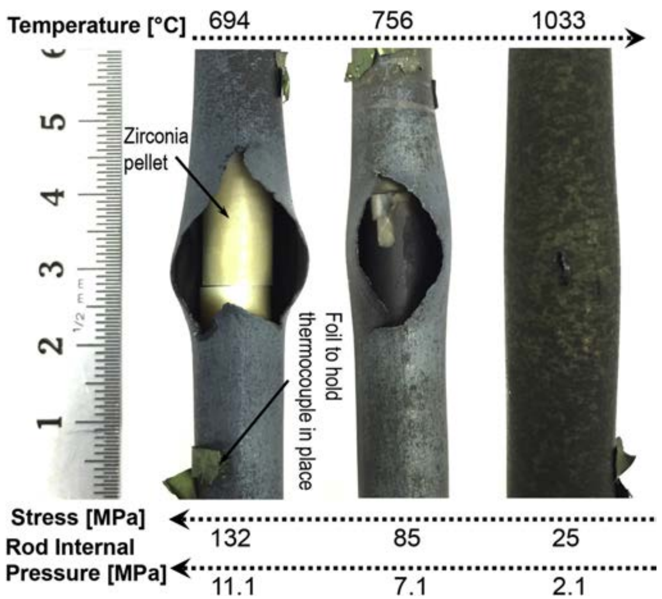
*FeCrAl cladding under irradiation in Hatch and ATF-1 (ATR).

FeCrAl Burst Model Results

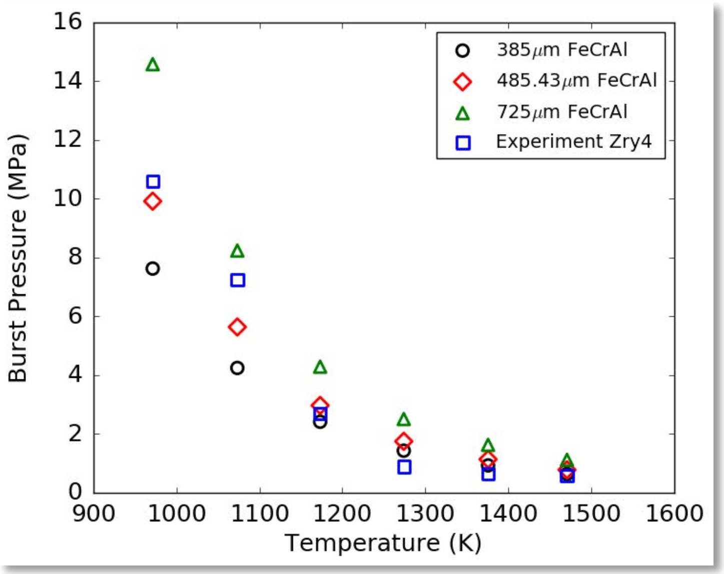
- Based experimental results, a criterion for the burst hoop stress was fit as a function of temperature.

$$\sigma_{burst} = \begin{cases} \text{Ultimate Tensile Strength}, & \text{for } T \leq 796.8\text{ K} \\ 28440.98e^{-0.005588T}, & \text{for } T > 796.8\text{ K} \end{cases}$$





Massey et al., JNM 470, 2016

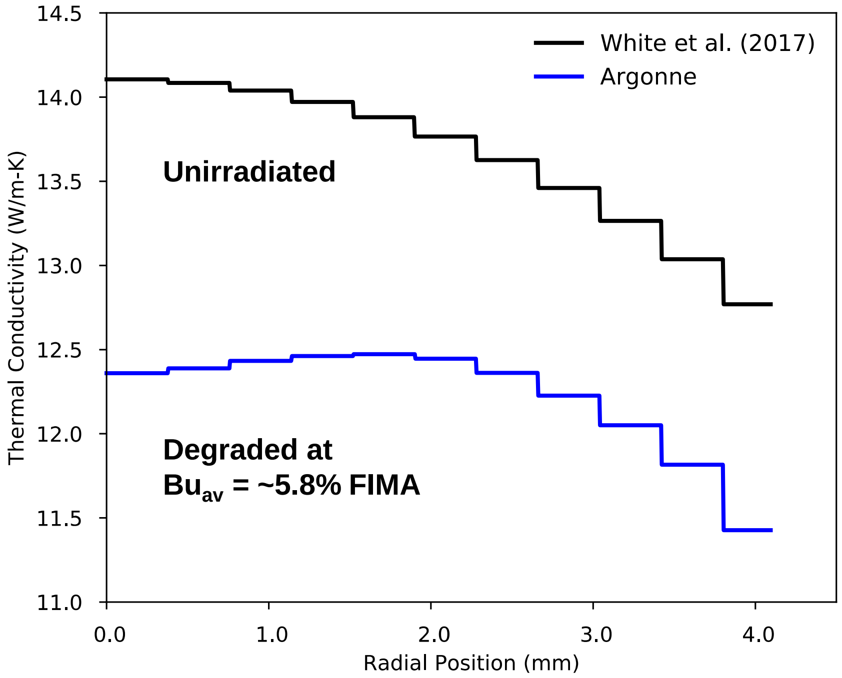


Comparison of burst predictions using a variety of cladding thicknesses indicates that the burst behavior of FeCrAl will be similar to that of Zircaloy.

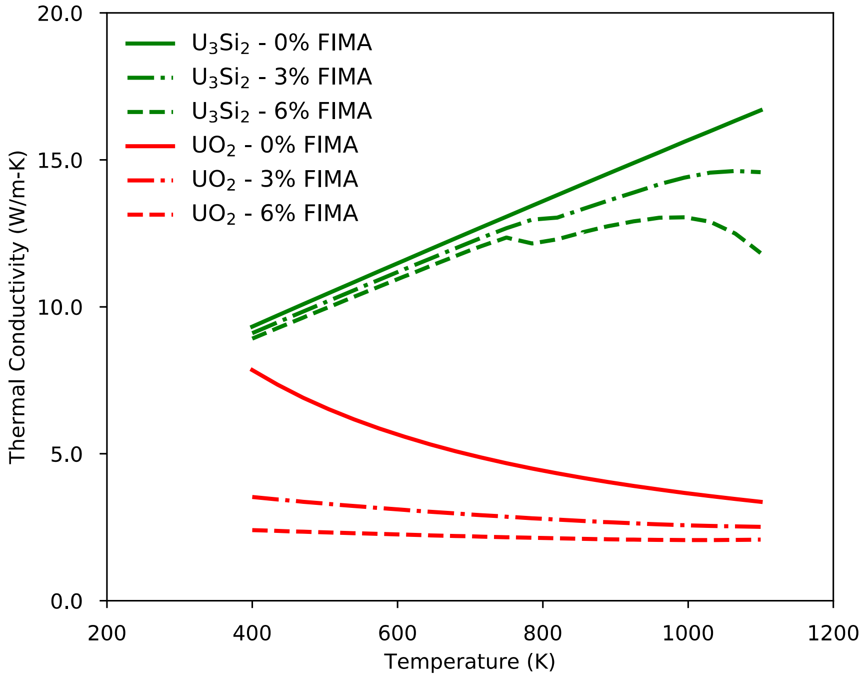
U_3Si_2 Fuel: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes	No	Yes	Yes	Yes
Basic mechanical properties	Yes (constant values for elasticity)	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Swelling	Yes	Yes (very little)	Yes	Yes	Yes
Fission gas release	Yes	Yes (very little)	Yes	Yes	Yes

U_3Si_2 Thermal Conductivity Model Results



Element averaged thermal conductivity at the midplane of a 10 pellet RZ-axisymmetric rodlet.



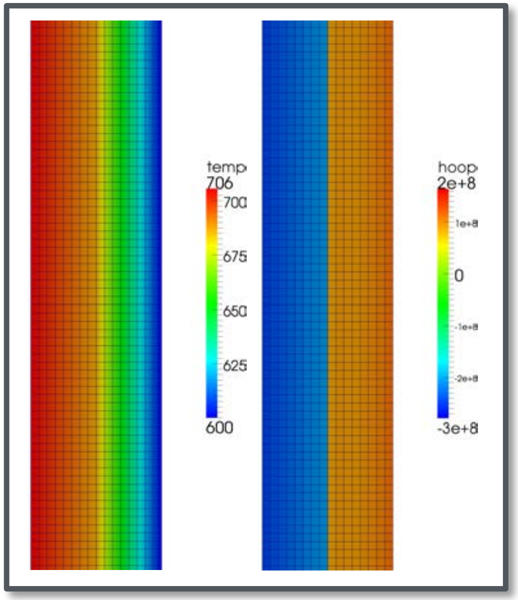
Degraded thermal conductivity comparisons between U_3Si_2 and UO_2 for a temperatures varying from 400 to 1100 K.

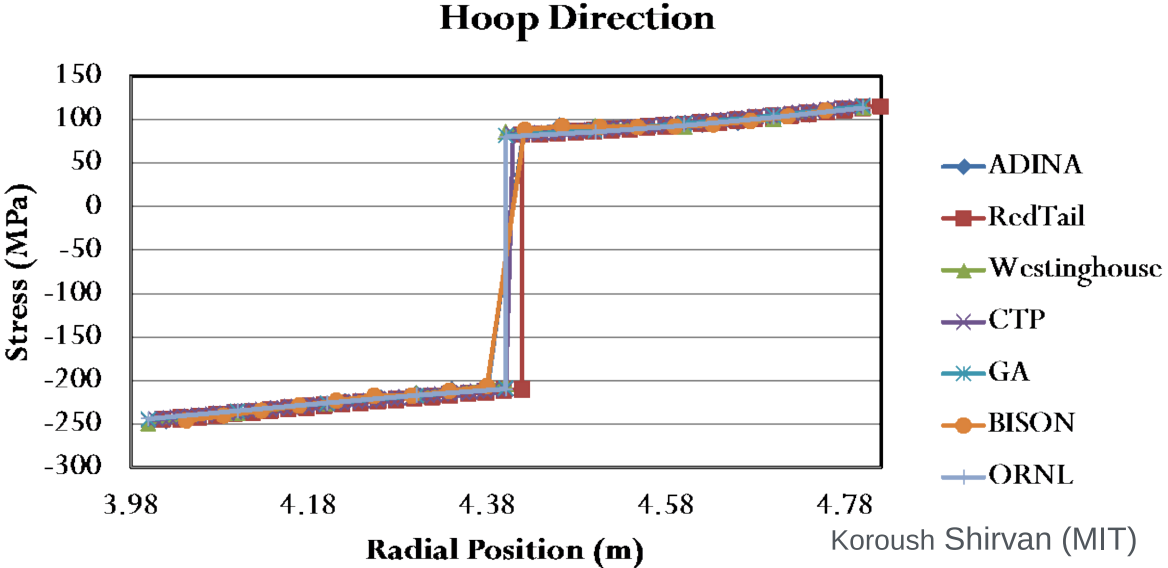
SiC/SiC Cladding: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Basic mechanical properties	Yes	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Swelling	In progress	Yes	No	In progress	In progress
Oxidation	Yes	Yes	No	Yes	Yes

SiC/SiC Cladding Model Results

- Verification tests of the SiC models exist, but comparison with experimental results is pending.
- An early, simple benchmark problem organized by MIT demonstrates that **Bison** results are consistent with those of other codes.





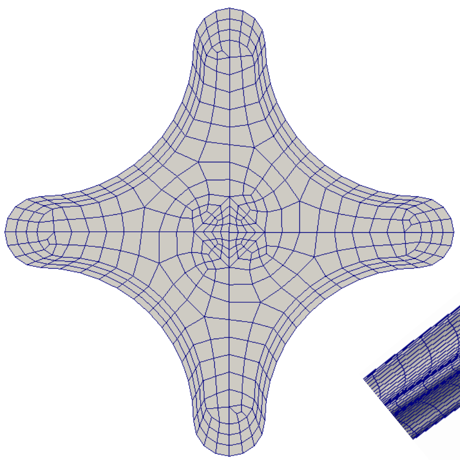
Koroush Shirvan (MIT)

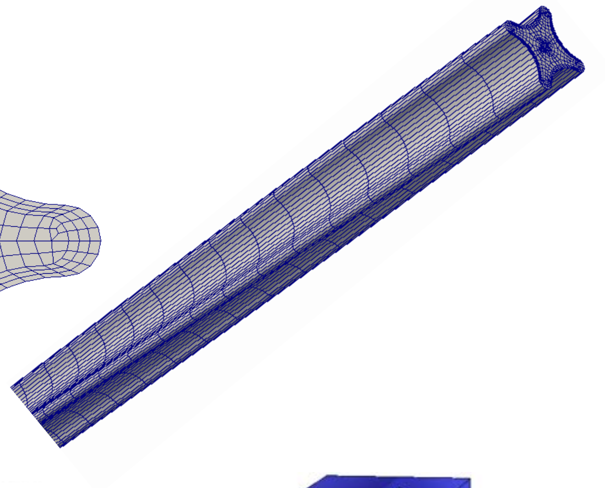
Non-Cylindrical Metallic Fuel: Model Summary

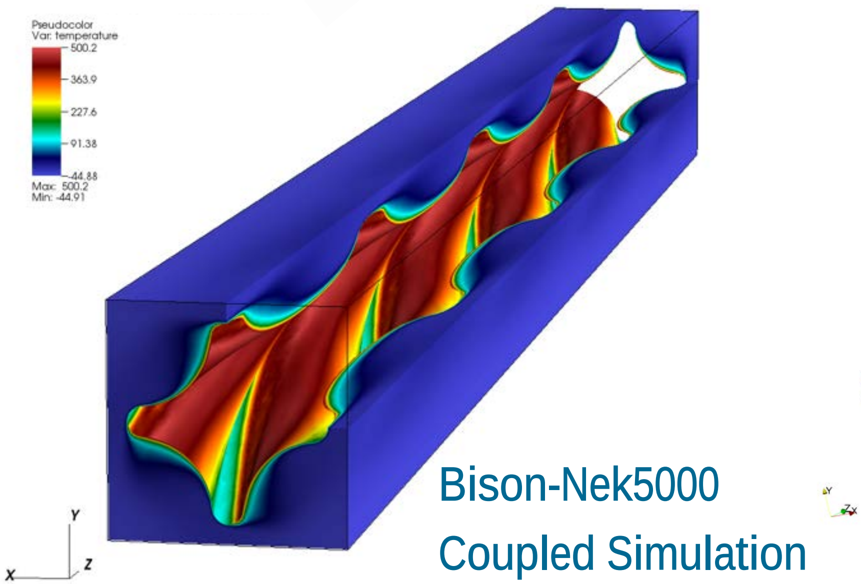
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Thermal properties	Yes*	Yes	In progress	Yes	Yes
Cladding mechanical	Yes*	Yes	No	Yes	Yes
Fuel mechanical	Yes*	Yes	No	Yes	Yes
Fission gas behavior	Yes*	Yes	In progress	Yes	Yes
Radial pin power distribution	No	No	-	-	-

Illustration of Simulation Capabilities

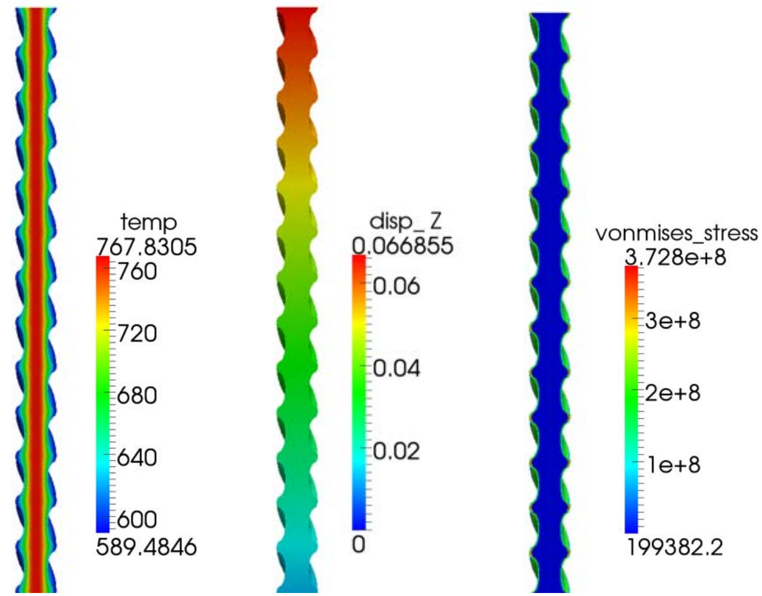
Simulations Performed on Model Problem, <u>not</u> Lightbridge Design

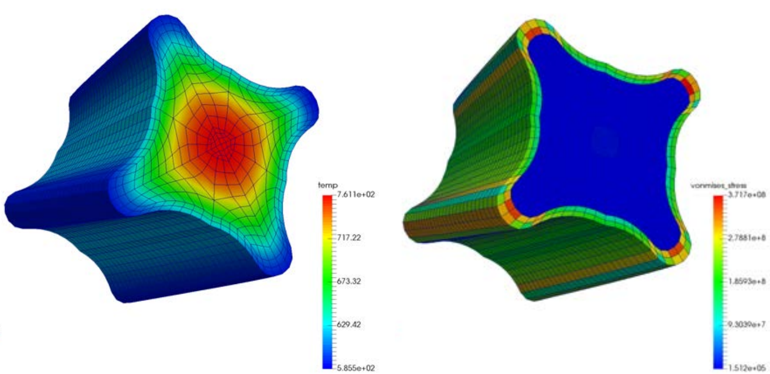






Bison-Nek5000
Coupled Simulation

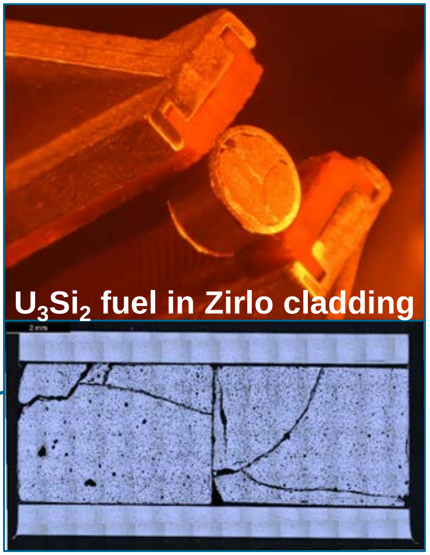




Validation for ATF

Data Generation for ATF Validation

- **DOE-sponsored testing of ATF concepts is underway**
  - Close partnership with industry ATF teams
    - *Exception:* Lightbridge
  - Heavy reliance on ATR and TREAT
  - Halden tests must be redirected (ATR, BR-2, HFIR, MITR, TREAT)
    - *Priority:* partner w/Halden staff on instrumentation implementation
  - Expanded use of LTR/LTA programs will be required
    - Quantitative PIE on important LTRs/LTAs
    - Re-fabrication/instrumentation of LTR segments for subsequent ATR, TREAT, LOCA testing
- **Fuel behavior data needed for ATF validation is being generated**


U_3Si_2 fuel in Zirlo cladding

Validation Challenges for ATF

- **There will be less experimental data (near-term) for validating ATF performance models/codes**
  - M&S of ATF not intended to replace experiments/data
  - Still need experimental data that bound operations
  - Requires close integration between modelers, experimenters, industry ATF teams, and regulator to maximize quality and applicability of data
- **Multiscale, mechanistic approach to developing fuel behavior models (at level of microstructure)**
  - Separate effects testing can play a role in model validation
  - Integral fuel rod tests still priority for **Bison** validation
  - Benefits from microstructural characterization of . . .
    - As-fabricated fuels
    - Irradiated fuels

The Irradiated Materials Characterization Laboratory (IMCL) is a new facility at INL for the microstructural characterization of irradiated fuels.

Summary and Conclusions

- **DOE's most advanced fuel performance modeling tools are being enhanced for ATF simulations**
  - **Bison** (world-class, well-validated for LWR fuel applications)
  - Multiscale modeling approach delivered demonstrated results for UO_2
  - Marmot w/atom. sims building mechanistic behavior models for ATF
- **Opportunity for Accelerated Fuel Development and Qualification**
  1) Use of **Bison** by industry and/or NRC
  2) Implementation of fuel behavior models in vendor and/or NRC codes
  3) Use insights obtained from **Bison** and mechanistic fuel models to inform experimental programs and speed licensing

Bison is available for use by industry and NRC

Questions?

Clean. Reliable. **Nuclear.**

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Neutronics and Thermal-Hydraulics Modeling for Accident Tolerant Fuels

August 21, 2018

DOE Briefing to ACRS:

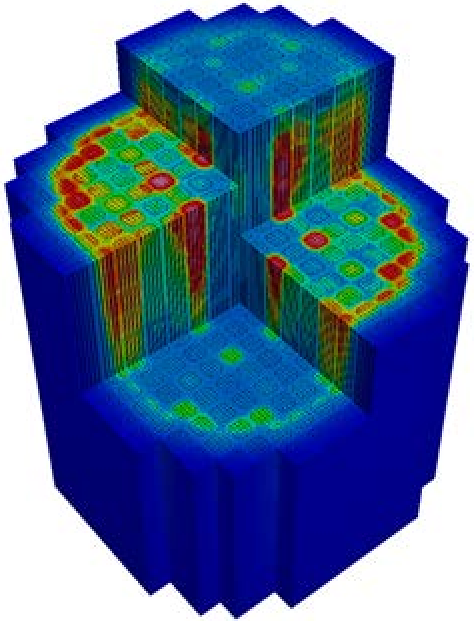
Advanced Modeling & Simulation Tools for Accident Tolerant Fuels

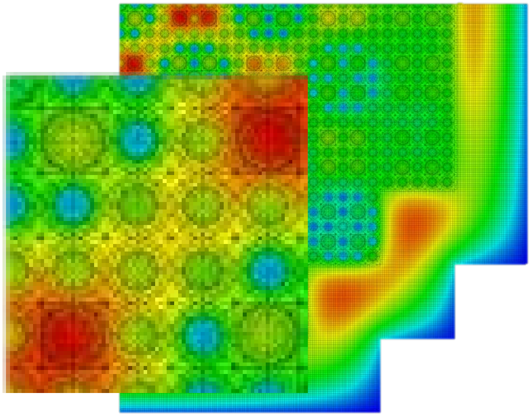
Presentation Outline

- Introduction
- Code Descriptions
- Code Validation
- Capabilities and Gaps for Accident Tolerant Fuels
- Conclusions

Introduction

- DOE has developed a fully coupled and resolved multi-physics core simulator for LWRs – Virtual Environment for Reactor Applications (VERA):
  - Neutronics (pin-by-pin fuel rod powers)
  - Thermal-hydraulics (subchannel two-phase density and flow distributions)
  - Fuel (temperature distributions)
  - Chemistry (crud build-up)
  - Detailed isotopic depletion
- Developed for applications to currently operating plants
  - Emphasis on zirconium-alloy clad UO2 in PWRs
  - For operational performance and safety analysis
  - Applied and compared to operational data from many plants
- Strong industry engagement in development and application of capabilities, including evaluation of capabilities for ATF



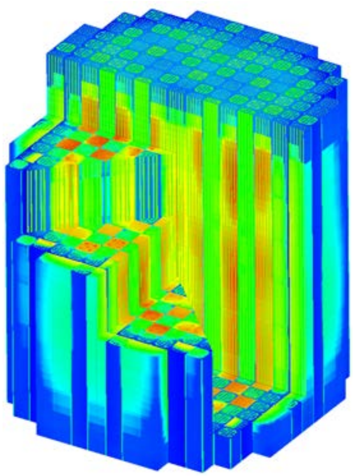


Overall Applicability to Accident Tolerant Fuels

- The DOE neutronics and thermal-hydraulics code capabilities are well established and demonstrated for LWR, particularly PWR applications
  - Steady-state operation, investigations of crud induced power shift, fuel pellet-cladding interaction
  - Operational transients, startup, shutdown, power maneuver
  - Select transients, such as reactivity insertion accidents, and departure from nucleate boiling
- The material and geometry of most ATF concepts are within current VERA capabilities with some modifications required for non-cylindrical fuel geometry
- The codes are validated for current fuels (Zr-clad UO_2) and operations and can be extended for ATF concepts

Codes and Coupling for LWR Simulations

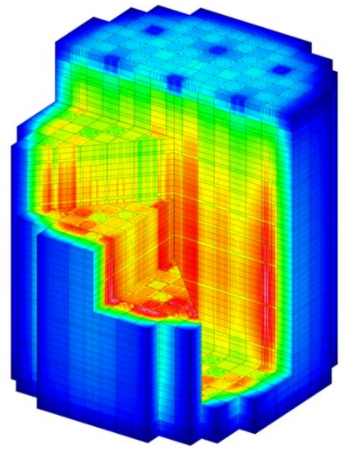
Fuel Performance



BISON

Fuel performance code modeling thermo-mechanics of standard and advanced fuel and cladding

Neutronics



MPACT

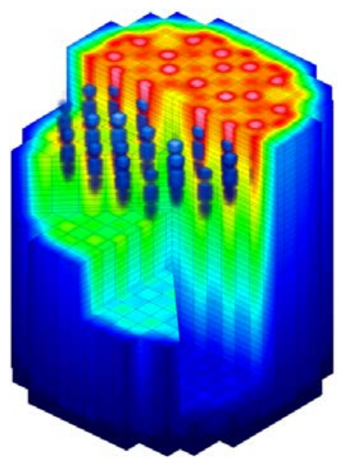
Pin-resolved 3-D whole-core neutron transport in 51 energy groups and >5M unique cross section regions

ORIGEN

Isotopic depletion and decay

SHIFT

Massively Parallel Monte Carlo transport to perform high-fidelity reference solutions to inform MPACT



Thermal Hydraulics

CTF

Subchannel thermal-hydraulics with transient two-fluid, three-field (i.e., liquid film, liquid drops, and vapor) solutions in 14,000 coolant channels with crossflow

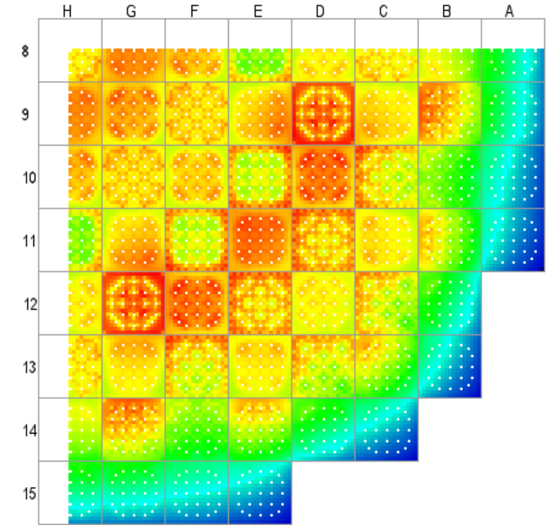
CFD

Commercial (Star-CCM+) and DOE-developed (NEK5000) capabilities to inform subchannel and provide reference solutions

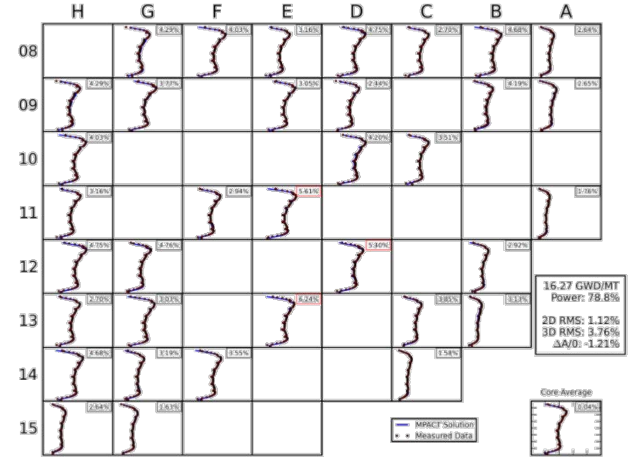
MPACT 3D Core Pin-Resolved Neutronics

- Optimized neutronics for determining detailed pin-by-pin neutron flux distribution
  - In-line resonance self-shielding at local conditions
  - Method-of-Characteristics (MoC) transport theory solution on exact geometry in 2D planes
  - Global 3D CMFD solution for average fluxes and axial leakage
- Currently models cylindrical fuel rod geometry without standard industry code approximations
  - Full geometry detail, no assembly homogenization
  - Pin powers computed explicitly, no pin-power reconstruction
  - Direct feedback calculation, no cross section functionalization
- Development emphasis has been on PWR with initial BWR capabilities being further developed
- Physics methods fully-applicable to ATF and elimination of approximations allows direct investigation ATF concepts

Watts Bar Unit 1 Cycle 14
Beginning-of-Cycle Power Distribution

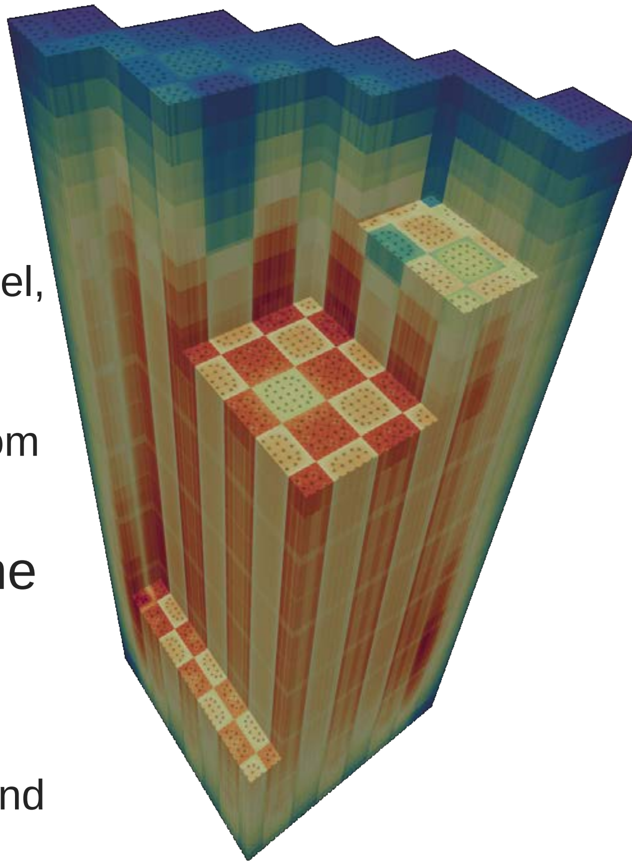


Example of Comparisons with Reactor Operating Data (flux maps)



SHIFT Monte Carlo Neutronics Capabilities

- Advanced Monte Carlo neutronics code designed to support a range of computers: from serial to massively parallel systems
- Most direct physics simulation of neutronics currently available
  - Detailed three-dimensional geometry representation of fuel, core and ex-core geometries and materials
  - Continuous energy neutron transport
  - Utilizes detailed isotopic and temperature distributions from MPACT
- Combined with large-scale computers provides the best available means to verify more approximate physics models
  - Used within DOE to verify MPACT reactivity and 3D pin power distributions for zero power physics experiments and reactor operations
- Provides means to easily verify and confirm physics models for ATF fuels including reactivity and detailed pin powers on a full-core scale



AP1000 fission rate distribution

Benefits of Advanced Neutronics Capabilities for ATF

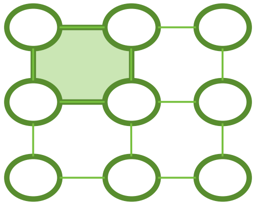
- Whole-core, fully coupled, steady-state and transient neutronics, thermal-hydraulics, and fuel performance modeling
- Removes modeling assumptions in standard codes, reducing need to investigate and confirm approximations
- Sensitivity analysis can be used to investigate changes caused by insertion of ATF fuel concepts

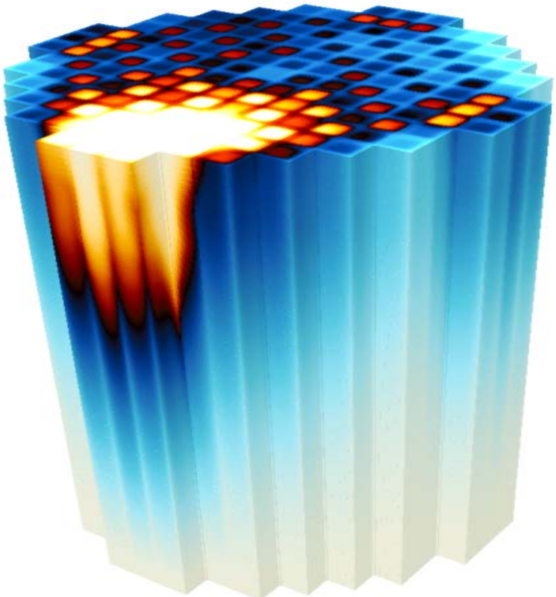
Physics Model	Industry Practice	DOE Codes (VERA)
Neutron Transport	Core: 3D diffusion, 2 energy groups, Lattice: 2D transport, 40-70 energy groups	3-D transport 51 energy groups
Power Distribution	nodal average with pin-power reconstruction	fuel pin resolved
Thermal-Hydraulics	1-D assembly-averaged	Fuel rod subchannel (w/crossflow)
Fuel Temperatures	nodal average	fuel pin resolved
Xenon/Sm	nodal average w/correction	fuel pin resolved
Depletion	lattice-averaged cross sections history corrections	fuel pin resolved
Target Platforms	workstation (single-core)	1,000 – 10,000 cores

COBRA-TF (CTF): Whole-Core T/H

- Two-fluid, three-field representation of two-phase flow
  - Continuous vapor (mass, momentum and energy)
  - Continuous liquid (mass, momentum and energy)
  - Entrained liquid drops (mass and momentum)
  - Non-condensable gas mixture (mass)
- Rod-channel resolution
  - Applied to every fuel rod channel in the core
  - Transient and steady-state simulations
  - Includes cross flow between channels
- CFD-informed models under development to improve fidelity and modeling detail
  - Grid spacer grid models
  - Azimuthal heat-transfer coefficients
- Applications include:
  - PWR & BWR steady-state and transient
  - Main steam line break analysis
  - Reactivity insertion accident
- CFD-informed rod-by-rod thermal hydraulics can model insertion of ATF to investigate impacts

Sub-Channel Discretization for the entire core





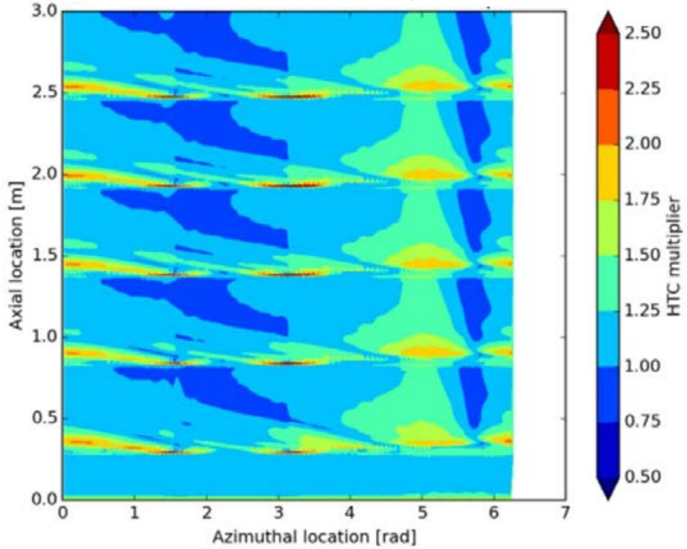
Main Steam Line Break Application of CTF coupled with MPACT – core power distribution

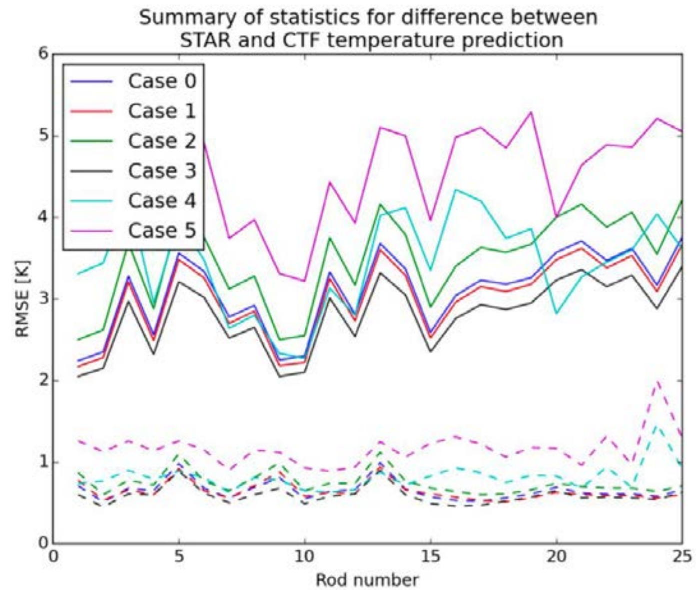
CFD-Informed Subchannel Modeling Example

DOE has been using CFD to inform subchannel to provide more detail on clad surface heat transfer to model corrosion product (CRUD) deposition on cladding

Case	Outlet pressure [bar]	Inlet temperature [°C]	Mass flux [$kg\,m^{-1}\,s^{-2}$]	Heat rate [$kW\,m^{-1}$]
0	159.9	292.7	3684.0	18.26
1	159.9	310.8	3647.2	18.26
2	159.9	292.7	3131.5	18.26
3	159.9	292.7	4236.7	18.26
4	159.9	292.7	3684.0	18.26
5	159.9	292.7	3684.0	22.82

HTC rod surface map data developed by STAR-CCM+ and read by CTF





Heat transfer coefficient map on “unrolled” cladding surface reconstructed from CTF based on CFD calibration data

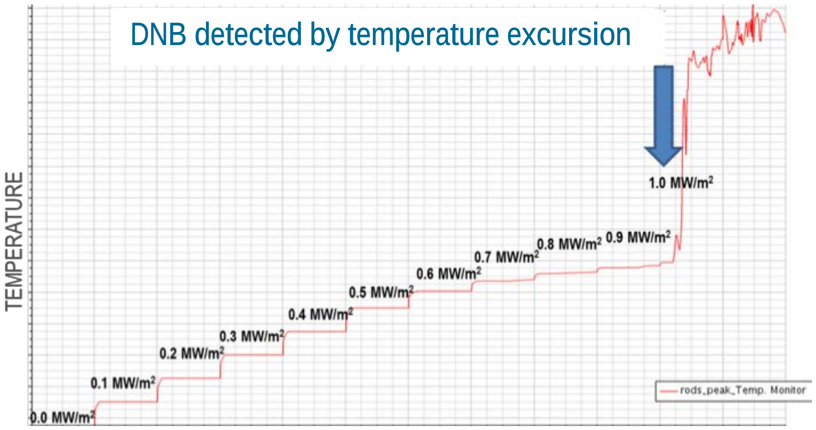
Comparison of RMS error between CFD and CTF surface temperature prediction, with and without CFD-informed heat transfer

CFD Evaluations of DNB

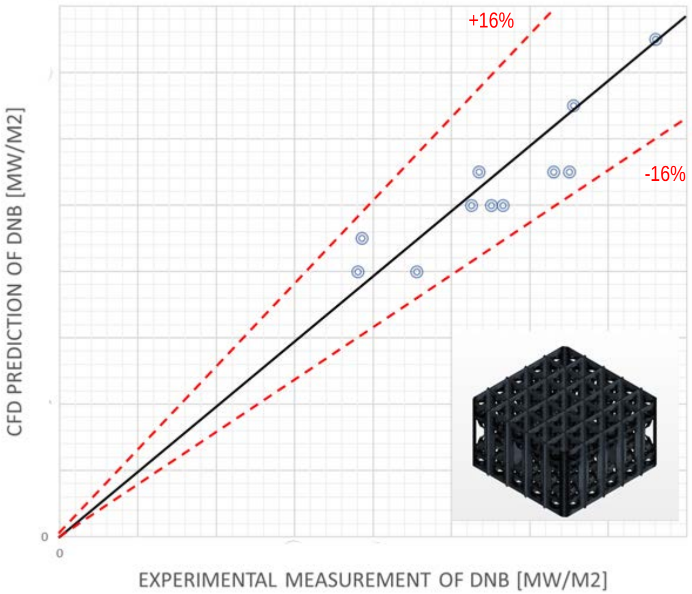
- Two-fluid Eulerian-Eulerian multiphase Navier-Stokes solution
- Carrier phase evaluated using standard single phase CFD models
- Sub-grid models define dynamic behaviors of bubble/droplet populations
  - Wall heat partitioning
    - Single phase convection
    - Bubble formation
    - Sliding bubble convection
    - quenching
  - Bubble dynamics
    - Lift and drag as a consequence of bubble size and shape
    - Bubble induced turbulence
    - Coalescence and breakup
  - Nucleation site interactions

Developing capability that can be used for support DNB analysis of ATF fuels

DNB simulations mimic electrically heated DNB experiments

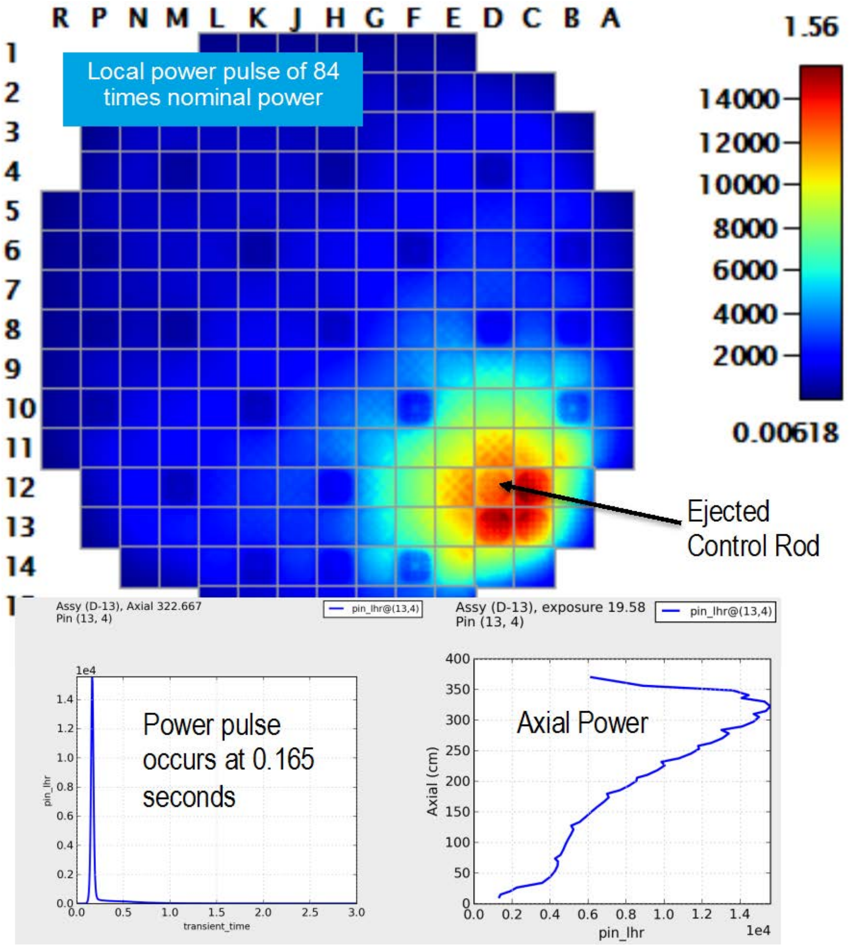


Validation for full height 5x5 bundle with nonmixing vane grid



Transient Capabilities – Reactivity Insertion Accident

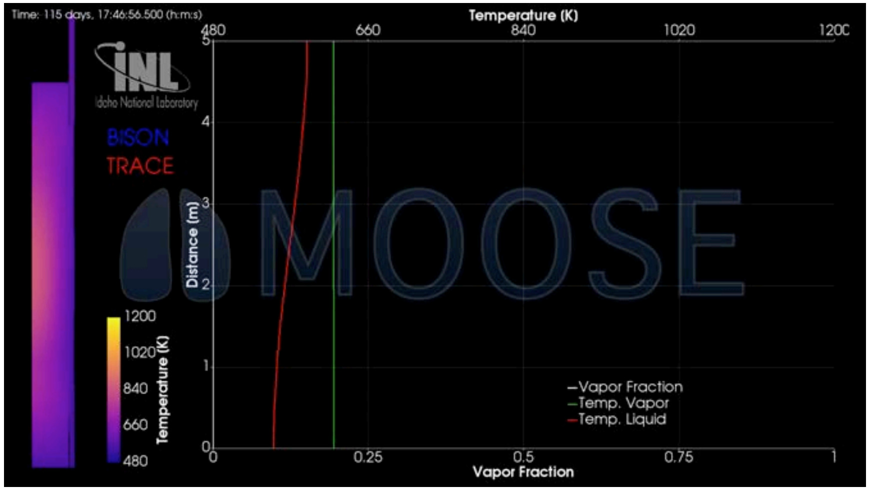
- A target problem for the development of the DOE coupled simulation codes is a Reactivity Insertion Accident (RIA)
- Time-dependent and coupled neutronics/thermal-hydraulics (MPACT/CTF) has been applied to a PWR control rod ejection
  - Maintains fuel pin and channel resolved capabilities as previously discussed
  - Fuel rod temperature model provided fuel temperature feedback
- Calculates fuel rod power profiles and histories are used as inputs for BISON fuel performance simulations
- Capability applicable to ATF assessments



Full-Core PWR Control Rod Ejection Simulation
Existing commercial Westinghouse 4-loop core design at End-of-Cycle

Coupling DOE Codes with Reactor Systems Codes

- Provides systems code capability and analyze flow regimes for which CTF has not been validated/confirmed (for example, LOCA)
- Coupling envisioned with industry and NRC systems code
- A joint DOE-NRC effort to couple NRC's TRACE code with BISON has been performed as a demonstration of the use of both DOE and NRC codes
  - Combines BISON's capabilities for ATF with NRC's systems analysis code that has been widely applied for confirmatory analysis
  - Purpose of coupling is to analyze LWR ATF concepts for normal reactor operation up to Large Break LOCA events, normal operation, blowdown phase, refill phase, and reflood phase.
- An initial demonstration of systems code and fuels coupling for a typical transient has been performed (Station Black Out)

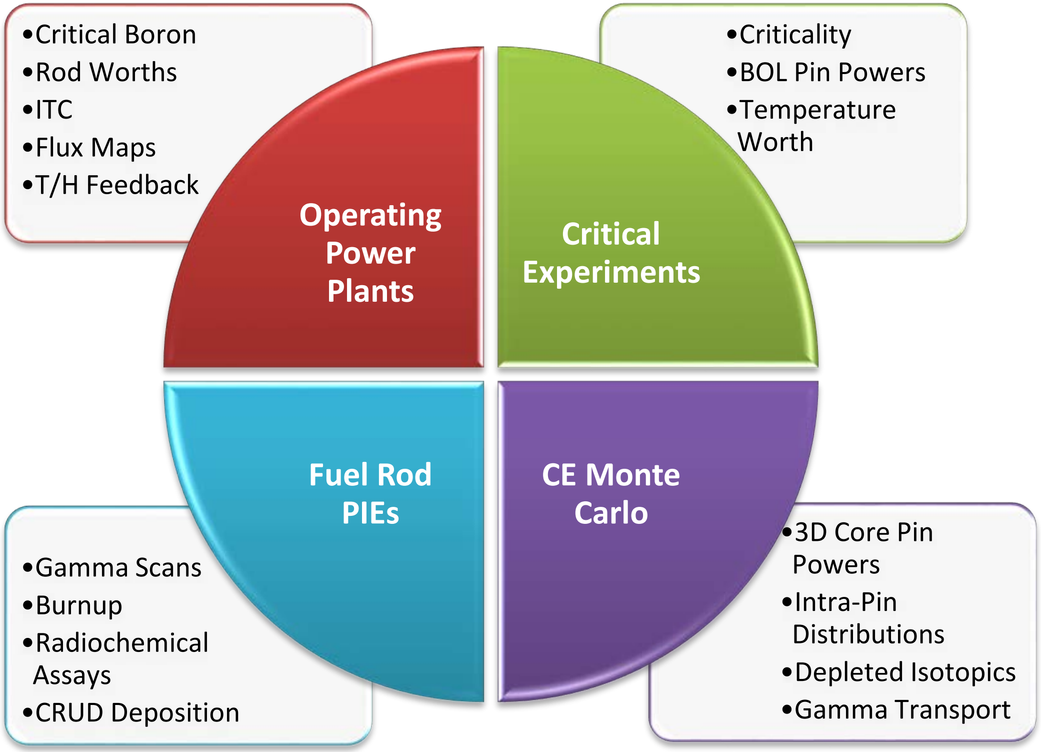


DOE Code Applications for Source Terms for ATF

- Primary application of DOE Neutronics/TH codes is to provide a high-resolution reactor inventory that can be used with a severe accident code, such as MELCOR
  - Can provide a detailed rod-by-rod inventory for all fuel assemblies in reactor and spent fuel pool
  - Validation with data from PIE and reactor operation
- Detailed SCALE/ORIGEN isotopics, consistent with NRC applications, are available for source term inventories.
- BISON fuel performance code calculates fission gas release that can be used in source term models
- Transient simulation capability can be used to provide detailed power rod-by-rod power distributions and fuel enthalpy for comparison with coarser methods.

Neutronics and Core Modeling Validation

- Validation includes single and coupled multi-physics
- Focused on existing fuels and plant operation
- Continuous energy Monte Carlo benchmark calculations supplement measured data



Subchannel Thermal-hydraulics Validation

- CTF Subchannel validation is against publicly-available data and some specific proprietary vendor data

Phenomenon for Validation:

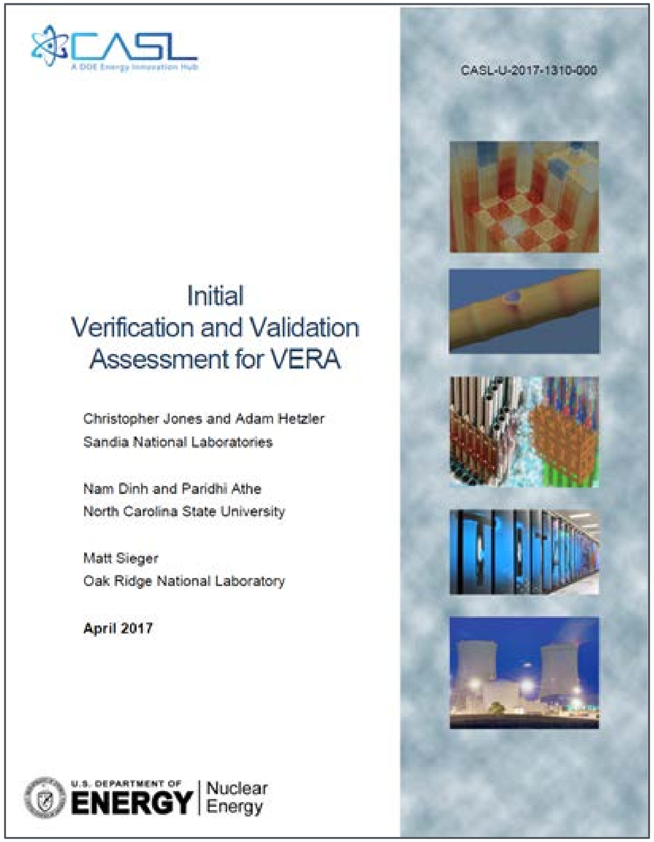
- Single phase convection
- Sub-cooled boiling heat transfer
- Single and two-phase wall shear
- Single and two-phase grid pressure drop
- Single and two-phase turbulent mixing
- Grid heat transfer enhancement (PWR)
- Nucleate boiling heat transfer
- Vapor generation (near-wall condensation)
- Void drift
- Pressure directed cross flow
- Transition boiling
- Radiative heat transfer
- Critical heat flux

Validation Experiments Examples

- Full channel
  - PSBT (PWR)
    - Pressure drop
    - Critical heat flux
  - BFBT (BWR)
    - Pressure drop and void
    - Critical power
  - FRIGG Loop
    - Single & two-phase pressure drop
    - Axial & radial void distribution
    - Dryout
  - Harwell High Pressure Two-Phase Heat Transfer Loop
- Subchannel
  - PNNL 2x6, CE 5x5, GE 3x3, RPI 2x2, Kumamoto 2x3
    - Single and two-phase heat transfer
    - Flow qualities
    - Mixing and void drift
- Vendor proprietary data
  - Departure from nucleate boiling

VERA Validation – Existing Plants and Fuels

- Integrated codes applied to a number of PWR plants and operating cycles for validation
- Typical comparisons include:
  - Zero power physics tests (criticality, rod worth), flux maps during power escalation
  - Operational measurements (soluble boron, flux maps)
  - Operational transients
- Plant and cycles also chosen for validation of nominal and operational occurrences
- Specific plants include:
  - Watts Bar Unit 1 (Cycles 1-15) (W 4-loop, 17x17 fuel)
  - Watts Bar Unit 2 (Cycles 1-2) (W 4-loop, 171x17 fuel)
  - Callaway 1 (Cycles 1-8) (W 4-loop, 17x17 fuel)
  - Catawba 2 (Cycles 8-21) (W 4-loop, 17x17 fuel)
  - Seabrook Unit 1 (Cycles 1-5) (W 4-loop, 17x17 fuel)
  - Palo Verde 2 (Cycles 1-9) (CE System 80, 16x16 fuel)
  - Davis-Besse Cycles 12-15 (B&W, 15x15 fuel)
  - Oconee 3 (Cycle 25) (B&W, 15x15 fuel)
  - TMI Cycles 1-10 (B&W, 15x15 fuel)
  - Byron 1 (Cycles 17-21) (W 4-loop, 17x17 fuel)
  - AP1000® startup


CASL

CASL-U-2017-1310-000

Initial
Verification and Validation
Assessment for VERA

Christopher Jones and Adam Hetzler
Sandia National Laboratories

Nam Dinh and Paridhi Athe
North Carolina State University

Matt Sieger
Oak Ridge National Laboratory

April 2017

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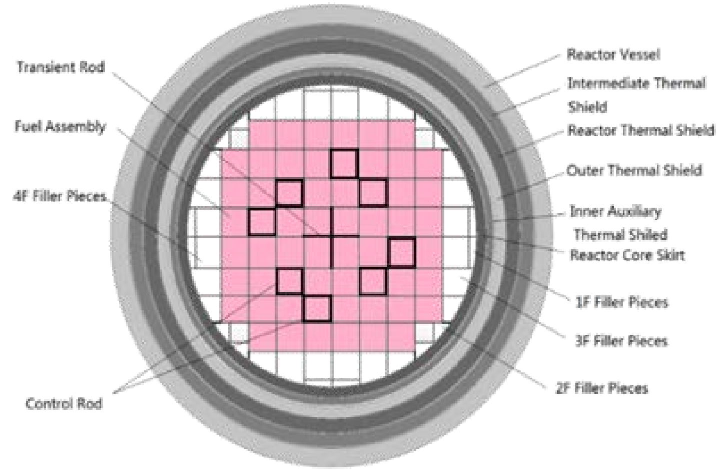
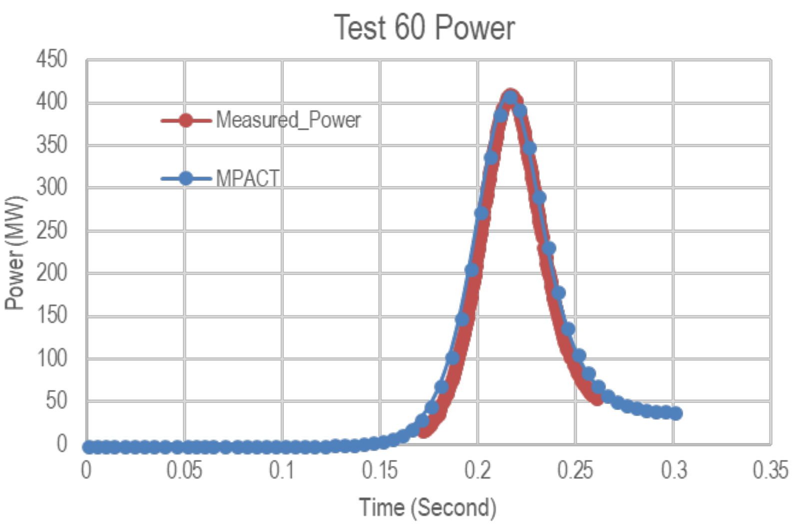
VERA Transient Validation - SPERT-III

- Special Power Excursion Reactor Test III (SPERT III)
  - PWR Test Reactor
  - Purpose to investigate power excursion kinetic behavior series of transient tests provide validation for coupled multi-physics
  - Widely used for validation of codes for reactivity insertion accidents (RIA)
- SPERT III Transient Experiment Modeling
  - 60 assemblies radially and 20 layers axially
  - Initial core inlet temperature is at 502 oF $\pm$4 oF.
  - Initial Power is 19 $\pm$ 1 MW.
  - Fully coupled neutronics, thermal-hydraulics, fuel temperature model
- Good agreement between VERA and measured results

SPERT-III Core Geometry



SPERT-III Power Comparison



Neutronics Capability Assessment for ATF

Modeling	UO2 Fuel	Coated Clad	Doped Fuel	FeCrAl Clad	U3Si2 Fuel	SiC Clad	U Metal Fuel
Geometry	Yes	Yes	Yes	Yes	Yes	Yes	No
Physics Models	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Materials & Nuclear Data	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Validation Performed	Yes	Yes (UO_2)	Yes (UO_2)	No	No	No	No
Design Specific Validation data Availability	Yes	Yes (UO_2)	Yes (UO_2)	No	No	No	No

- Significant validation for UO2 – zirconium clad fuel performed and underpins validation for all fuel concepts. Historical experience for steel-based cladding.
- Material perturbations can be investigated with DOE codes and sensitivity/uncertainty approaches to determine need for additional validation.
- Comparisons with Monte Carlo methods can provide confirmation of ability to codes to model non-cylindrical geometry fuels.
- Lead test rods and assemblies, startup physics testing can provide additional pre-operational data.

Thermal-Hydraulic Capabilities for ATF

Modeling	Zirc Clad	Coated Clad	Doped Fuel	FeCrAl Clad	U3Si2 Fuel	SiC Clad	U Metal Fuel
Geometry	Yes	Yes	Yes	Yes	Yes	Yes	No
T/H Models	Yes	Yes	n/a	Yes	n/a	Yes	No
Generic Validation Performed	Yes	Yes	n/a	Yes	n/a	Yes	No
Design Specific Validation Data Available	Yes	No	n/a	No	n/a	No	No

- Assessment for conventional rod bundle T/H completed and is expected to be applicable to ATF.
- Design specific information for surface roughness, wettability, spacer grid location, top/bottom fuel nozzle form losses needed to verify existing validation.
- Design specific data needed for CHF and two-phase CFD validation. CFD validation of DNB underway for non-mixing and mixing vane 5x5 experiments.
- Metallic fuel with non-cylindrical geometry is the greatest challenge.

Conclusions on Neutronics/Thermal Hydraulics Models

- Higher-resolution, fully coupled modeling capabilities have been developed and are applicable for ATF
  - Direct whole-core simulation with explicit representation of local heterogeneities can be used for ATF, including the design and analysis of LTA test programs and reload cores
  - Approaches using higher-accuracy methods (Monte Carlo, CFD) to verify and inform engineering-scale simulations provides means to accommodate ATF modeling
  - Can be reduce time to perform analysis by eliminating investigation of applicability of and more directly simulate impacts of insertion of ATF
- Significant validation for existing UO_2 fuels forms can be leveraged for ATF analysis
  - Use of sensitivity/uncertainty methods and higher-order methods (Monte Carlo/CFD) can be used to quantify the impact of ATF in areas such as criticality and thermal-hydraulic performance
  - Can be used by Industry and NRC for analysis or support confirmation of current Industry or NRC codes
- System code coupling allows for evaluation of transient licensing events and demonstrates use of NRC and DOE codes together

Questions?

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Introduction to non-LWR Session

August 21, 2018

DOE Briefing to ACRS:

Advanced Computer Models for Reactor Safety Applications

Outline of non Non-LWR Presentations

	SFR	HTGR	FHR	MSR
Neutronics	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake
Fuels	MARMOT, BISON	MARMOT, BISON	MARMOT, BISON	In progress chemistry code
T-H	Nek-5000, SAM, SOCKEYE	Nek-5000, Pronghorn, SAM	Nek-5000, Pronghorn, SAM	Nek-5000, SAM
Source term	SAM, PERSENT, BISON	Pronghorn, BISON	SAM, Nek5000, Pronghorn, BISON	SAM, Nek5000

Outline of non Non-LWR Presentations

1. **Tanju Sofu**
2. **Rich Williamson**
3. **Elia Merzari**
4. **Tanju Sofu**

	SFR	HTGR	FHR	MSR
Neutronics	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake
Fuels	MARMOT, BISON	MARMOT, BISON	MARMOT, BISON	In progress chemistry code
T-H	Nek-5000, SAM, SOCKEYE	Nek-5000, Pronghorn, SAM	Nek-5000, Pronghorn, SAM	Nek-5000, SAM
Source term	SAM, PERSENT, BISON	Pronghorn, BISON	SAM, Nek-5000, Pronghorn, BISON	SAM, Nek-5000

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Neutronics Analysis Capabilities for Advanced Reactors

DOE Briefing to ACRS:

Advanced Modeling & Simulation Tools for Advanced Reactors

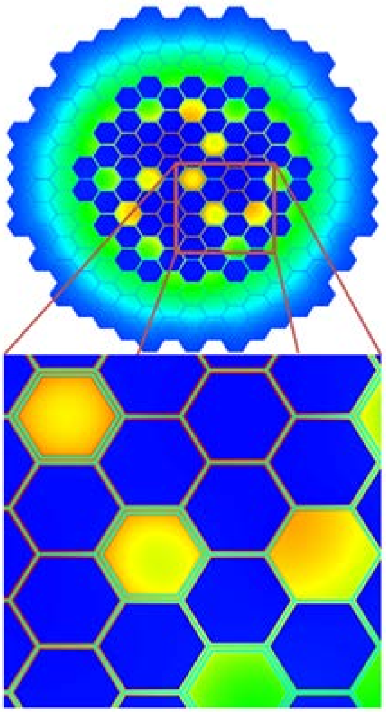
Outline

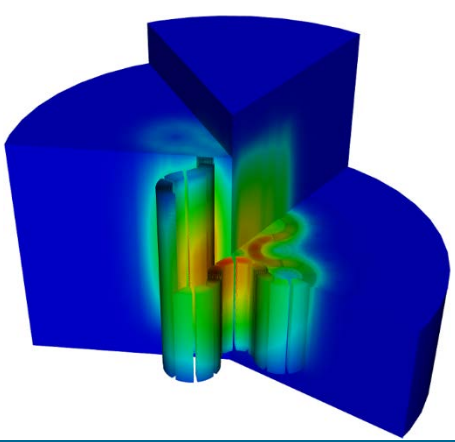
- Background
- Neutronics analysis code suite
- Validation basis
  - Criticality experiments
  - Integral tests at EBR-II and FFTF
- Advanced reactor applications
  - SFRs
  - MSRs
  - HTGRs
  - Multiphysics analysis
- Conclusions

Background

- DOE's Nuclear Energy Advanced Modeling and Simulation program supports development of high-fidelity capable neutron transport code suite for advanced reactors
  - Deterministic tools to complement Monte Carlo techniques by compensating for their limitations
    - Transient analyses with deforming mesh
    - Fine-grid flux distributions for rigorous treatment of multi-physics phenomena
    - Shielding and dose rate calculations in regions with low flux
  - High-fidelity capability extends application regime to complex geometries and sharply heterogeneous material compositions
- Desired impact
  - Improved operational and safety margins through higher-order modeling
  - "Close to first principles" solutions for benchmarking lower-fidelity/order modeling approaches
  - Multi-physics interface with matching levels of fidelity
  - Enhance the impact of experiments to support reactor design/licensing

PROTEUS Neutronics Suite





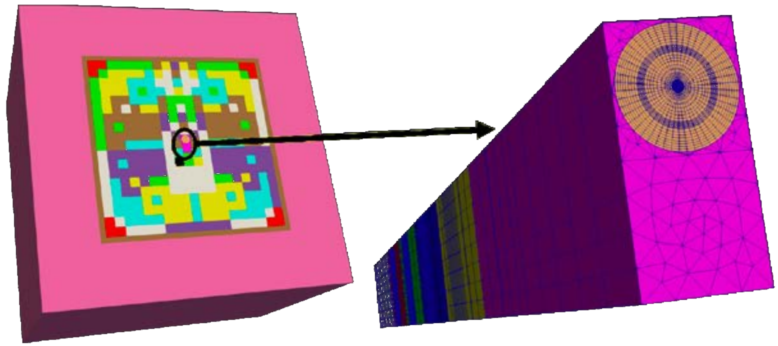
- Complete package with unstructured finite element meshing tools, range of multi-group cross-section generation options (for both thermal and fast spectrum), neutron/radiation transport solvers, depletion and sensitivity analyses, and post-processing capabilities
  - Multi-physics interface for thermal and core deformation feedback
- **MC^2-3 and Cross Section API**: For high-quality multi-group cross section generation with local heterogeneity effects
  - https://www.anl.gov/technology/project/mc2-3-multigroup-cross-sections-fast-reactors
- **PROTEUS**: Two high-fidelity, highly-scalable neutron transport solver options (SN and MOC) and a nodal transport solver option (NODAL)
  - https://www.ne.anl.gov/codes/proteus/
- **PERSENT**: Perturbation and sensitivity analyses based on the variational nodal transport method (to determine reactivity feedback coefficients)

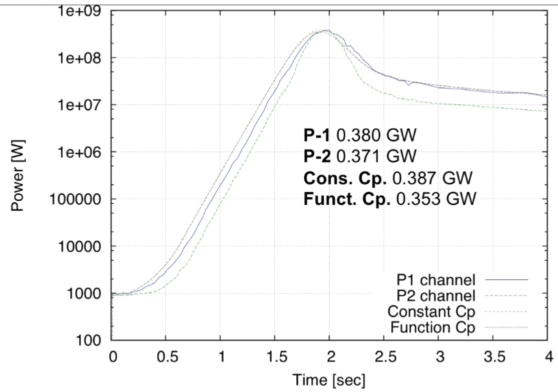
RattleSnake

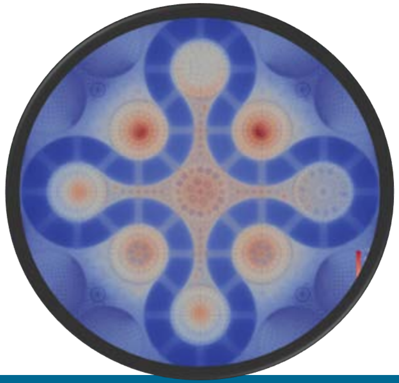
A multi-scheme radiation transport application

Deterministic radiation transport solver for linearized time-dependent Boltzmann radiation transport equation

- Originally developed to support TREAT reactor restart and experiment modeling, based on a finite element solver for SN and PN approximations
- Designed for tightly coupled nonlinear multiphysics simulations to capture the impact of temperature and material density changes on time-dependent flux distribution, reaction rates, and power profile
- Multi-scheme capability for a fine-scale resolution in places where interesting multiphysics phenomena take place
  - Uses a lower order and/or homogenized solution for less interesting areas
- Lattice, pebble bed and hexagonal fuels, complex configurations such as Advanced Test Reactor (ATR) and the Transient Reactor Test Facility (TREAT)
- https://rattlesnake.inl.gov/SitePages/Home.aspx





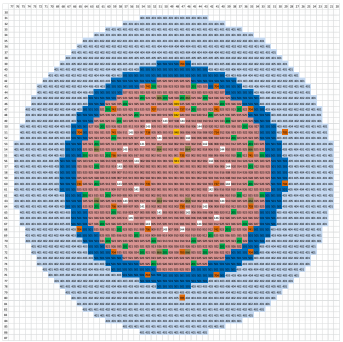


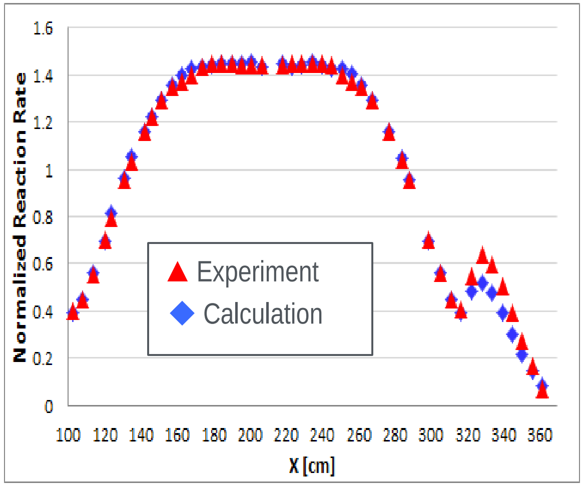
Validation basis

PROTEUS: Criticality Experiments

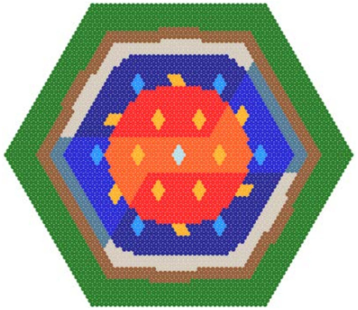
- LANL Experiments
  (Flattop, Godiva, Jezebel, Bigten)
  - Criticality, reaction rates
- ZPR-6 assemblies 6, 7A experiments
  - Criticality, foil measurements
- ZPPR-21 Phases A - F experiments
- ZPPR-15 Phases A - D experiments
  - Criticality, sodium void worth, control rod worth, Doppler, axial expansion, gamma dose, neutron spectrum
- EBR-II experiments (Runs 130B – 170A)
  - Criticality, depletion, isotopic mass
- BFS experiments (109-2A, 76-1A, 73-1)
  - Criticality, sodium void worth, control rod worth, foil measurement
- Monju startup experiments
  - Criticality, temperature coefficients
- CEFR physics startup tests (ongoing)

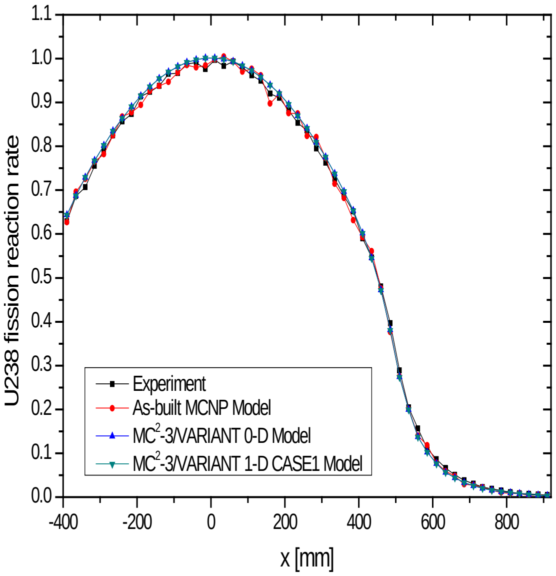
ZPPR-15





BFS-76-1

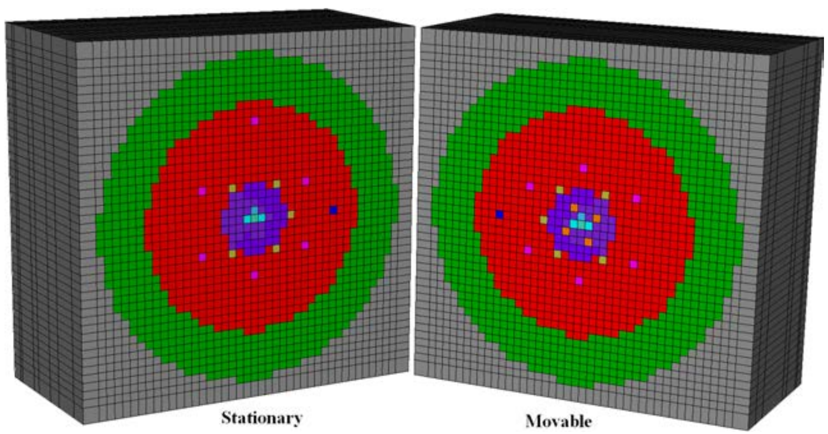




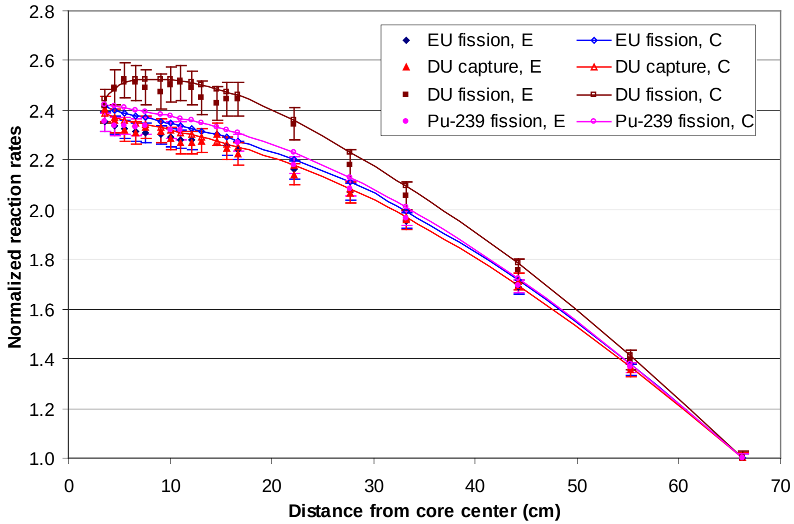
PROTEUS: Criticality Experiments (cont.)

Detailed ZPR-6/7 Comparisons as an example

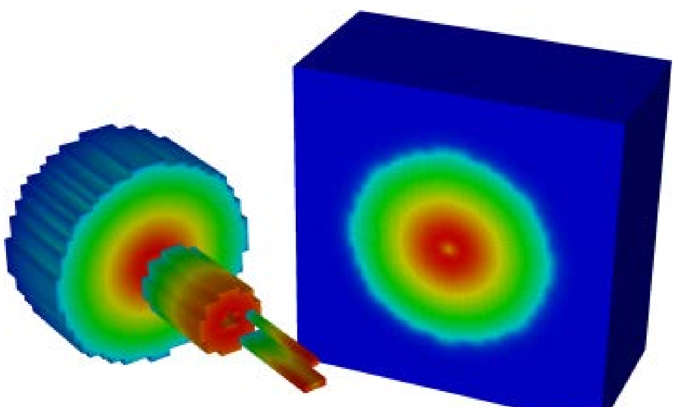
- Good agreement of core eigenvalues with the measurements within ~80 pcm
- Foil reaction rates predicted within 1 sigma of experimental uncertainties



Load	PROTEUS	Experiment
104	1.00147	1.00072
106	1.00134	1.00091
120	1.00127	1.00099
132	1.00016	1.00040



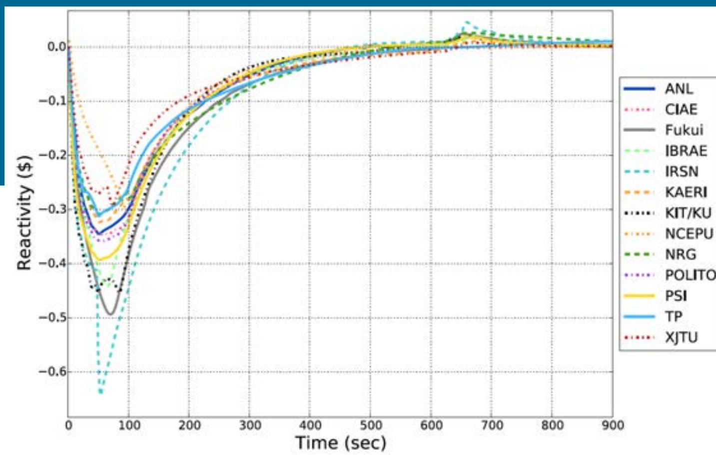
Foil Reaction Rate Measurement

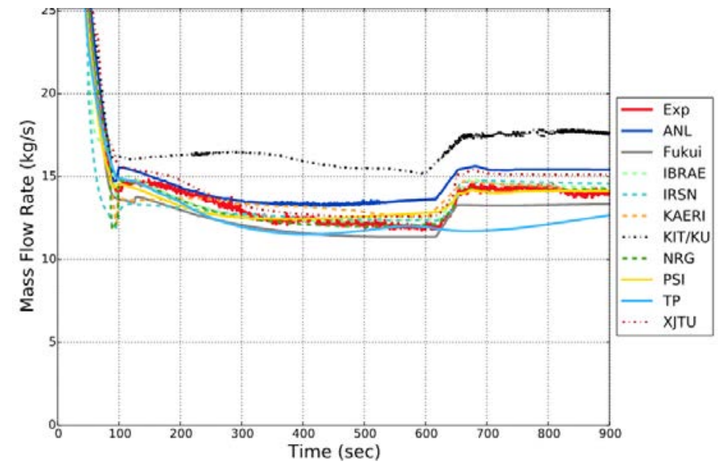


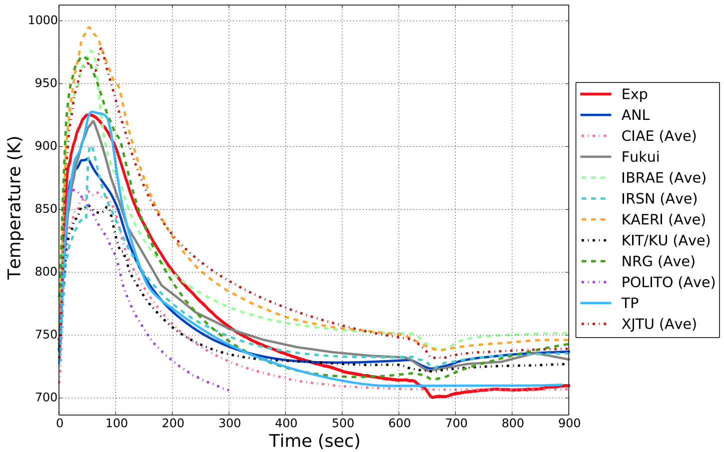
Flux in group 1 of 70 (10 MeV to 14 MeV)
Loading 106

PROTEUS: EBR-II Inherent Safety Demonstration Test

- SHRT-45R: Unprotected (no-scram) station blackout from full power to demonstrate inherent safety
  - Instrumented fuel assemblies for in-assembly temperature and flow measurements
- Neutronic benchmark for reactivity feedback coefficients
  - Following detailed depletion analyses for several run cycles based on known core loading and assembly fuel compositions
  - Doppler, fuel/cladding axial expansion, core radial expansion, coolant density changes, and CRDL expansion effects)
  - International benchmark with 19 participating organizations from 11 countries
- Good agreement with test data confirming validity against data from a rare integral test

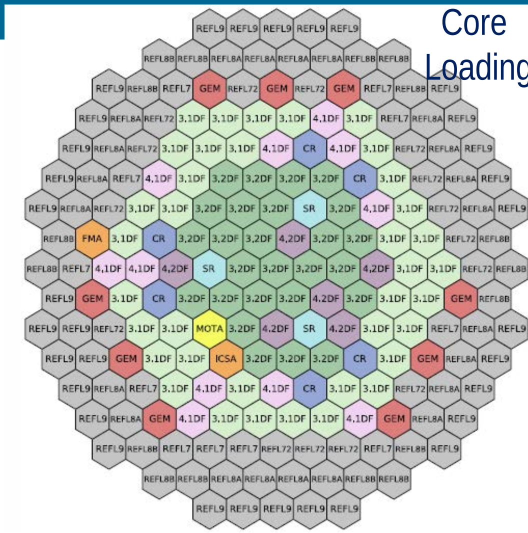




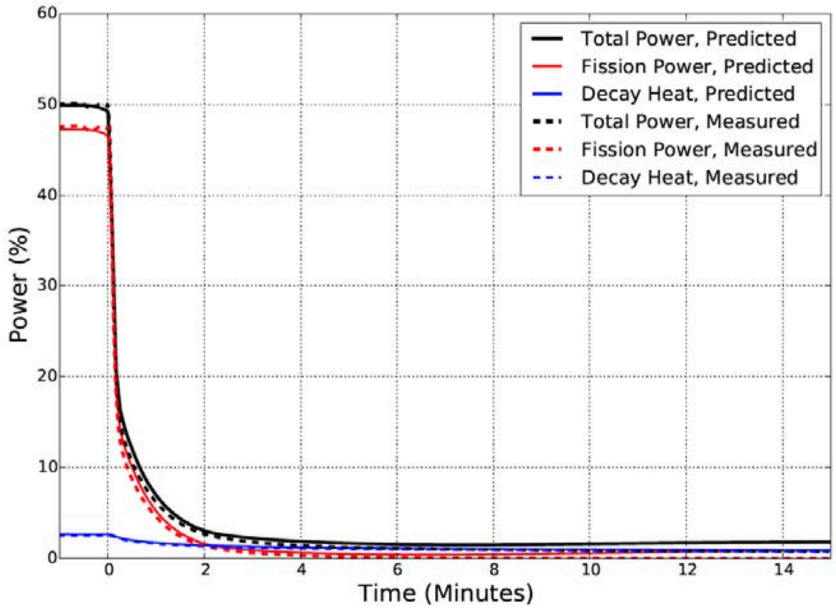


PROTEUS: FFTF Passive Safety Demonstration Test

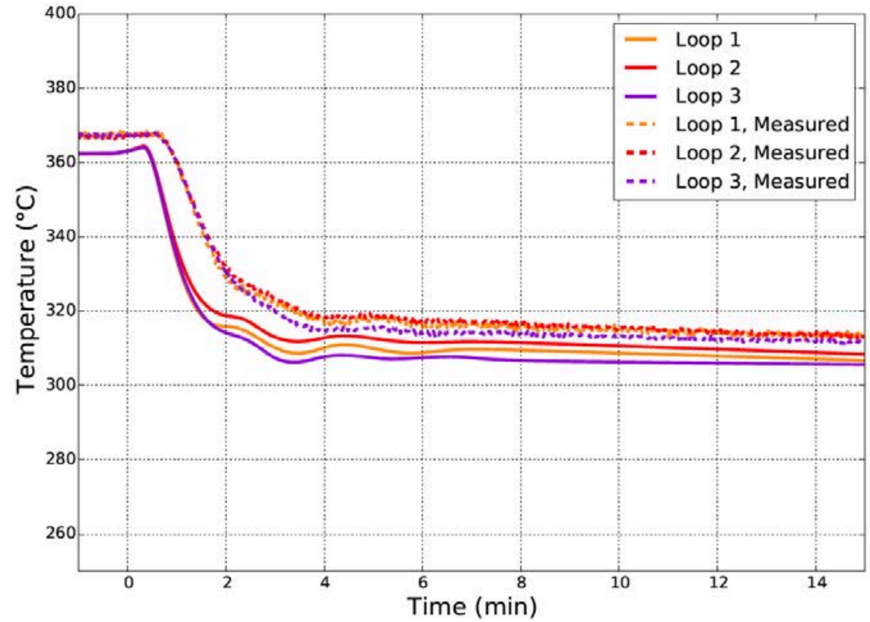
Core Loading



- LOFWOS #13: Unprotected loss of flow without scram from 50% power at full flow
  - Also with instrumented fuel assemblies for in-assembly temperature and flow measurements
  - Gas Expansion Module (GEM) as a passive reactivity reduction device
- Good agreement with measured power, coolant temperatures and natural circulation flow rate



Predicted and Measured Power and Decay Heat



Predicted and Measured Secondary Hot-Leg Temperatures

RattleSnake V&V

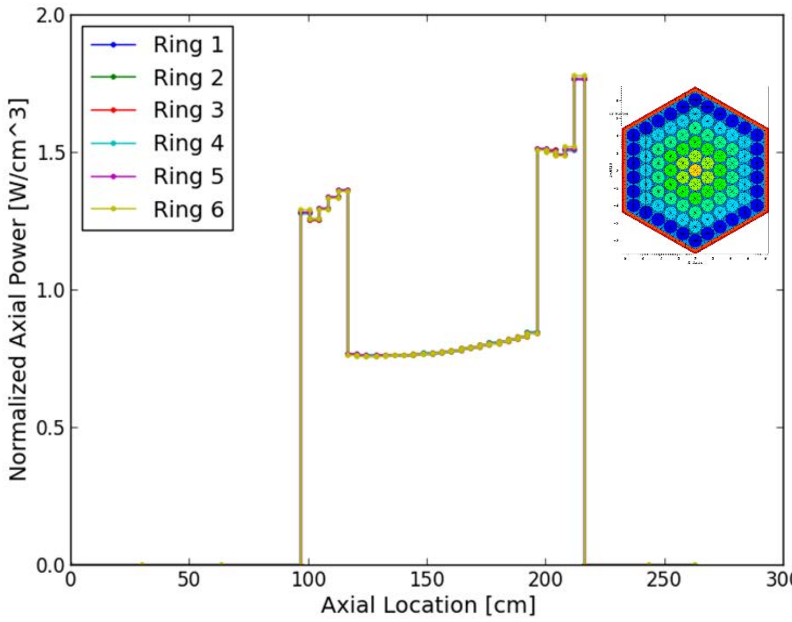
- Completed
  - Validation cases
    - TREAT Minimum Core
    - TREAT M8 Calibration Series (steady state and transient)
  - Computational benchmarks
    - C5G7
    - LRA BWR kinetics
    - BEAVRS
    - IAEA 3-D PWR
    - KAIST-3A reactor quarter core
    - OECD 3-D MHTGR-350 Core
- In Progress
  - ATR 94CIC (reactor data/ IRPhE benchmark)
  - GODIVA neutronic/thermal-mechanical benchmark (reactor data/IRPhE benchmark)
  - C5G7-TD (computational benchmark)
  - TREAT M2/M3 Calibration Measurements (reactor data)
  - 2018 TREAT Transient Prescription Measurements (reactor data, steady state and transient)

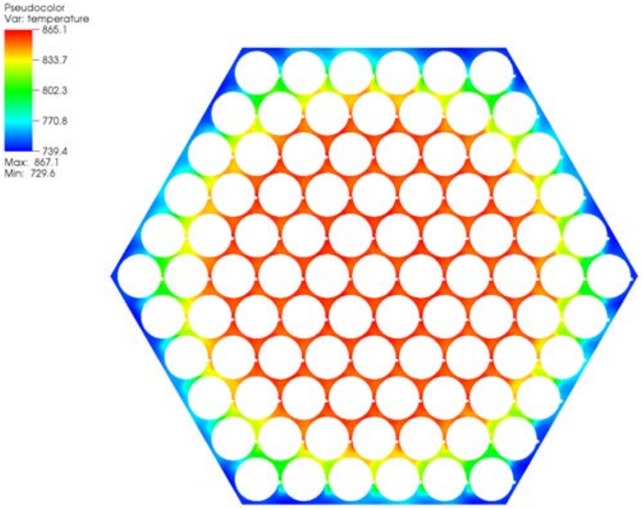
Application of neutronics codes to advanced reactors

SFR Hot Channel Factor Evaluation

High fidelity evaluation using PROTEUS-MOC and Nek5000

- AFR-100 (SFR design) inner assembly - unique enrichment zoning, U-Zr binary metallic fuel
- Coupling of axial power distributions between PROTEUS-MOC/Nek5000
- Reevaluated numerous hot channel factors to demonstrate safety margins





Top: 91-pin wire wrapped bundle velocity (Nek5000)
Left: MOC power distribution

SFR Hot Channel Factor Evaluation

High-fidelity multi-physics evaluations with PROTEUS and Nek5000

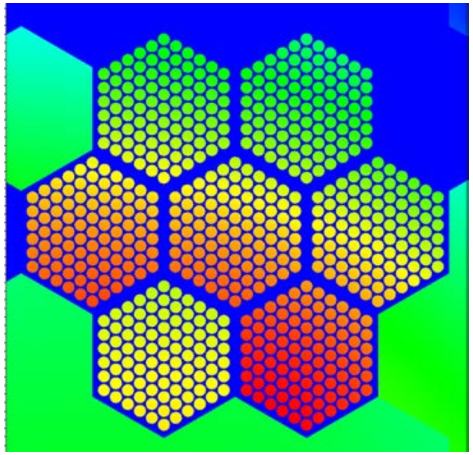
- AFR-100 (SFR design) inner core assembly
  - Unique enrichment zoning with U-Zr binary metallic fuel
- Coupling of axial power distributions between PROTEUS-MOC/Nek5000
- Reevaluated numerous hot channel factors to demonstrate safety margins

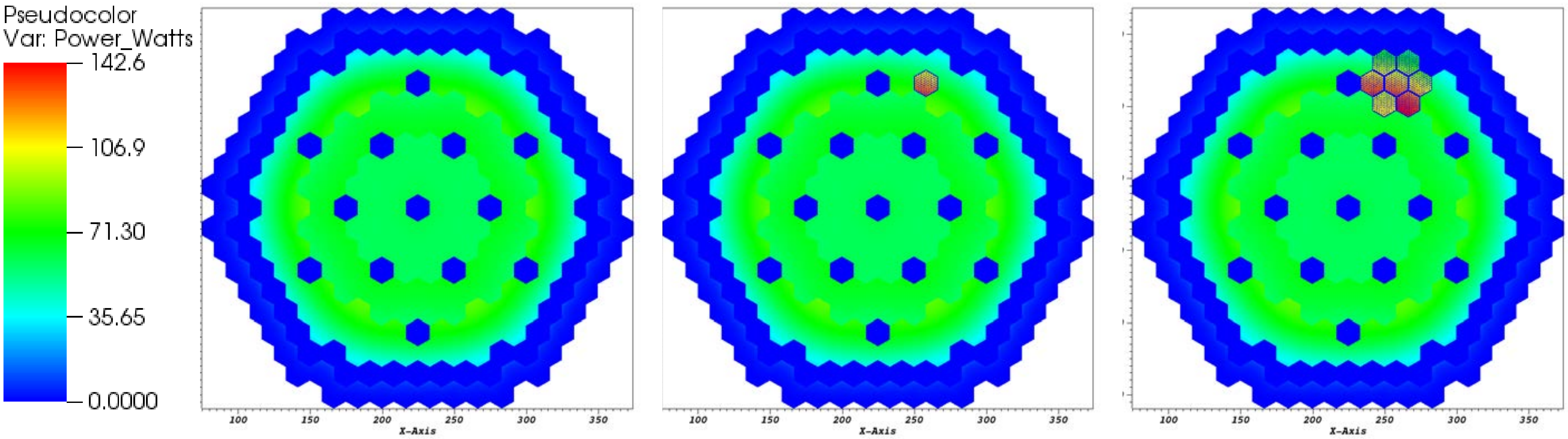
		Cladding thickness	Cladding thermal conductivity	Fuel thermal conductivity	Coolant density	Cladding circumferential temp.	Wire orientation
Uncertainties (3s), %		±3	±7	±25	±0.5	-	-
Cladding Outer Wall	Nominal	868.2	868.2	868.2	868.2	868.2	853.6
	Perturbed	-	-	-	869.1	866.4	856.2
	HCF-Legacy	-	-	-	1.016	2.19	1.01
	HCF-SHARP	-	-	-	1.001	1.002*	1.003*
Cladding Inner Wall	Nominal	894.3	894.3	894.3	894.3	894.3	-
	Perturbed	910.4	932.8	-	-	896.1	-
	HCF-Legacy	1.03 ~ 1.05	1.088	-	-	1.02	-
	HCF-SHARP	1.018	1.043	-	-	1.002	-
Fuel Centerline	Nominal	1000.5	1000.5	1000.5	1000.5	1000.5	-
	Perturbed	-	-	1226.6	-	-	-
	HCF-Legacy	-	-	1.25		-	-
	HCF-SHARP	-	-	1.226	-	-	-

Demonstration of Multi-Scale Modeling Capability for an SFR

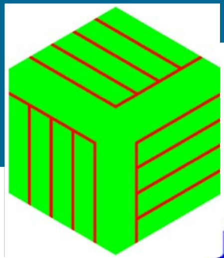
Model detailed focal assembly at reduced computational expense

- Cross section processing with MC^2-3 preserves heterogeneity effects in homogenized core model
- Can be applied for more accurate HCF calculation (includes global spectrum effects) at reduced computational expense
- Consistent k-eff and average power profiles across 3 cases using PROTEUS-SN solver
- Consistent pin-by-pin power distributions in focal assembly

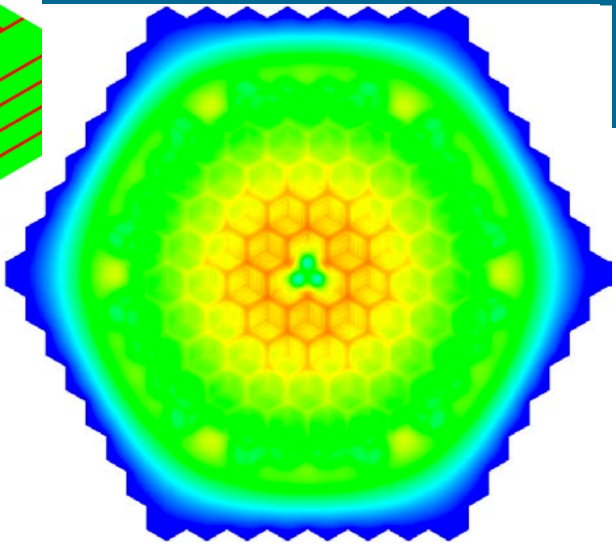




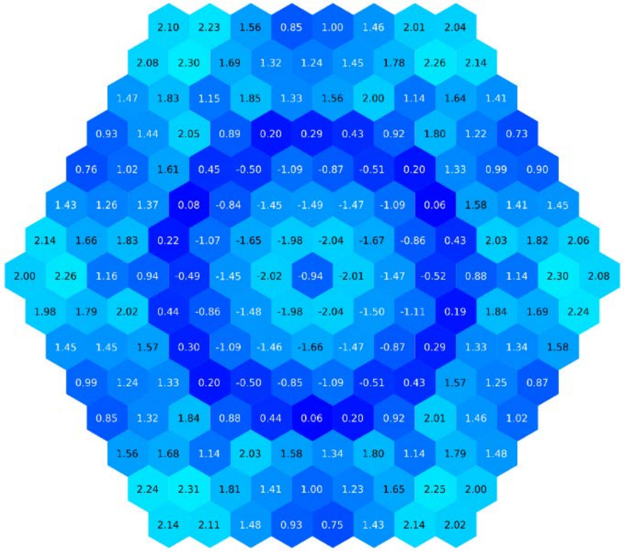
MSR Core Evaluations



- Analysis of a commercial thermal spectrum, graphite moderated design
- 2D stationary core calculation with **heterogeneous geometry** using PROTEUS-MOC
- 3D stationary core (378 cm high) calculation with **homogeneous assembly** using PROTEUS-NODAL



Thermal Flux (PROTEUS-MOC)



% Difference in Assembly Flux (< 2.3%) between PROTEUS-MOC and OpenMC

Eigenvalue Comparison

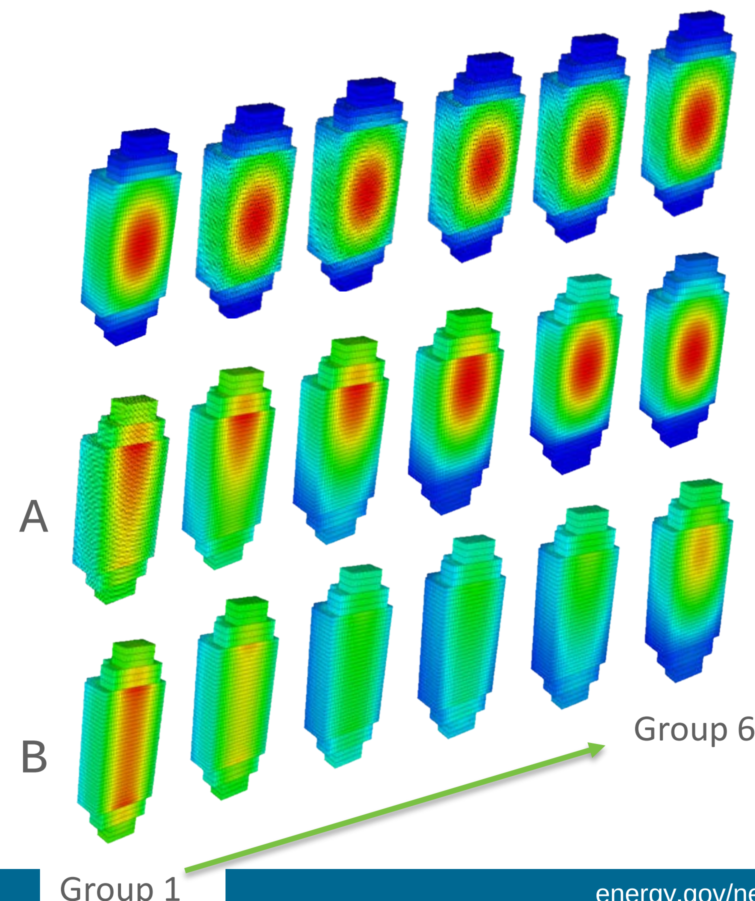
Code	2D	3D
OpenMC	1.01282	0.99196
PROTEUS (Δk, pcm)	-124 (MOC)	207 (NODAL)

Flowing Fuel Treatment for MSRs

Delayed-neutron precursor drift model in PROTEUS-NODAL

- Flow path of molten salt fuel, associated channels, and transit time of inside/outside core specified by user
- Evaluate the effect of the velocity field on neutronics
- Fast-spectrum MSR benchmark problem
  - 2,050 MWt with $PuCl_3$ (370x370x480 cm)
  - Fuel, blanket, shield regions
  - Moving fuel in the inner core and blanket regions
  - Computed core eigenvalue and precursor concentrations as a function of transit time inside/outside core
- Eigenvalue decreases with flow due to delayed neutron loss outside of the core
  - (A) 10 sec transit in core, 5 sec outside of core
  - (B) 1 sec transit in core, 0.3 sec outside of core

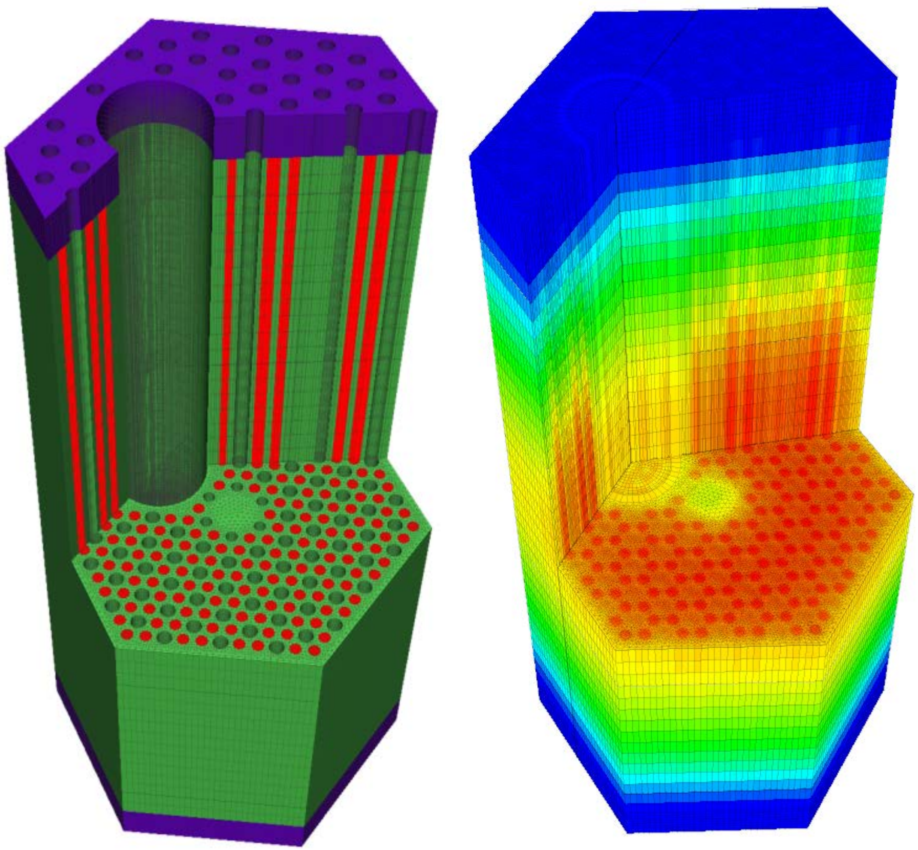
Model	Eigenvalue
Stationary Fuel	1.01458
Fuel Flowing A	1.01350
Fuel Flowing B	1.01289



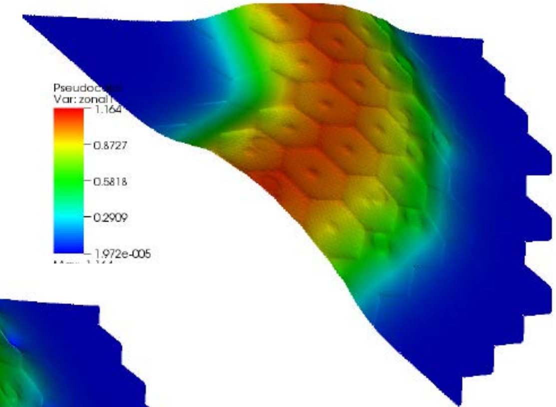
High Temperature Gas-cooled Reactor Applications

Model for 3D prismatic fuel assemblies

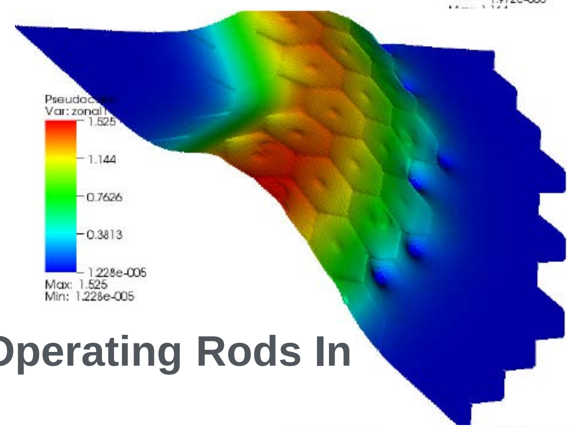
- Challenges for modeling the control channel leading to large neutron streaming



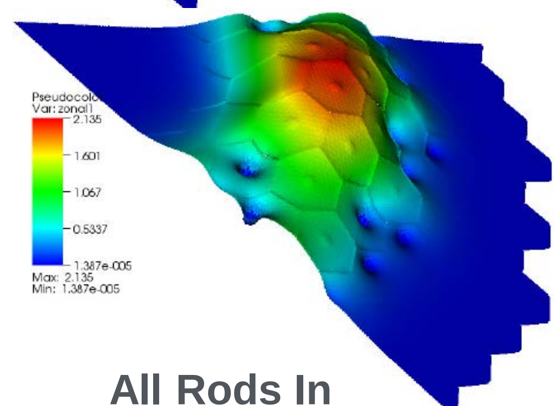
VHTR whole-core calculations



All Rods Out



Operating Rods In



All Rods In

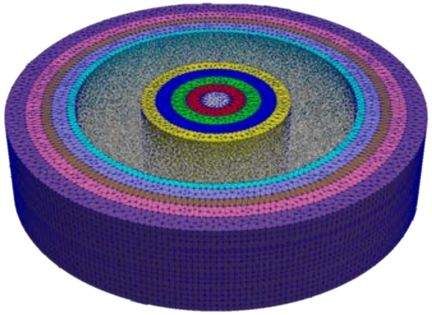
Pebble Tracking Transport (PTT) Algorithm for Pebble Bed Reactor Analysis

Motivation:

- Support high resolution multi-physics simulations of pebble motion
- Enable direct transport calculations with pebble tracking

Capabilities

- DEM (discrete element method) to provides time-dependent positions of all pebbles for establishing an equilibrium core

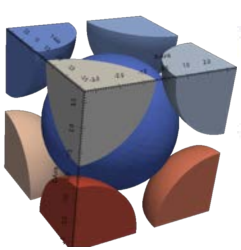


HTR-10 Pebble Bed Mesh: Total 437,735 tetrahedra. 76,869 node points. Pebble packing region has 291,107 tetrahedra, reflection top and bottom.

Goal: Ability to track burnup of individual pebbles as they move down the core

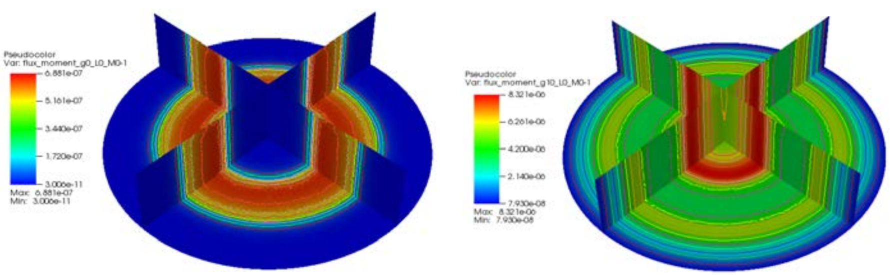
Preliminary Results:

- PTT can converge k_{eff} and reaction rates less than 0.1% for all cases with respect to reference case with Serpent (simple 9-sphere model, fresh fuel)



Error in k_{eff} (pcm) relative to reference model

SN	P				
	1	2	3	4	5
2	43.2377	43.3009	43.3141	43.3378	43.3579
4	43.2400	43.2653	43.2696	43.2783	43.2817
6	43.2406	43.2660	43.2707	43.2794	43.2824
8	43.2411	43.2657	43.2702	43.2796	43.2827

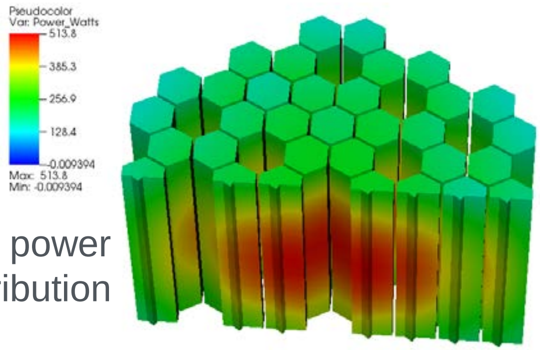


Fast (left) and thermal (right) fluxes in HTR-10 simulation

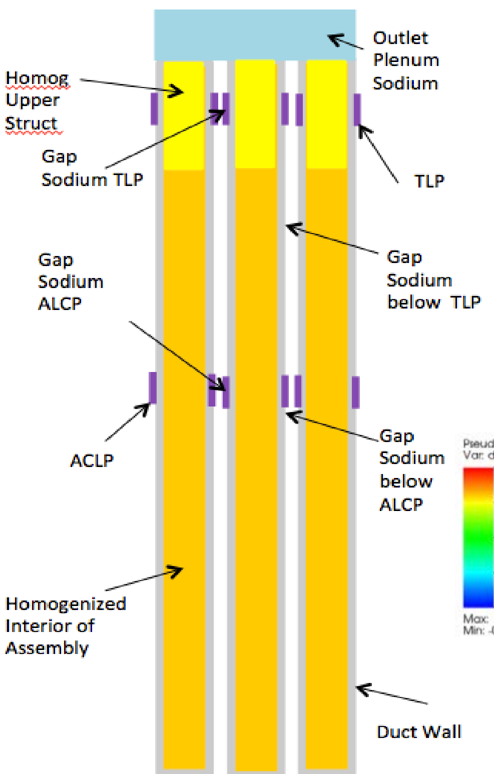
Multi-physics Analysis for SFR Core Deformation

Multi-physics simulation with PROTEUS-SN + Nek5000 + Diablo (SHARP)

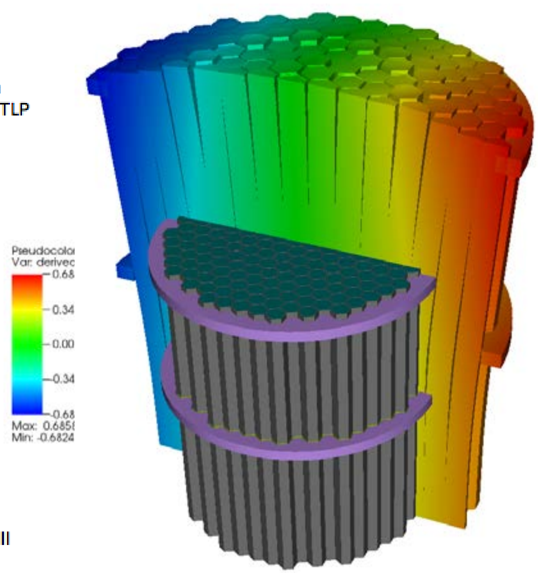
- Core deformation by thermal expansion and irradiation induced swelling is an important reactivity feedback in SFRs in both normal and transient operation
- Trial calculation for ULOF in ABTR

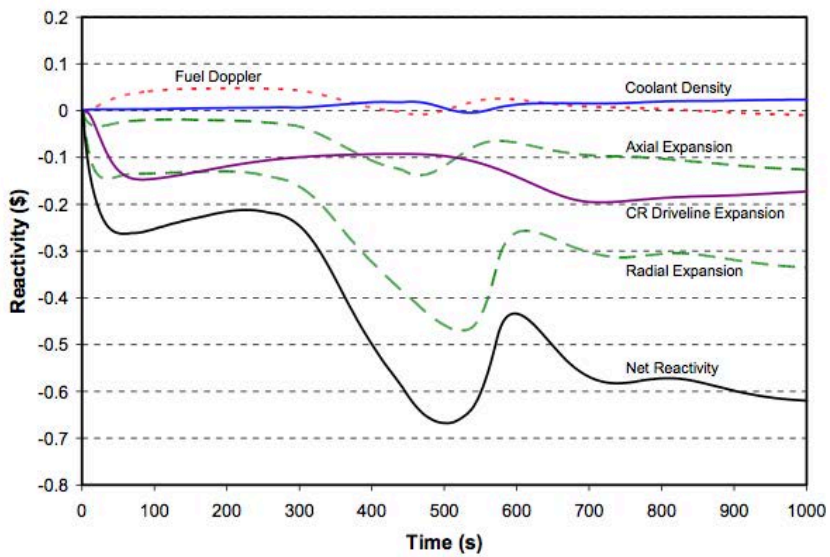


Fission power distribution



ABTR core deformation (magnified 100x) computed with SHARP





Conclusions

- PROTEUS and RATTLESNAKE are developed to accurately and deterministically simulate various advanced reactor cores with complex geometry and compositions
  - Multiple user options for improved flexibility and applicability
- MC^2-3 as a well-validated cross-section generation tools against numerous fast reactor experiments (ZPR-6, ZPPR-15, BFS, EBR-II, Monju, etc.)
  - Being used by DOE's VTR project, TerraPower and KAERI to support core design
  - Also used by other companies, universities, national labs for the research and development purpose
- PERSENT for assessment of reactivity feedback effects
- Multiphysics simulations with PROTEUS (neutronics) and SAM, Nek5000, and Cobra-TF (thermal fluid) are in progress for SFR, HTGR, and MSR applications

Questions?

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Fuel Performance Modeling for Advanced Reactors

August 21, 2018

DOE Briefing to ACRS:

Advanced Modeling & Simulation for Advanced Reactors

Outline of Presentation

- **Background and Presentation Objective**
- **The Bison Fuel Performance Code**
  - Overview
  - Verification and Validation
  - Documentation
- **Bison for TRISO Particle Fuel**
  - Capabilities/Examples
  - Validation
  - Development/Validation Plans
- **Bison for Metallic Fuel**
  - Capabilities/Example
  - Validation
  - Development/Validation Plans
- **Summary and Conclusions**

Background and Objective

Background

- DOE is developing modern fuel performance modeling tools applicable to a wide variety of fuel and reactor types, operating conditions, geometries and spatial scales
- Capability has been developed for both advanced and traditional LWR concepts, with LWR fuel receiving greatest early emphasis
- Multiscale modeling approach (Bison/Marmot) provides improved mechanistic material models and has delivered demonstrated results for UO_2 fuel

Presentation Objective

- Provide current status of DOE fuel codes for application to specific advanced reactor concepts including: code capabilities, current validation status, future development and validation plans

Concept	SFR	MHTGR	FHR	MSR
Fuel Type	Metallic Alloy	TRISO particle	TRISO particle	Liquid
Fuel Element	Pin	Pebble/Prism	Pebble	N/A
Coolant	Liquid Metal	Gas	Molten fluoride salt	Molten salt
Applicable DOE Fuel Codes	Bison/Marmot	Bison/Marmot	Bison/Marmot	None

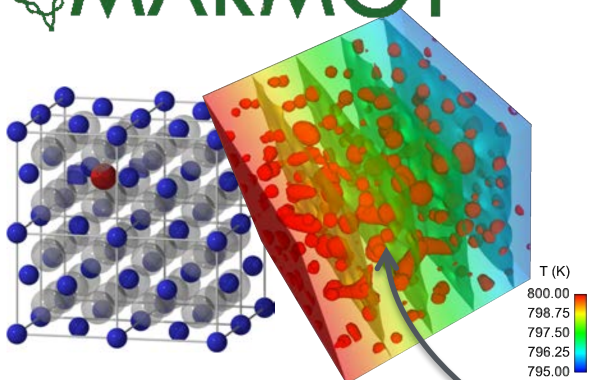
Bison/Marmot Fuel Performance Codes

1) Overview
2) Verification and Validation
3) Documentation

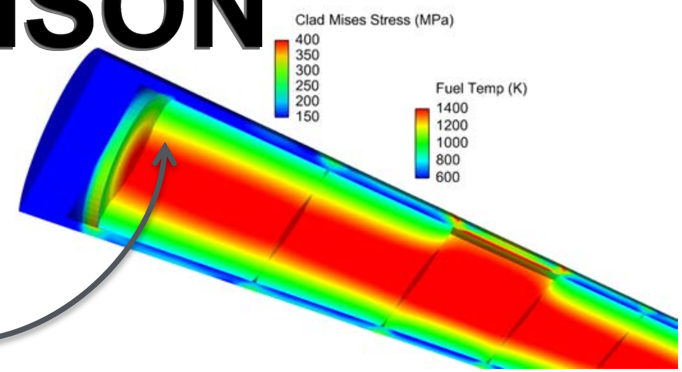
MOOSE-**Bison**-Marmot (MBM)

- The MOOSE-Bison-Marmot (MBM) codes provide an advanced multidimensional, multiphysics, multiscale fuel performance capability

MARMOT



BISON



Atomistic/Mesoscale Material Model Development

- Predicts microstructure evolution in fuel and cladding
- Used with atomistic methods to develop multiscale materials models

Advanced Multidimensional Fuel Performance Code

- Models a wide variety of fuel types and geometries at an engineering scale
- Applicable for steady, transient and accident conditions

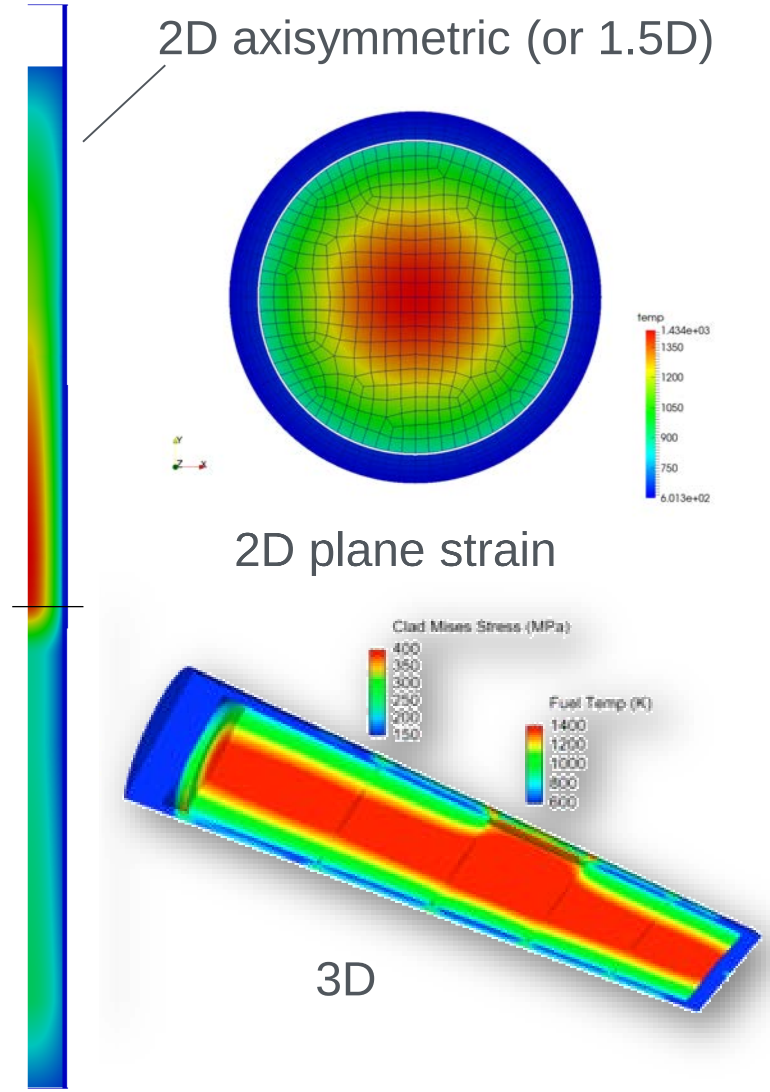
MOOSE

Multiphysics Object-Oriented Simulation Environment

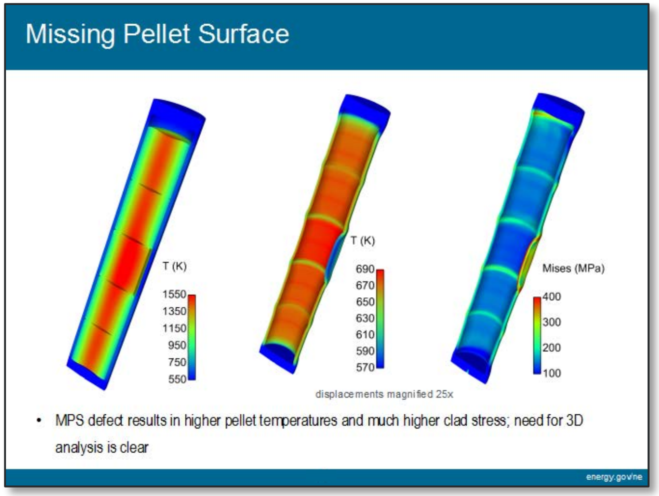
- Simulation framework allowing rapid development of FEM-based applications

Bison Fuel Performance Code

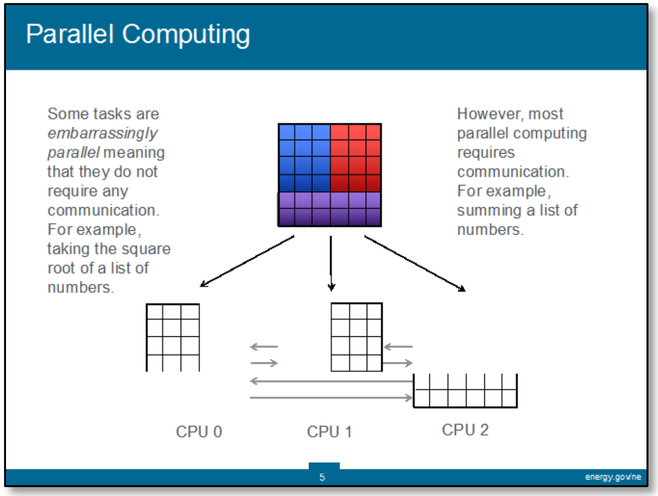
- Finite element-based engineering scale fuel performance code
- Solves the fully-coupled thermomechanics and species diffusion equations in 1D, 1.5D, 2D axisymmetric or plane-strain, or full 3D
- Used for LWR, ATF, TRISO, and metallic fuels
- Applicable to both steady and transient operations and includes LOCA and RIA capability for LWR fuel
- Readily coupled to lower length scale material models
- Designed for efficient use on parallel computers
- Development follows NQA-1 process



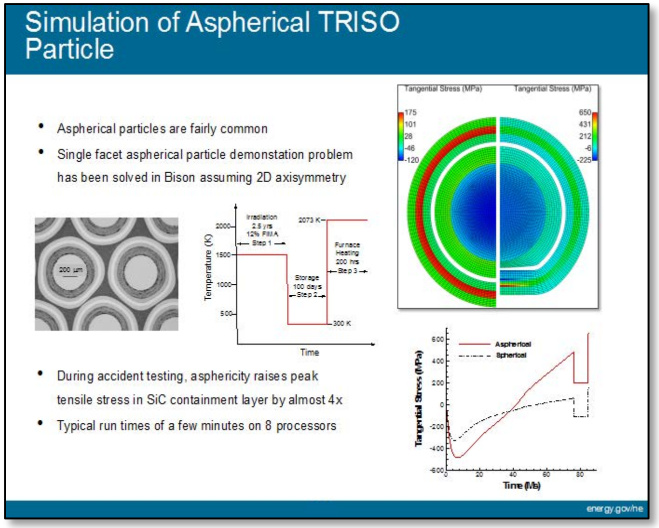
What Makes **Bison** Different?



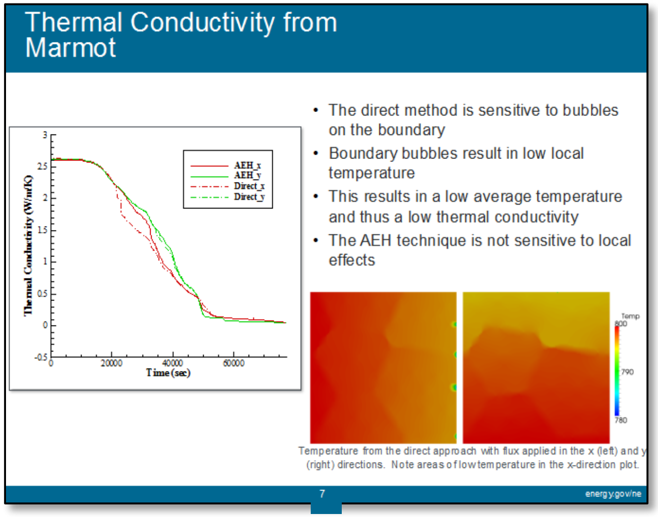
3D FEM: Applicable to any geometry



Parallel Computing: Large problems



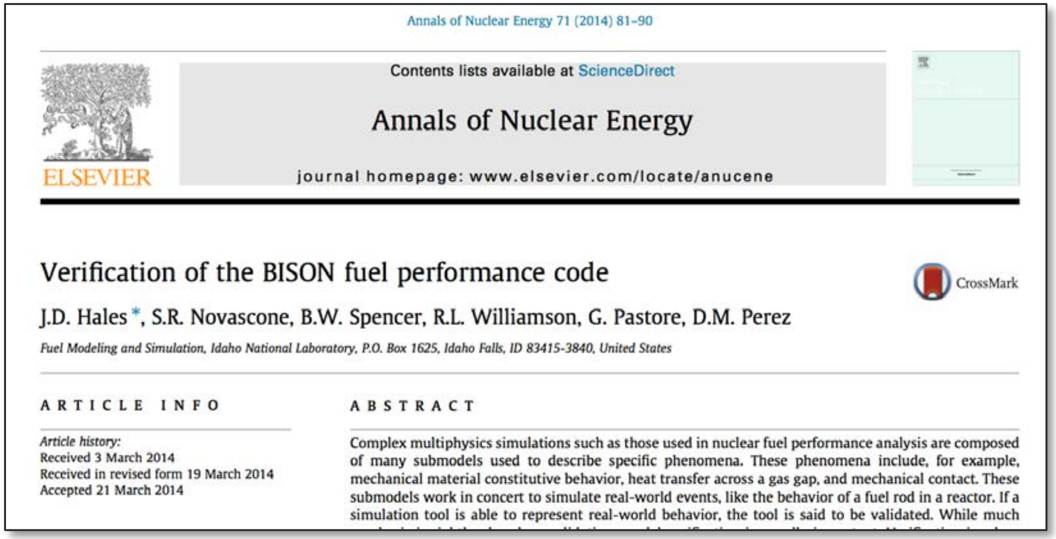
Multiple fuel/reactor applicability



Readily couples to LLS or other codes

Bison V&V and Statistical Analysis

- Code Verification
  - MOOSE/**Bison** is supported by >2000 unit and regression tests
  - All new code must be accompanied with verification testing; all tests are required to pass prior to any code change
- LWR Validation
  - ~**75** integral, normal operation and ramp fuel rod experiments
  - **47** LOCA cases (43 burst tests, 5 integral rods)
  - **19** RIA cases
  - More detail in ATF presentation
- Coupled to DAKOTA to enable constitutive model calibration, sensitivity analysis and uncertainty quantification


Annals of Nuclear Energy 71 (2014) 81–90

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Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

ELSEVIER

Verification of the BISON fuel performance code

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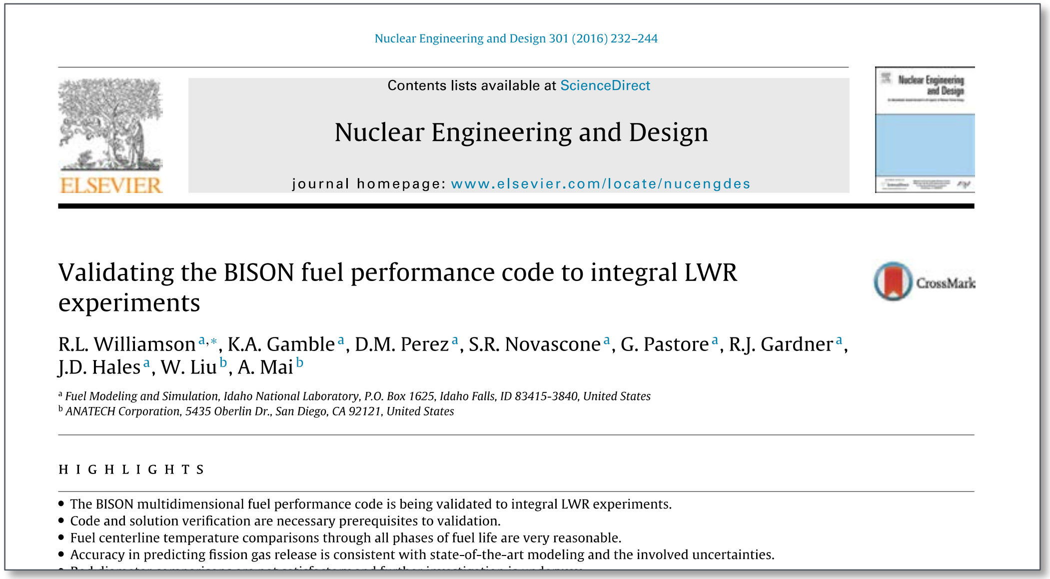
ABSTRACT

Complex multiphysics simulations such as those used in nuclear fuel performance analysis are composed of many submodels used to describe specific phenomena. These phenomena include, for example, mechanical material constitutive behavior, heat transfer across a gas gap, and mechanical contact. These submodels work in concert to simulate real-world events, like the behavior of a fuel rod in a reactor. If a simulation tool is able to represent real-world behavior, the tool is said to be validated. While much


Nuclear Engineering and Design 301 (2016) 232–244

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

ELSEVIER

Validating the BISON fuel performance code to integral LWR experiments

R.L. Williamson [a,*], K.A. Gamble [a], D.M. Perez [a], S.R. Novascone [a], G. Pastore [a], R.J. Gardner [a], J.D. Hales [a], W. Liu [b], A. Mai [b]

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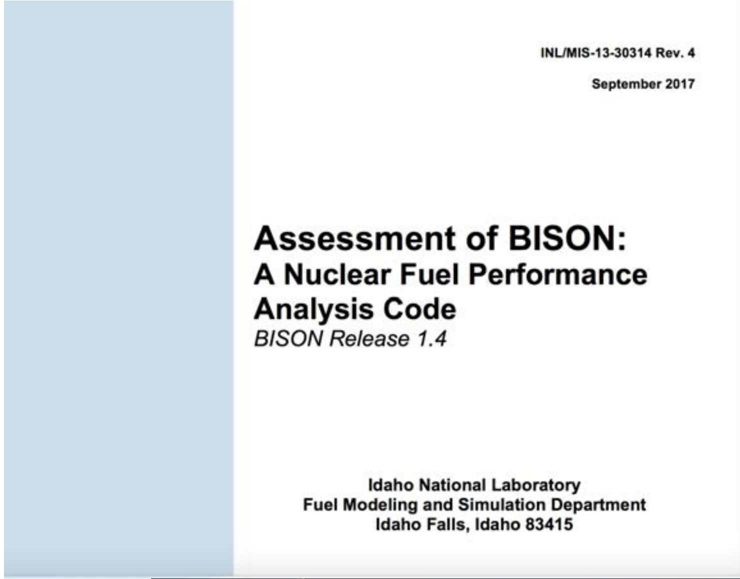
HIGHLIGHTS

- The BISON multidimensional fuel performance code is being validated to integral LWR experiments.
- Code and solution verification are necessary prerequisites to validation.
- Fuel centerline temperature comparisons through all phases of fuel life are very reasonable.
- Accuracy in predicting fission gas release is consistent with state-of-the-art modeling and the involved uncertainties.

Bison Documentation

- Latest externally released documentation (pdf files) available at: https://bison.inl.gov/SitePages/Manuals.aspx
  - Theory manual
  - User manual
  - Training workshop slides
  - Link to code verification article
  - Assessment report

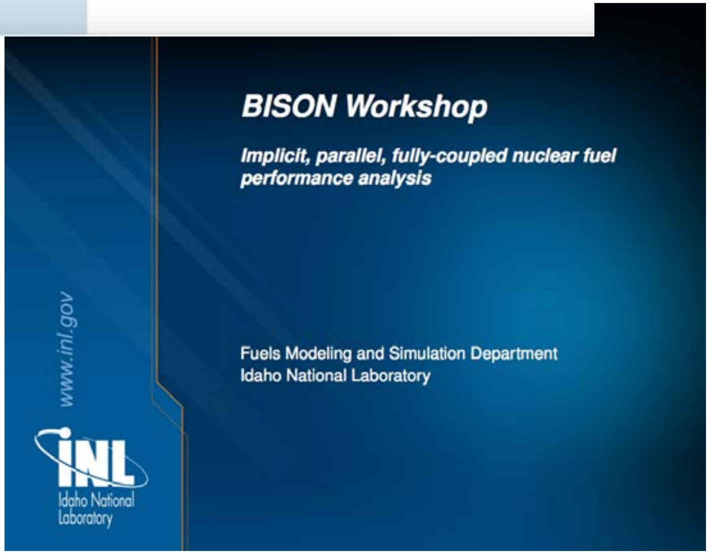
- Currently transitioning to a web-based documentation system
  - Combines theory and user manuals
  - Imposes strict requirements on documentation of new code
  - Much more of the documentation exists within and builds from the source code


INL/MIS-13-30314 Rev. 4

September 2017

Assessment of BISON:
A Nuclear Fuel Performance Analysis Code
BISON Release 1.4

Idaho National Laboratory
Fuel Modeling and Simulation Department
Idaho Falls, Idaho 83415



TRISO Particle Fuel

Bison - Particle Fuel Capabilities

General Capabilities

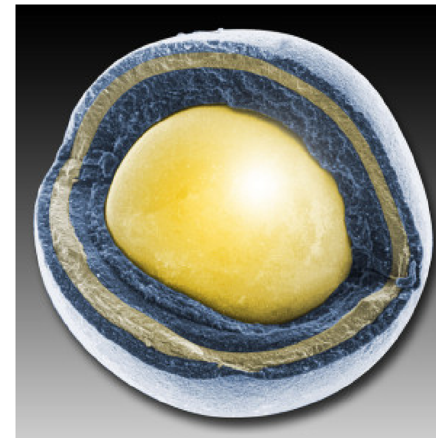
- Finite element based 1D-Spherical, 2D-RZ and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Elasticity with thermal expansion
- Steady and transient behavior
- Parallel computation

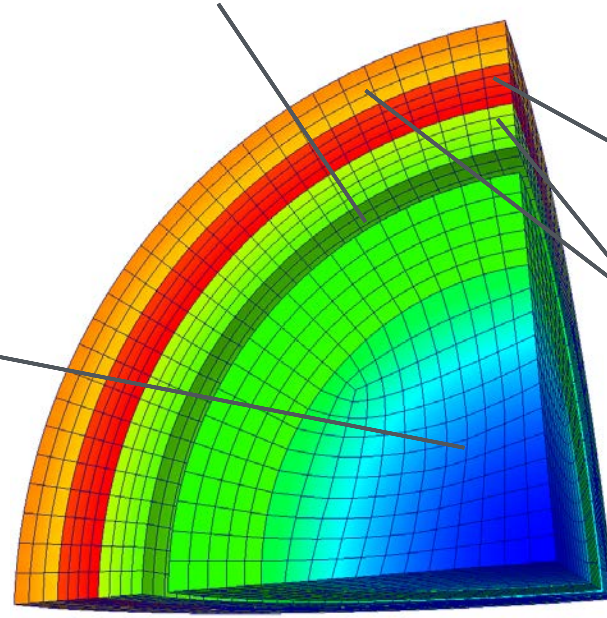
Fuel Kernel (UO_2)

- Temperature/burnup/porosity dependent thermal conductivity
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fission gas release (two stage)
- CO production
- Radioactive decay

Gap Behavior

- Gap heat transfer with k_g= f (T, n)
- Gap mass transfer
- Mechanical contact (master/slave)
- Particle pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR and CO model)
  - gas temperature approximation





Tangential Stress

Silicon Carbide

- irradiation creep

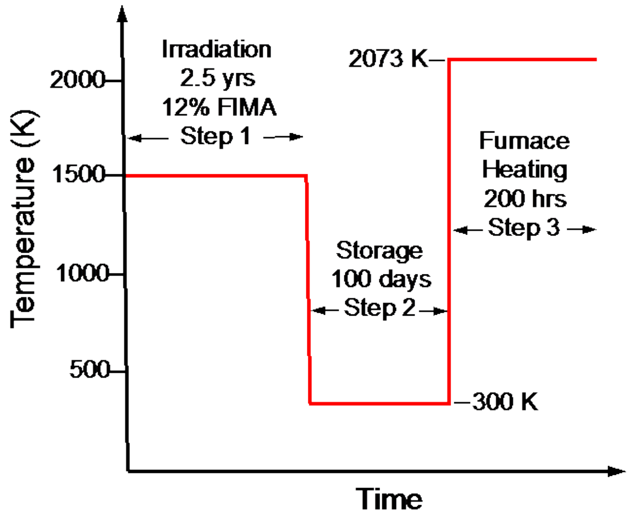
Pyrolytic Carbon

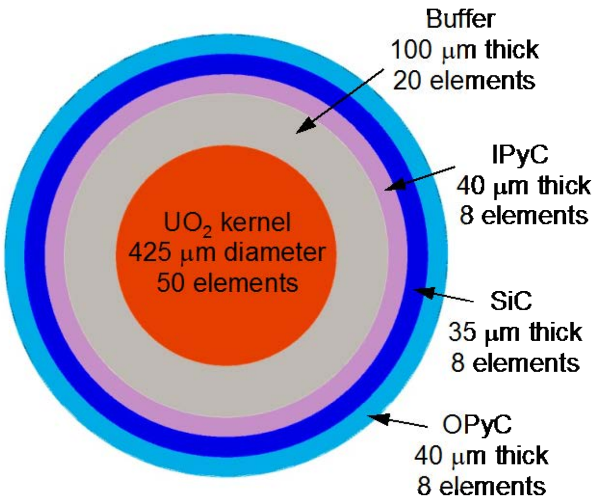
- Anisotropic irradiation-induced strain
- Irradiation creep

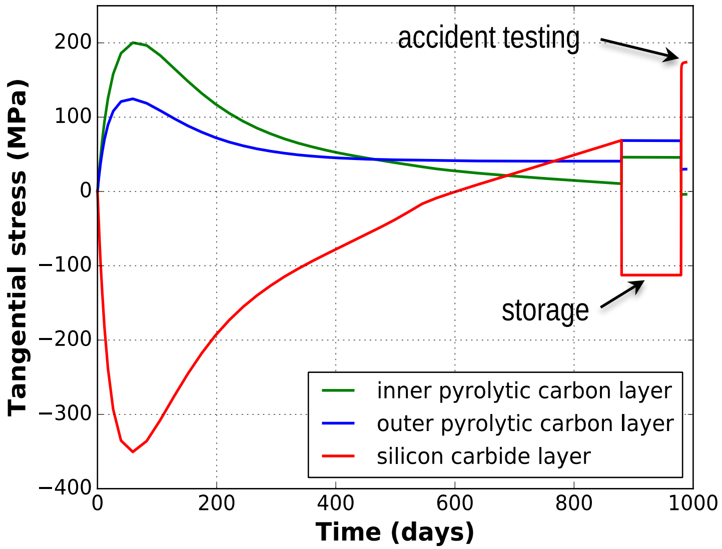
Empirical models for SiC and PyC from:
D. Petti, P. Martin, M. Phelip, R. Ballinger, Development of improved models and designs for coated-particle gas reactor fuels. Technical Report INL/EXT-05-02615, December 2004.

Example:1D Spherical Particle

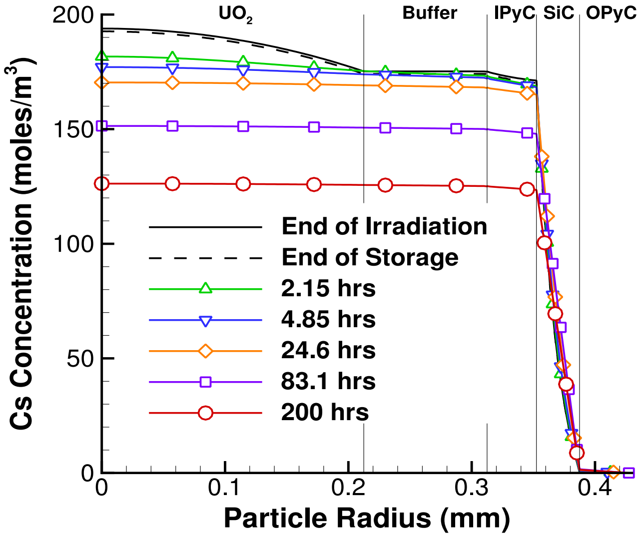
- Spherically symmetric
- Thermo-mechanics plus cesium diffusion
- Analysis of normal irradiation, storage, and accident testing periods
- Run times of ~1 s permit rapid analysis of large numbers of particles







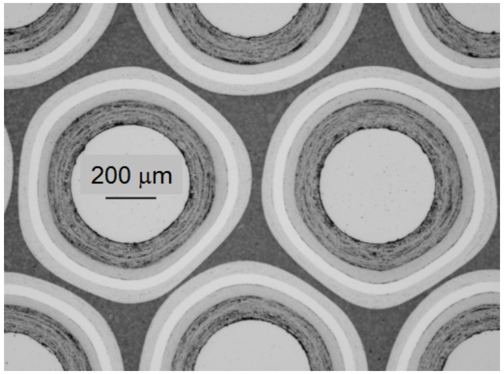
Tangential stress histories

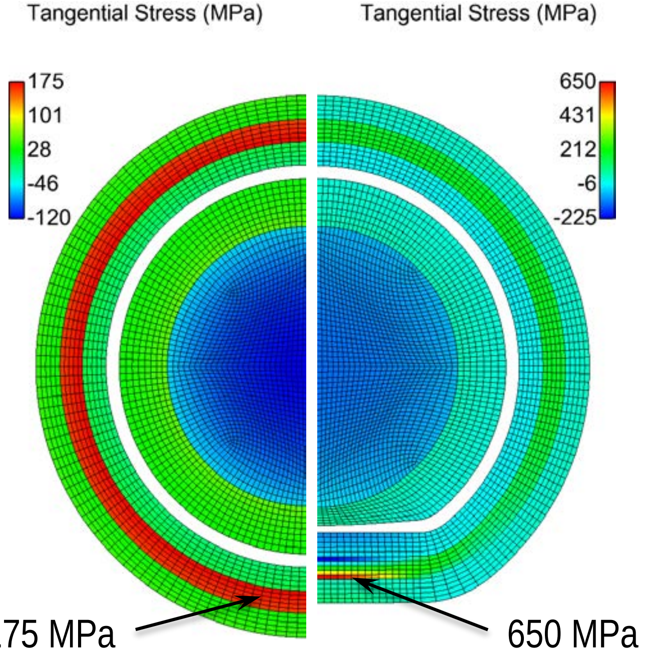


Cesium radial profiles

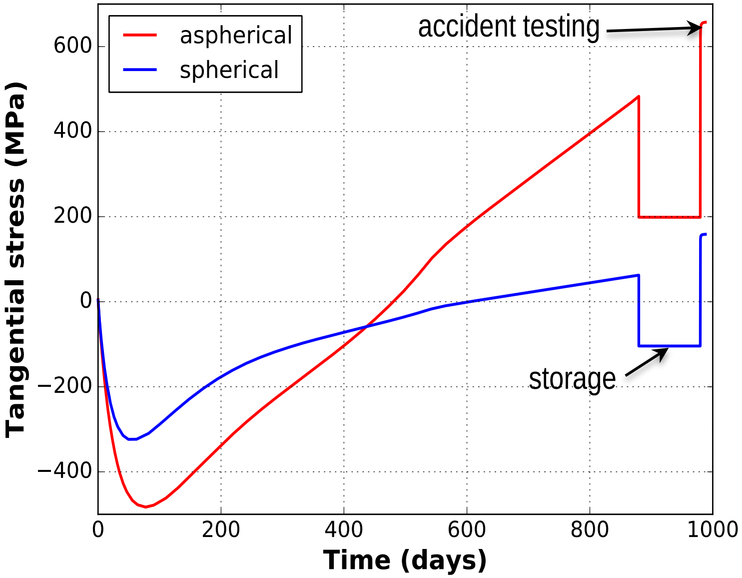
Example: 2D RZ - Aspherical Particle

- Aspherical TRISO particles can occur during manufacturing
- Single facet particle simulated assuming 2D axisymmetry
- During simulated accident, asphericity raised peak tensile stress in SiC layer by ~4x
- Typical run times of a few minutes using 8 processors





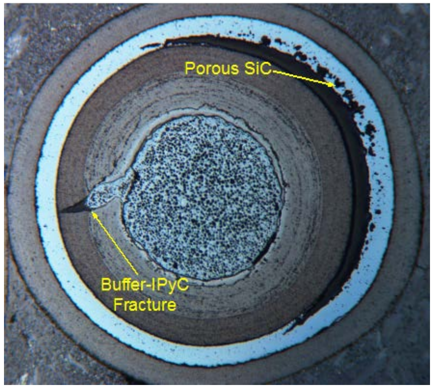
Tangential stress comparison for a spherical and aspherical particle following simulated accident

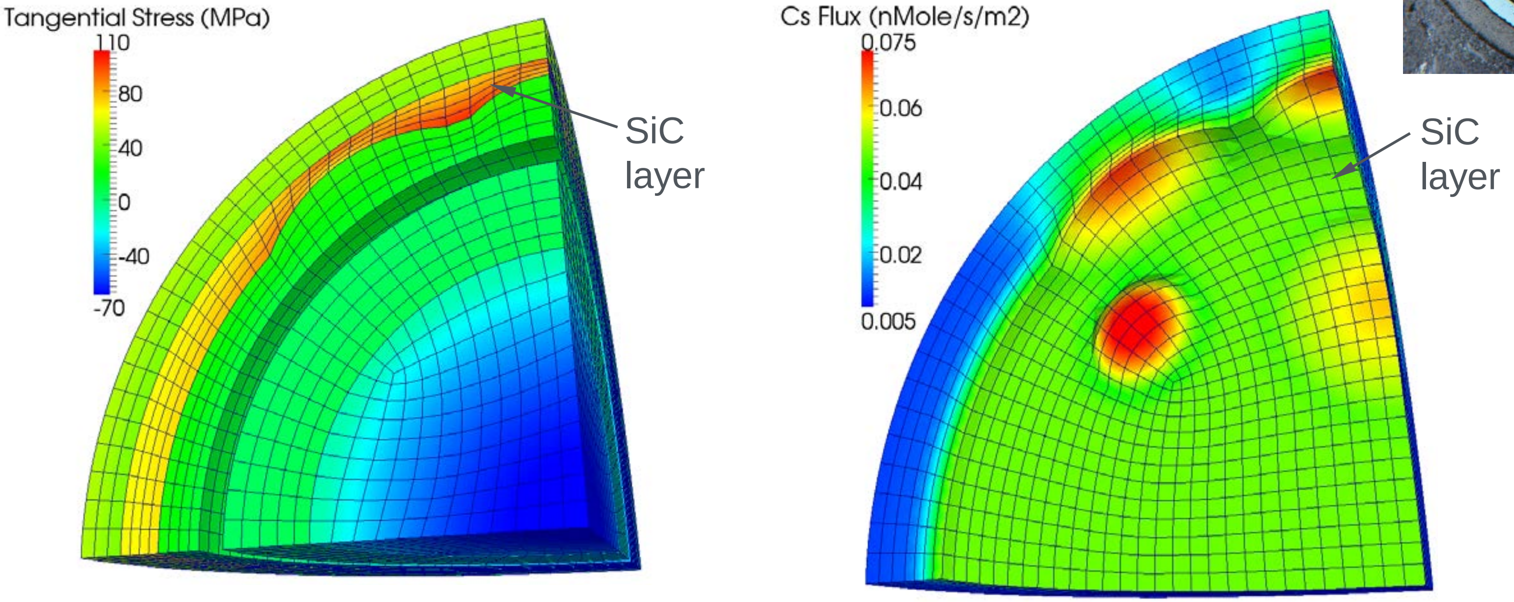


Stress history at the outer SiC surface

Example: 3D – Defective SiC layer

- Localized thinning of SiC layer can occur due to soot inclusions or fission product interaction
- BISON 3D capability demonstrated on an eighth-particle with localized thinning of the SiC layer at random locations





- Thinned SiC regions experience significantly higher tensile stress and greater cesium release; impossible to predict with 1D analysis
- Typical run times of a few hours on 8 processors

Comparison to IAEA Benchmarks (1/2)

- IAEA CRP-6 on HTGR technology developed a set of fuel performance code benchmarking cases for normal operation and operational transients
- Ranged in complexity from a simple fuel kernel having a single elastic coating layer, to realistic TRISO-coated particles under a variety of irradiation conditions
- Bison assessed against analytical solutions and other particle fuel codes for 13 cases

Case Descriptions

Case	Geometry	Description
1	SiC layer	Elastic only
2	IPyC layer	Elastic only
3	IPyC/SiC	Elastic with no fluence
4a	IPyC/SiC	Swelling and no creep
4b	IPyC/SiC	Creep and no swelling
4c	IPyC/SiC	Creep and swelling
4d	IPyC/SiC	Creep- and fluence-dependent swelling
5	TRISO	350 μm kernel, real conditions
6	TRISO	500 μm kernel, real conditions
7	TRISO	Same as 6 with high BAF PyC
8	TRISO	Same as 6 with cyclic temperature
10	HFR-K3	10% FIMA, 5.3×10^{-25}n/m^2 fluence
11	HFR-P4	14% FIMA, 7.2×10^{-25}n/m^2 fluence

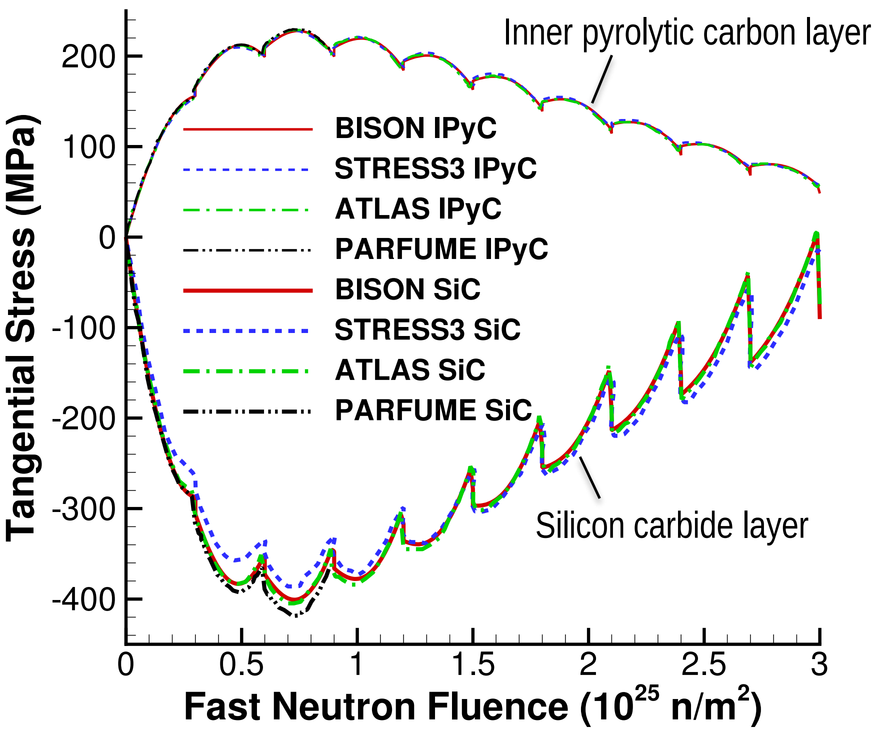
Comparisons of tangential stress at end of simulation

Case	Layer	Analytical	BISON	Error (%)
1	SiC	125.19	125.23	0.032
2	IPyC	50.200	50.287	0.173
3	IPyC/SiC	8.8/104.4	8.7/104.5	1.14/0.10

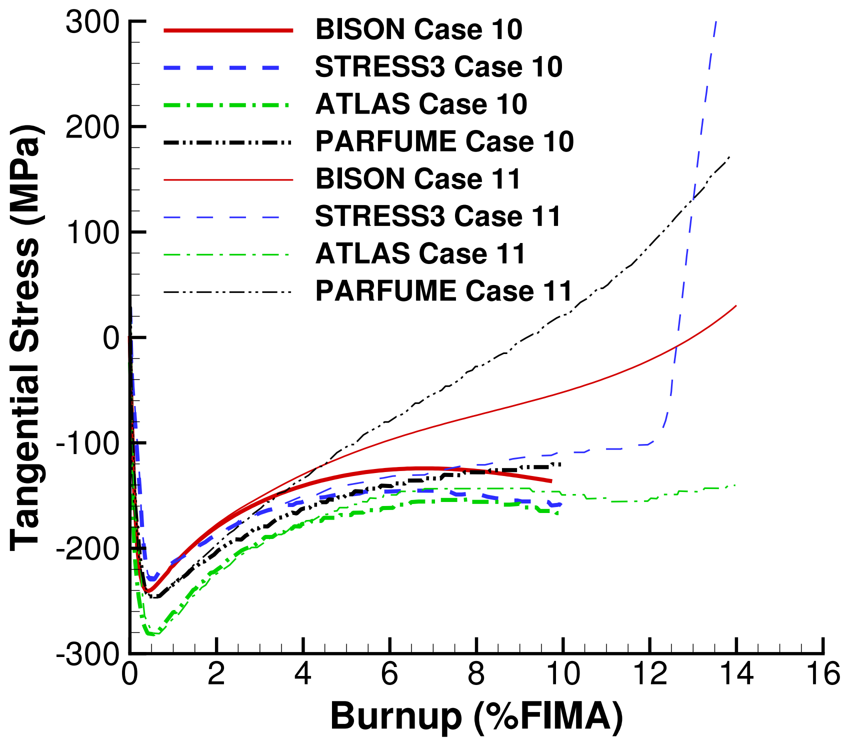
Case	Layer	CRP-6 codes [range]	BISON
4a	IPyC/SiC	[925, 970]/[-775, -850]	928/-819
4b	IPyC/SiC	[-25, -25]/[138, 142]	-25.0/139
4c	IPyC/SiC	[25, 27]/[83, 92]	26.0/89.4
4d	IPyC/SiC	[25, 35]/[71, 88]	27.8/87.0
5	IPyC/SiC	[40, 58]/[-56, -28]	41.9/-32.2
6	IPyC/SiC	[27, 38]/[28, 48]	29.2/44.9
7	IPyC/SiC	[37, 50]/[10, 25]	38.0/24.6

Comparison to IAEA Benchmarks (2/2)

- Bison comparisons to PARFUME (US), STRESS3 (UK) and ATLAS (France)



Case 8: Code comparisons for the cyclic particle temperature in pebble bed reactor



Cases 10 and 11: Code comparisons of the tangential stress at the inner SiC wall. Variations attributed to differences in fission gas release and CO production models.

TRISO Particle Fuel - Documentation

TRISO particle capability development, examples and benchmarking are documented in 2013 journal article

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Multidimensional multiphysics simulation of TRISO particle fuel

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ABSTRACT

Multidimensional multiphysics analysis of TRISO-coated particle fuel using the BISON finite element nuclear fuels code is described. The governing equations and material models applicable to particle fuel and implemented in BISON are outlined. Code verification based on a recent IAEA benchmarking exercise is described, and excellent comparisons are reported. Multiple TRISO-coated particles of increasing geometric complexity are considered. The code's ability to use the same algorithms and models to solve problems of varying dimensionality from 1D through 3D is demonstrated. The code provides rapid solutions of 1D spherically symmetric and 2D axially symmetric models, and its scalable parallel processing capability allows for solutions of large, complex 3D models. Additionally, the flexibility to easily include new physical and material models and straightforward ability to couple to lower length scale simulations makes BISON a powerful tool for simulation of coated-particle fuel. Future code development activities and potential applications are identified.

Particle Fuel Development/Validation Plan

Development

- PARFUME/Bison capability gap analysis (FY18)
- UCO fuel models (FY19)
- Mechanistic CO production (FY19)
- Particle failure probabilities (FY20)
- Partial debonding and SiC fracture with XFEM (FY20)

Validation

- Investigate data base and approach for existing particle fuel codes (FY18)
- Review NRC HTGR research plan (FY19)
- Develop Bison particle fuel validation plan (FY19)
- Prepare highest priority validation cases (FY19 forward)

Metallic Fuel

Bison Metallic Fuel Capabilities

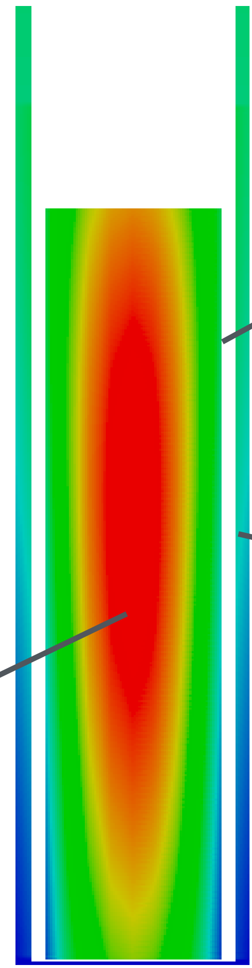
General Capabilities

- Finite element 1.5D, 2D-RZ axisymmetric and Cartesian and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Elasticity with thermal expansion
- Steady and transient operation
- Parallel computation

Metallic Fuel Behavior

UPuZr and UZr

- Temperature/species dependent conductivity
- Anisotropic Swelling
- Thermal and irradiation creep
- Fission gas release (porosity based)
- Zr diffusion



Temperature

Gap/Plenum Behavior

- Gap heat transfer (sodium conductivity)
- Mechanical contact (master/slave)
- Plenum pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR model)
  - gas temperature approximation

Cladding Behavior

HT-9 and 316 Stainless Steel

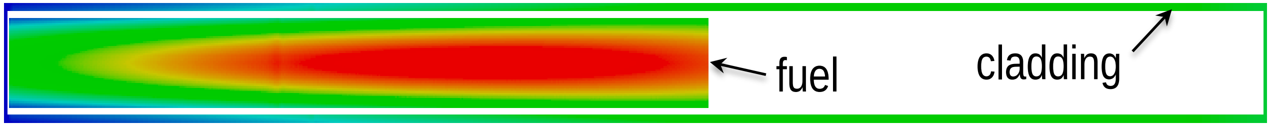
- Temperature dependent conductivity
- Thermal and Irradiation creep
- Failure model for HT-9

Coolant Channel

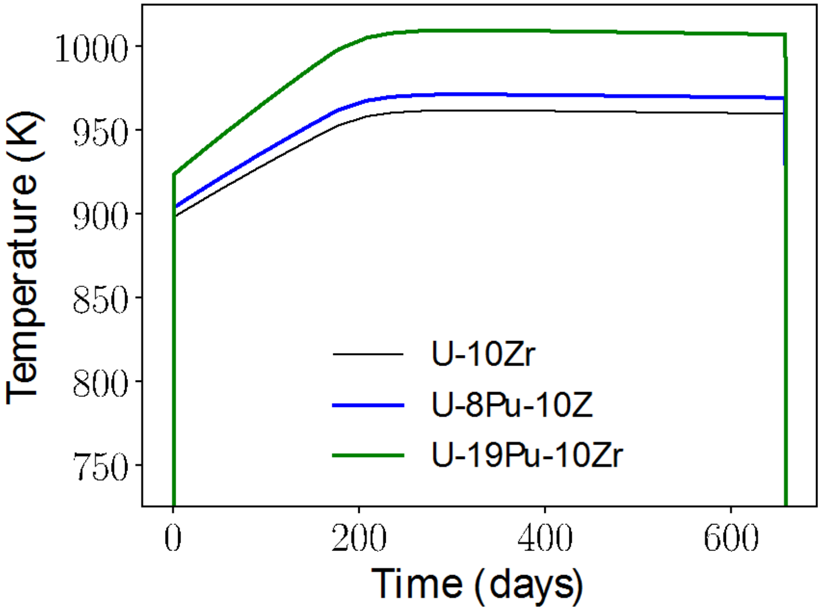
- Closed channel thermal hydraulics with heat transfer coefficients
- Sodium fluid properties

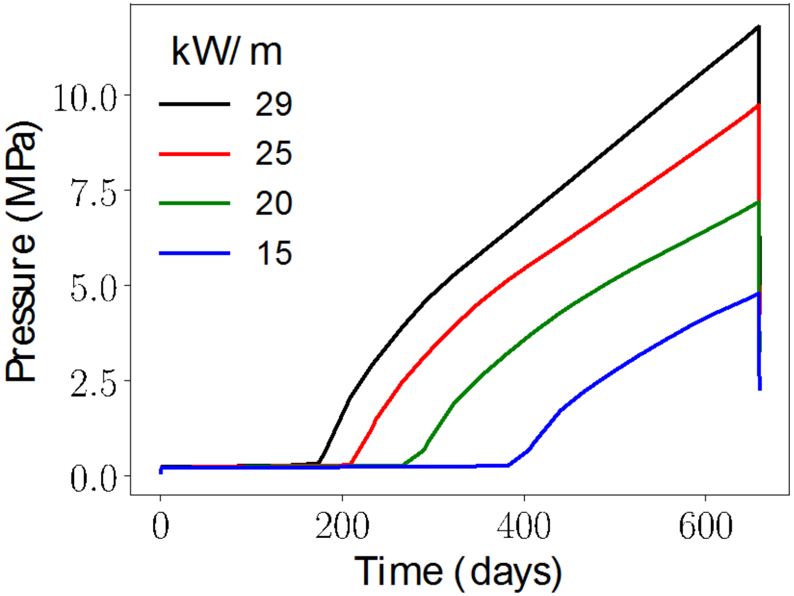
Example: EBR-II Fuel Pin

- Representative EBR-II pin geometry modelled assuming axisymmetry (2D-RZ)
- Thermo-mechanics plus Zr diffusion in the fuel alloy
- Sodium bonded with sodium coolant channel
- Variations considered in fuel alloy composition and pin power



Typical temperature field (geometry scaled 10x radially)





Metallic Fuel Validation

- With basic capability established, validation efforts have begun
- Data bases include experiments from EBR-II and TREAT

EBR-II

TREAT

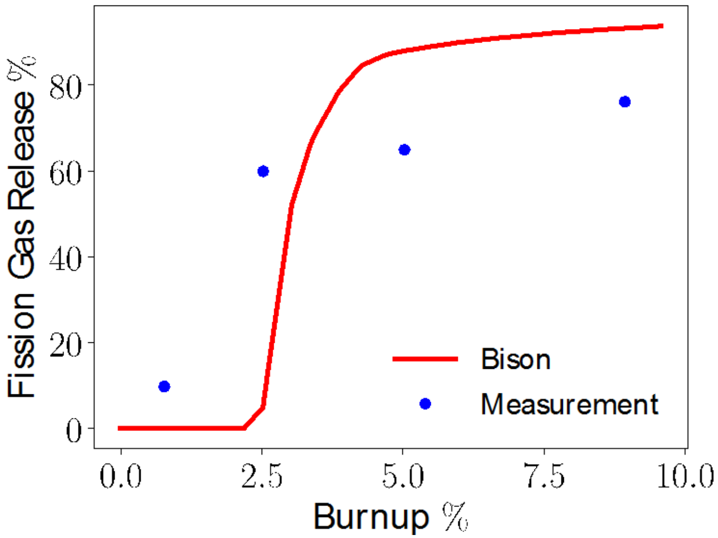
Cases in progress and scheduled for completion in FY18

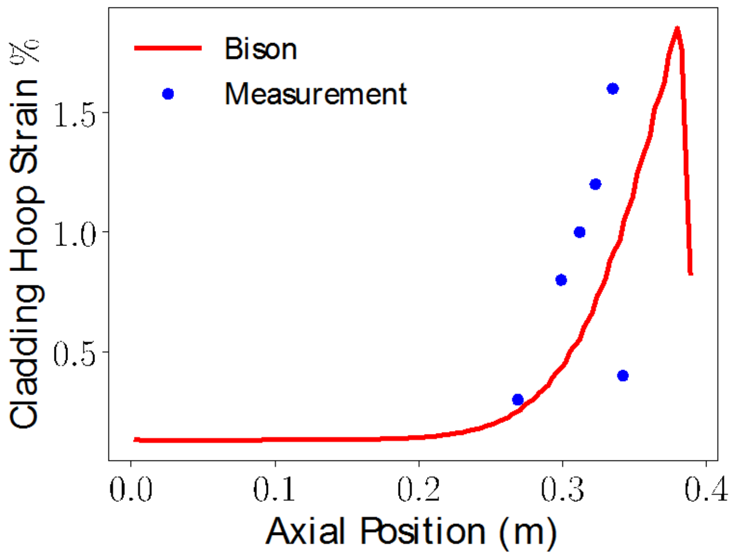
Experiment	Fuel type	Cladding	Measurements
X447 (EBR-II)	U10Zr	HT9/D9	Pin profilometry, fission gas release
X441 (EBR-II)	U10Zr U19PuxZr	HT9	Pin profilometry, cladding strain, plenum pressure, fission gas release
X423 (EBR-II)	U10Zr UxPu10Zr	316 SS	Fuel slug dimensions
M7-IFR (TREAT)	U10Zr U19Pu10Zr	HT9/D9	Cladding temperature history, cladding failure

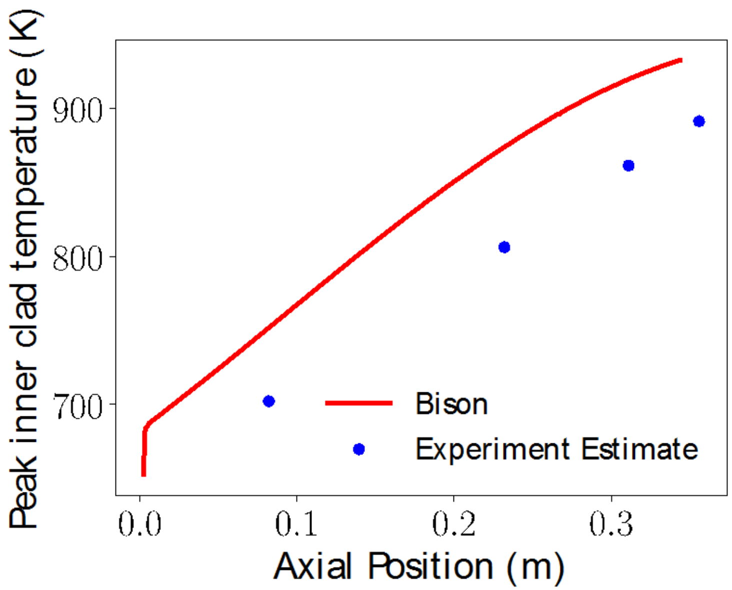
Metallic Fuel Validation: X447 Experiment

X447 experiment in EBR-II

- U10Zr fuel at average power of 30 kW/m for ~360 days
- Pins examined at multiple burnups
- First comparisons are very reasonable







Metallic Fuel Development/Validation Plans

Development

- Improvements and/or alternates to fuel swelling model – radial swelling is currently under-predicted (highest priority)
- Current Zr diffusion models are applicable to UPuZr; must be extended to UZr
- Lanthanide diffusion and Fuel Coolant Cladding Interaction (FCCI)
- Sodium infiltration
- Cladding swelling

Validation cases planned for FY19

Experiment	Fuel type	Cladding	Measurements
X429	U10Zr UxPu10Zr	HT9/316	Plenum volume, pressure, and gas analysis
X496	U10Zr	HT9	Bow and length measurements
X501	U10Zr UxPu10Zr	HT9	Minor actinide bearing fuel, plenum pressure and void volume

Summary and Conclusions

DOE is developing modern fuel performance modeling tools

- Applicable to a wide variety of fuel types, geometries, spatial scales and operating conditions
- Basic capabilities in place and demonstrated for high-priority advanced reactor fuel concepts including:
  - TRISO particle fuel (MHTGR and FHR)
  - Metallic fuel (SFR)
- Multiscale modeling approach (Bison/Marmot) has delivered demonstrated results for LWR fuel and will be extended to advanced reactor fuel
- While early comparisons to experimental data for particle and metallic fuel are very encouraging, additional validation is clearly needed
- In collaboration with the NRC and industrial collaborators, capability gaps are being identified and will be given high priority in future code development

Opportunities for cooperation

1) Implementation of fuel behavior models in vendor or NRC codes
2) Use of Bison by industry and/or NRC

Questions?

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Thermal-Hydraulic Capabilities for Advanced Reactors

August 21st, 2018

DOE Briefing to ACRS:

Advanced Modeling & Simulation Tools for Advanced Reactors

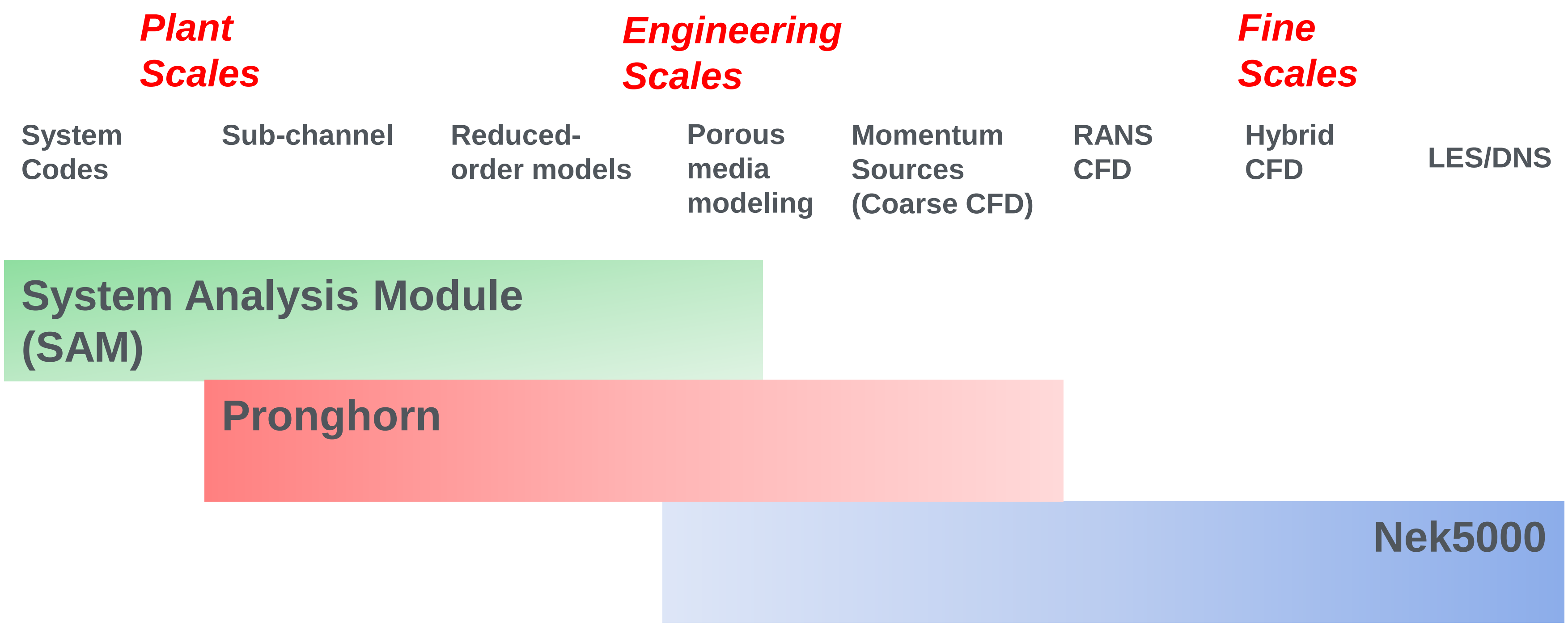
Outline of Presentation

- Background and Objective
- SAM
  - Capabilities/Examples
  - Validation
- Pronghorn
  - Capabilities/Examples
  - Validation
- Nek5000
  - Capabilities/Examples
  - Validation
- Summary and Conclusions

Overview of Thermal-hydraulic capabilities

Background

- DOE is developing modern multiscale thermal-hydraulic (T/H) tools applicable to a variety of advanced reactor concepts
- While validation focus has been primarily on Sodium Fast Reactors and Gas Reactors to date, the validation basis is being extended to other designs.
- Due to massive scale separation in nuclear systems a multiscale approach is desirable.



Objective

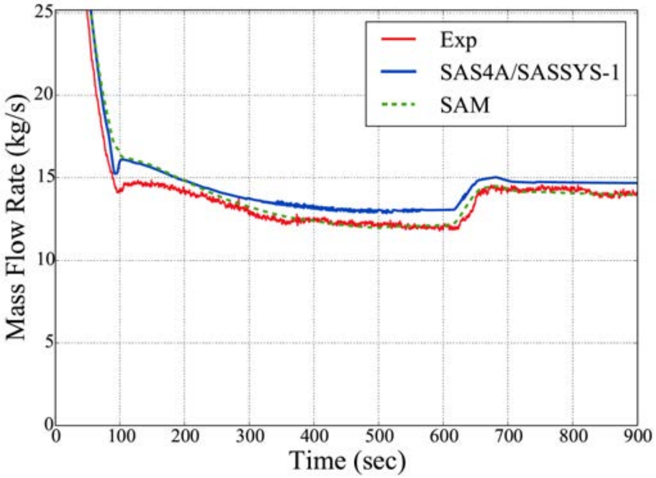
Objective

- Provide current status of DOE T/H codes for application to specific advanced reactor concepts including:
  - Code capabilities
  - Validation status
  - Future plans
- When 1D approximations are sufficient SAM is the applicable DOE code for safety analysis (LBEs).
  - It can be combined as desired with other DOE T/H codes when 1D approximations are inadequate.
  - Engineering and Fine scale codes can be used also to provide closure information to SAM.

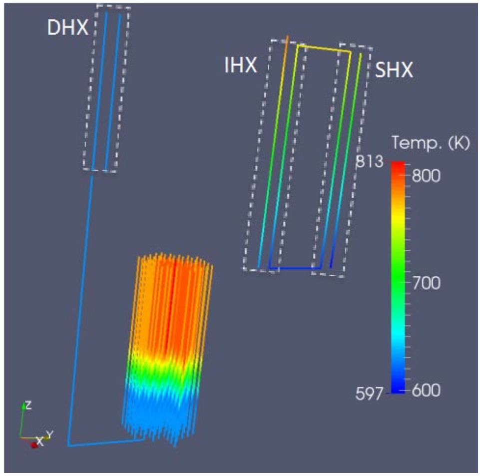
Concept	SFR	HTGR	FHR	MSR
Applicable DOE system code	SAM	SAM/ Pronghorn	SAM	SAM
Applicable DOE Engineering scale code	SAM	Pronghorn	Pronghorn	SAM
Applicable DOE fine scale code	Nek5000	Nek5000	Nek5000	Nek5000

SAM: Overview

- A modern plant-level system analysis tool for advanced reactors in liquid form (SFR, LFR, MSR/FHR) safety analysis. Some application to Gas reactors.
- Advances in software environments and design (MOOSE), numerical methods, and physical models.
- Focused on system T/H.
- **Enhancements in large volume modeling**: 0D, 1D stratification models and full 3D modeling (porous media).
- **Enhancements in core modeling**: Single-channel, Multiple-Channel and Intermediate fidelity (targeted toward SFR) core modeling.
- **Enhancements related to MSRs**: delayed neutron precursors transport, freeze and thaw models.
- **Flexible multi-scale multi-physics.**



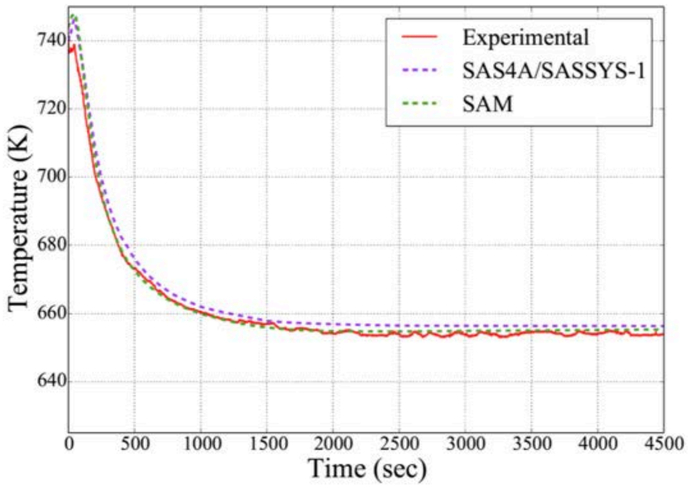
Mass flow rate in EBR-II SHRT-45R Benchmark

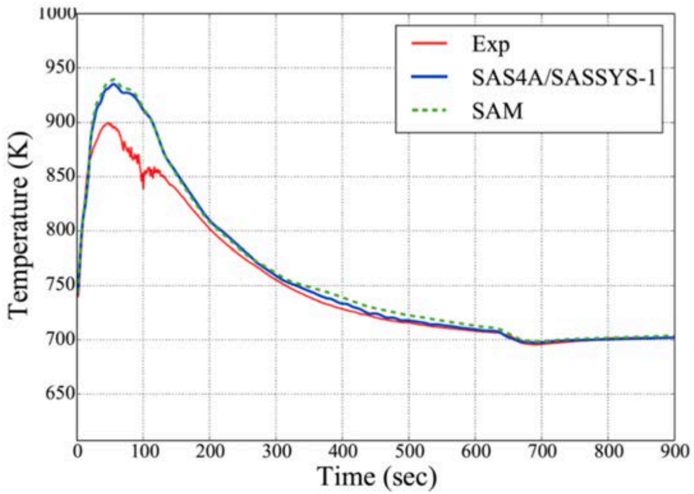


Representation of a PLOF in ABTR

SAM for Fast Reactors: Challenges & Status

- **Unique T/H challenges:**
  - Decay heat removal through passive heat removal mechanisms
  - Natural convection heat transfer for low Prandtl Fluids
  - Thermal stratification (impedes natural circulation in upper plenum)
- **SAM validation basis:**
  - SAM can reproduce behavior of several EBR-II and FFTF benchmarks
- **SAM improvements :**
  - Enhanced Multiphysics integration to connect separate phenomena (e.g., coupling of SAM to BISON)
  - Advanced Pool and stratification models in SAM
- **SAM Gaps:**
  - Spatial kinetics modeling to be integrated.

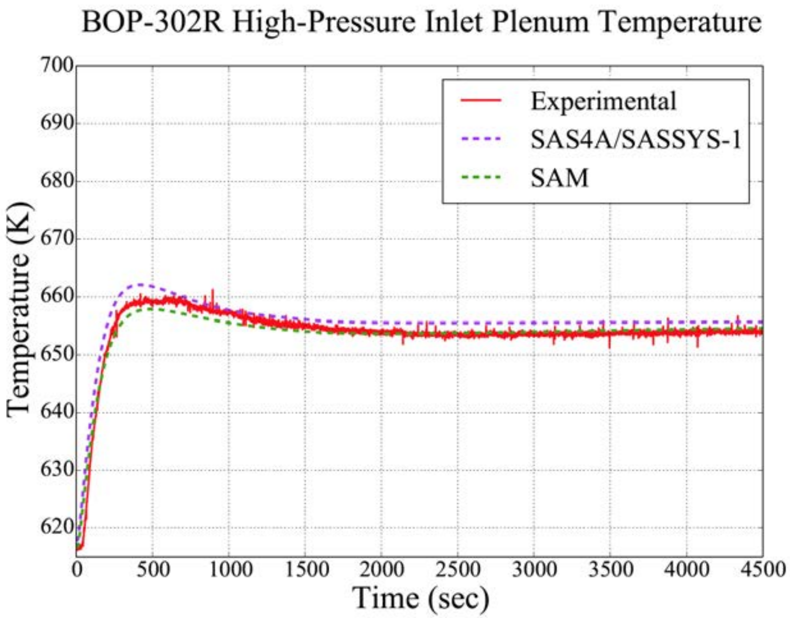




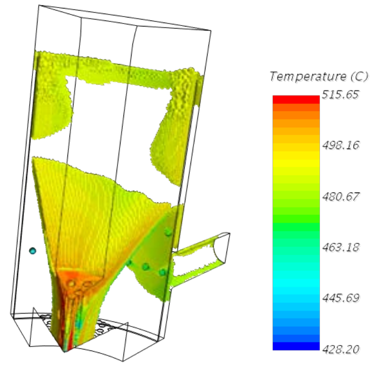
EBRII - Subassembly 6C4 outlet temperature during unprotected loss of heat rejection tests (BOP-302R - top) and unprotected loss of flow (SHRT-45R - bottom)

SAM for Fast Reactors: Options for stratification models

- Computationally efficient coarse-grid multi-D flow mixing and heat transfer model in SAM
  - Using a primitive variable based FEM formulation
  - Multiple options for shear stress modeling
- 1-D models and multiple 0-D volume modeling are also being pursued
- **Work in progress**: closure model developments and V&V of reduced-order models for thermal-stratification
- Coupling to CFD codes for additional accuracy and flexibility
  - Ideal usage is to calibrate 1D or reduced order models
- Several verification and validation tests have been completed or planned
  - Includes international collaborations (i.e., TALL-3D)



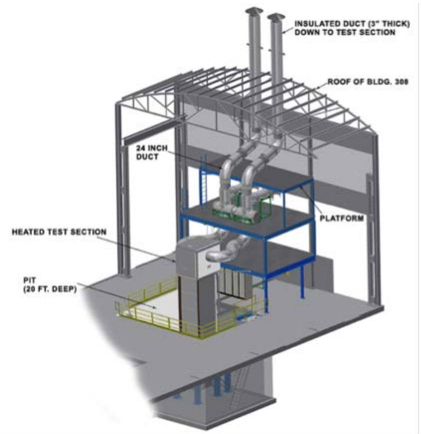
SAM EBR-II BOP-302R Simulation Results using multiple 0-D volume model

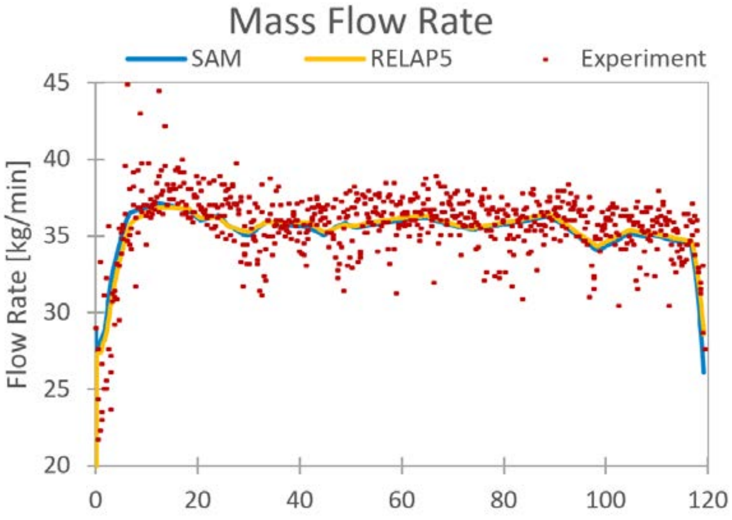


Coupled CFD calculation in the upper plenum of Monju (1995 turbine trip test) – Temperature predictions

SAM for Gas Reactors: RCCS applications

- **Unique T/H challenges:**
  - Decay heat removal through Reactor Cavity Cooling systems
    - Need to account for radiation effects
    - Environment effects
  - Unique accident scenarios (Air ingress, water ingress) not suited for current SAM formulation
- **SAM validation basis:**
  - SAM can reproduce RCCS tests at NSTF facility (Argonne)
- **SAM improvements :**
  - Novel environment condition models for RCCS
  - Coupling to Pronghorn and Nek5000 for detailed modeling of system.
- **SAM Gaps:**
  - Additional components and models would be needed for Air ingress and Water ingress transients.





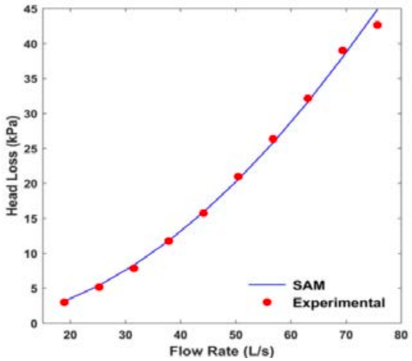
National Shutdown Test Facility validation. Picture of the facility (top), comparison between experiment RELAP5 and SAM results.

SAM for MSR Reactors: Challenges and Status

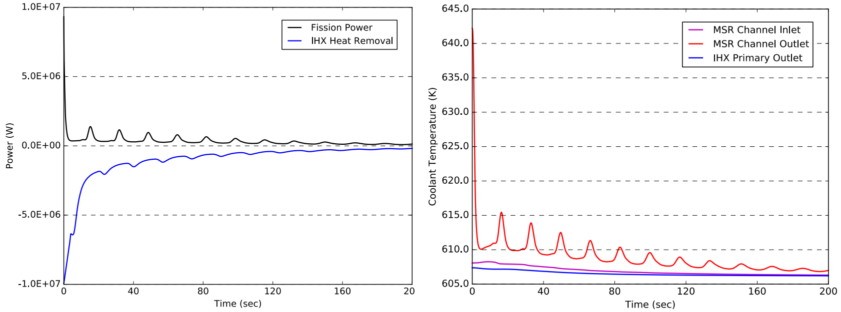
- **Unique T/H challenges:**
  - Heat is produced directly in the “coolant”
  - Unique design with “fuel circuit”
  - Unique core configurations with potential recirculation and stagnation zones
  - Reactivity management challenges
  - Delayed neutron precursor drift
  - Quick reconfiguration of the core geometry (gravitational draining) for passive safety
  - Salt thaw and freeze in overcooling transients.
- **SAM validation basis**: Ongoing validation effort against MSRE data in collaboration with PSU.
- **SAM improvements**:
  - Delayed neutron precursor generation and transport
  - Direct heat generation in coolant
  - Point Kinetics with DNP drift
  - Coupling to Nek5000 for 3D modeling (fast spectrum systems)
- **SAM gaps**:
  - Coupling to chemistry models for salt

TABLE II. Preliminary MSRE Model Results

Variable	Ref. 7	SAM
Power	10 MW_t	10 MW_t
Core Inlet Temperature	908 K	919 K
Core Outlet Temperature	936 K	942 K
Core Velocity	0.18-0.61 m/s	0.31 m/s



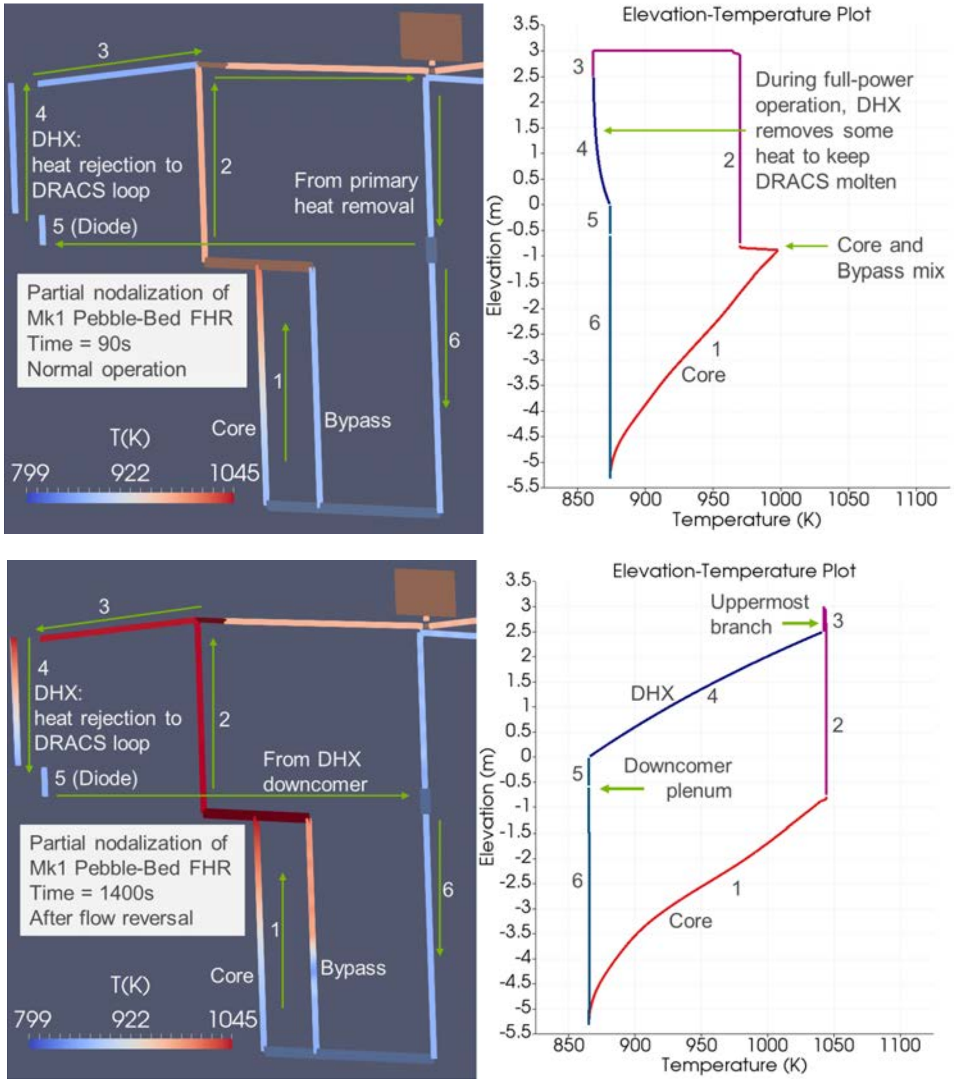
MSRE - Comparisons between available experimental data and SAM model. Top – overall reactor data, Bottom – Head loss comparison



Demonstration of Protected Loss of Flow Transient in simplified SAM MSR loop model for verification purposes.

SAM for Flouride High Temperature Reactors: Challenges and Status

- **Unique T/H challenges:**
  - FHRs (i.e., coolant salt reactors) combine features of molten salt and high temperature gas reactors.
  - High temperatures and associated material modeling issues
  - Salt may freeze in certain reactor transients. Freezing and thaw modeling are necessary.
- **SAM validation basis**: Ongoing validation effort against separate effect tests and MSRE.
  - Collaboration with vendors and universities.
- **SAM improvements**:
  - Salt thaw and freeze models.
  - Development of specific components needed for FHRs (flow diodes)
- **SAM Gaps**:
  - Need of data for validation.



PB-FHR- LOFC Transient with flow reversal in the primary side of DHX

Fast Reactors: SAM Validation Status and Plans

- Extensive validation performed or planned. C- Complete, O-Ongoing, P- Planned.

TEST MATRIX FOR SAM VALIDATION - LMR Applications

	TAMU-Wire Warpped Fuel Assembly	KIT-KALLA	UW-Sodium Test	UTK-Square Cavity	CEA-SUPERCAVNA	ENEA-NACIE	KTH-TALL/TALL3D	JAEA-PLANTD L	EBR-II	FFTF	Phenix	MONJU
BASIC PHENOMENOLOGICAL MODELS												
Wire-wrap bundle wall drag friction	P	P				P		P	C	O	P	P
Wire-wrap bundle intra-assembly flow	P	P				P		P	P			
Wire-wrap bundle heat transfer		P				P		P	C	O	P	P
Inter-assembly heat transfer		P						P	P	P	P	P
Low Prandtl number fluid convective heat transfer		P	P		P	P	P	P	C	O	P	P
Fluid conduction		P	P		P	P	P	P	C	O	P	P
Parallel channel flow		P						P	C	O	P	P
Wall heat transfer for 0-D components							P		C	O	P	P
Mixed convection		P			P	P		P			P	P
Buoyancy driven flow			P	C	P	P	P	P	C	O	P	P
Mechanistic pump modeling						P		P	P	P	P	P
Pool dynamics			P	C	P	P	P	P	C	O	P	P
Plenum coupling with liquid level tracking									C	O	P	P
Inter-volume mixing			P		P		P	P	C	O	P	P
Reactor kinetics									P	P	P	P
Reactivity feedback									P	P	P	P
Decay heat generation									P	P	P	P
TYPES OF CALCULATIONS												
Single-phase flow trainsient			P		P	P	P	P	C	O	P	P
Transient heatup/cooldown			P		P	P	P	P	C	O	P	P
Pump coast-down						P	P	P	C	O	P	P
Thermal stratification			P		P		P	P	C	O	P	P
Transition to natural circulation						P	P	P	C	O	P	P
Subassembly flow redistribution						P			P			
Core flow redistribution									C	O	P	P
Coupled system and CFD code simulation							P	P	P			P
Coupled with spatial kinetics code simulation									P	P		
Numerical convergence							P	P	P	P		
Restart calculation						P	P	P	C	O	P	P

FHR/MSR: SAM Validation Status and Plans

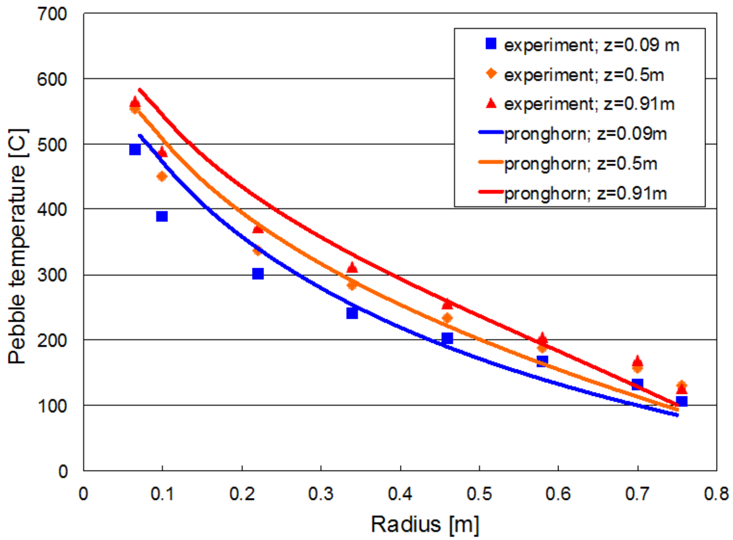
- Ongoing validation and plans identified. C- Complete, O- Ongoing, P-Planned.

TEST MATRIX FOR SAM VALIDATION - MSR/FHR Applications

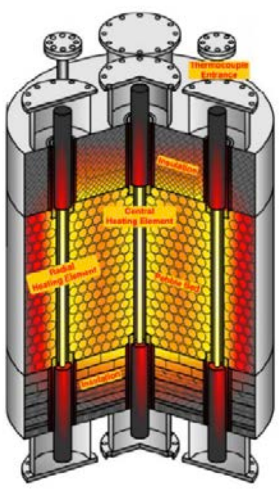
	UCB-PBHTE	UW-Flibe NC Loop	OSU-LTDF	UM-HTDF	UCB-CIET	ORNL LSTL	MSRE Water Mockup	MSRE
BASIC PHENOMENOLOGICAL MODELS								
Salt properties		P		P		P		O
Pebble-bed wall drag friction								
Pebble-bed convective heat transfer	P							
Pebble bed conduction models	P							
Salt freezing		P				P		
Heat generation in fluid components								O
Radiation heat transfer with salt		P		P		P		P
Species mass transport								O
Tritium transport								
Plenum coupling with liquid level tracking					O			
Delayed neutron precursor (DNP) and decay heat precursor decay								O
Delayed neutron precursor and decay heat precursor generation								O
Reactivity feedback								P
Reactor kinetics with DNP drift								O
TYPES OF CALCULATIONS								
Single-phase flow trainsient		P	O	P	O	P	C	O
Transient heatup/cooldown		P	O	P	O	P	C	O
Pump coast-down			O	P	O	P	C	O
Transition to natural circulation		P	O	P	O	P	C	O
Thermal stratification								O
Core flow redistribution								O
Numerical convergence		P	O	P	O			
Restart calculation		P	O	P	O	P	C	O

Pronghorn: Overview

- A modern engineering-level system analysis tool for advanced reactors.
- Advances in software environments and design (MOOSE), numerical methods, and physical models.
- Targeting primarily pebble bed reactors (FHR/HTGR) but extendable to other designs.
- Anisotropic porous media modeling as we well as more advanced formulations.
- **Enhanced formulation**: It can combine porous media regions with open regions. Flexible multi-scale multi-physics.
  - It can be described as homogenized conjugate heat transfer (CHT), where each finite element may contain a mixture of coolant, fuel, moderator, or other core internals.
  - Correlations for anisotropic resistance from Nek5000 can be implemented in a straightforward manner.
- **Coupling to SAM for RCCS modeling.**



Comparison between Pronghorn and SANA dataset. Pebble temperature at various axial locations.



B. Stocker and H. Nieben. Data Sets of the SANA Experiment 1994–1996. Technical report, Forschungszentrum Julich, 1996.

Pronghorn: Formulation

Think of the model as a two-phase flow problem where the second phase (pebble stack) is stationary.

Conservation of Mass, Momentum, Energy

$$\frac{\partial \alpha \rho_g}{\partial t} + \vec{\nabla} \cdot \alpha \rho_g \vec{u}_g = 0$$

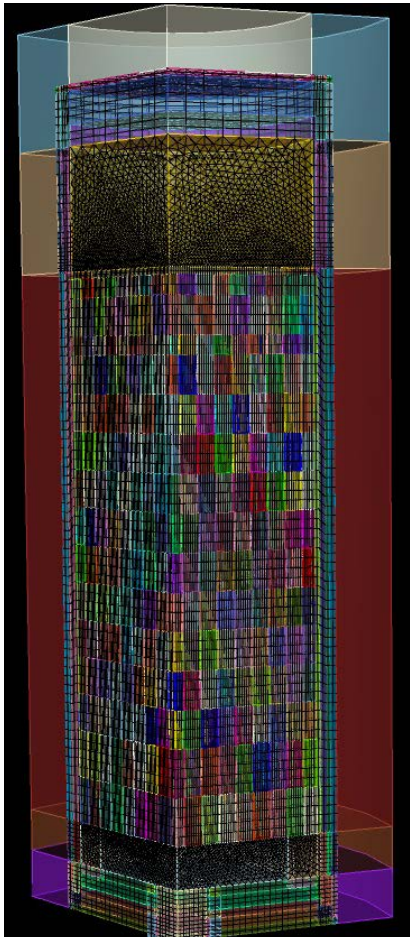
$$\frac{\partial \alpha \rho_g \vec{u}_g}{\partial t} + \vec{\nabla} \cdot \left(\alpha \rho_g \vec{u}_g \otimes \vec{u}_g \right) = -\alpha \vec{\nabla} p_g - \xi \rho_g \left\| \vec{u}_g \right\|^2 \vec{\nabla} \alpha - \lambda \vec{u}_g$$

$$\frac{\partial \alpha \rho_g E_g}{\partial t} + \vec{\nabla} \cdot \left(\alpha \rho_g \vec{u}_g H_g \right) + \vec{\nabla} \cdot \alpha \vec{q}_g - \alpha \rho_g \varepsilon_g = \vartheta \left(T_s - T_g \right)$$

$$\frac{\partial (1-\alpha) \rho_s e_s}{\partial t} + \vec{\nabla} \cdot (1-\alpha) \vec{q}_s - (1-\alpha) \rho_s \varepsilon_s = -\vartheta \left(T_s - T_g \right)$$

Assumptions:

1. No bed motion
2. No phase change
3. Ensemble-averaged turbulence effects



Nodalization for a gas reactor with Pronghorn

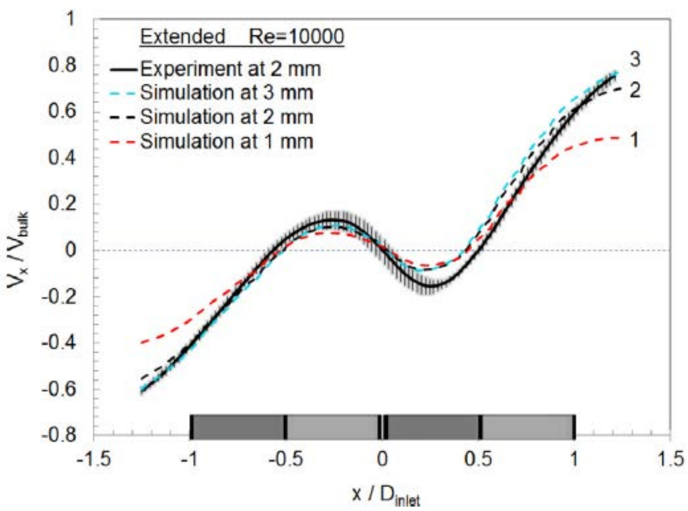
Gas Reactors: Pronghorn Validation Status and Plans

- Validation on SANA dataset for Pronghorn, other simulations are planned. C- Complete, O- Ongoing, P- Planned.

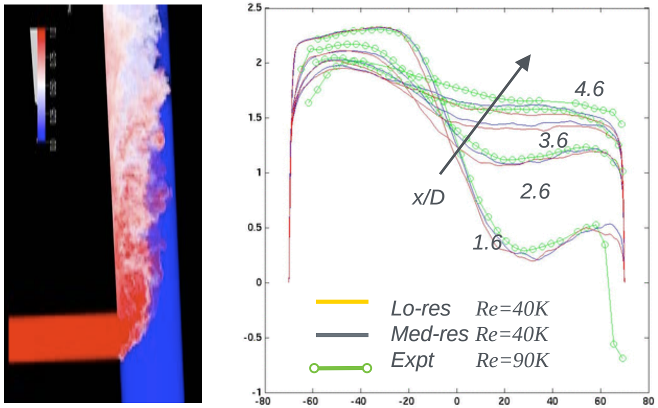
	Facilities									
	AVR (German)	**THTR-300 (German)**	**SANA (German)**	**HTR-10 (China)**	**HTR-PM (China)**	**HTTR (Japan)**	**RCCS facilities (ANL, SNU, TAMU)**	**HTTF (US)**	**FST (US)**	**PBHTX (UCB, US)**
BASIC PHENOMENOLOGICAL MODELS										
Gas properties (e.g., helium)	P	P	C	O	O	P		P	P	
Salt properties (e.g., flibe)										
Solid thermal properties (e.g., graphite)	P	P	C	O	O	P		P	P	
Pebble-bed convective heat transfer	P	P	C	O	O					P
Pebble-bed effective thermal conductivity	P	P	C	O	O					
Fuel pebble/element (composite solid) effective thermal conductivity	P	P		P	P	P		P	P	
Pebble-bed pressure drop	P	P	C	O	O					P
Wall-to-pebble-bed heat transfer			P	P	P					
Non-uniform porosity distribution				P	P					
Irradiated graphite thermal properties	P	P		P	P	P		P	P	
Graphite oxidation				P	P	P				
Thermal radiation and RCCS cooling				O	O	P	P			
Bypass flow				O	O	P		P		
Salt freezing										
Decay heat (via coupling)				O	O	P		P	P	
Reactivity feedback (for coupling)				O	O	P		P	P	
TYPES OF SIMULATIONS										
Forced convection	P	P		O	O	P		P	P	P
Natural circulation			C					P		
Multi-dimensional heat conduction	P	P	O	O	O	P	P	P	P	
Flow and heat transfer in pebble beds	P	P	C	O	O					P
Flow and conjugate heat transfer in channels						P	P	P	P	

Nek5000: Overview

- A state-of-the-art high-order computational fluid dynamics code.
  - Incompressible and compressible formulations.
- Extensive user base.
- **Easy to integrate**: Open-source, MOOSE-interface.
- **Range of fidelity**: from Direct Numerical Simulation to Large Eddy Simulation, Reynolds Averaged Navier-Stokes and Porous Media.
- **Scaling Performance**: it can be run on laptop as well as a supercomputer. On supercomputers it allows for state-of-the art scaling (which enables otherwise impossible large scale calculations).
- Flexible multi-scale multi-physics.
- **Extensive general validation basis**: Code has ranked #1 in several OECD/NEA blind benchmarks on CFD applications to reactor safety.



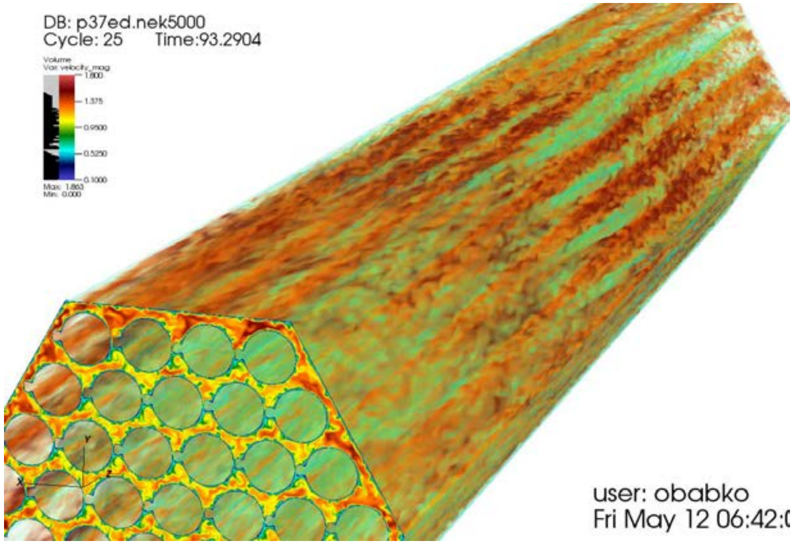
Comparison of near-wall velocity of two impinging jets predicted by Nek5000 for the MAX thermal-striping and mixing experiment.



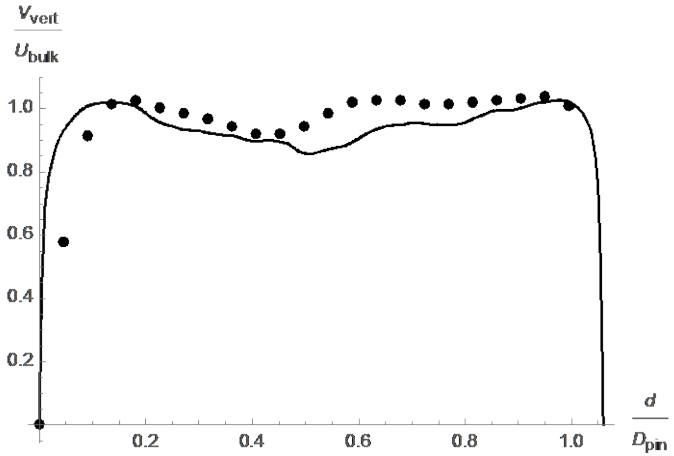
OECD/NEA blind benchmark on T-junction flow. Nek5000 ranked first in temperature predictions

Nek5000 for Fast Reactors: Challenges and Status

- **Unique T/H challenges:**
  - Turbulence modeling for low Prandtl Fluids in natural convection
  - Thermal striping is a a major concern for structures in the upper plenum
  - Mixing in Large enclosures
  - Complex flow structures in the fuel assembly require the evaluation of mixing coefficients.
- **Nek5000 validation Basis**:
  - Nek5000 has extensive validation for thermal striping
  - Evaluation of Nek5000 against legacy wire-wrapped fuel assembly experiments and new experimental campaigns.
- **Nek5000 improvements**:
  - Coupling to SAM for modeling of upper plenum
  - Coupling to Diablo (structural mechanics) for evaluation of thermal-striping in structures.
  - Accurate predictions through Large Eddy Simulation modeling
- **Nek5000 Gaps**:
  - Advanced turbulence modeling options for low Prandtl Fluids (in development)



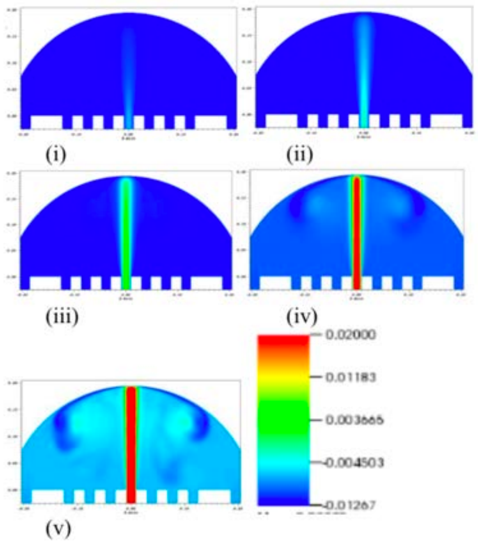
Wire-wrapped fuel assembly calculation (61 pins). Instantaneous velocity magnitude



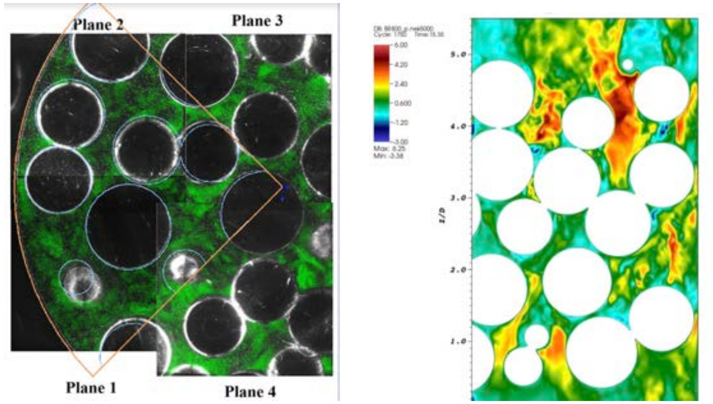
Comparison between Nek5000 and experimental data at TAMU (central subchannel of a 61 pin bundle)

Nek5000 for Gas Reactors: Challenges and Status

- **Unique T/H challenges:**
  - Modeling of Decay heat removal through Reactor Cavity Cooling systems to drive system code model development.
  - Simulation of onset of unique accident scenarios (Air ingress, water ingress).
  - Mixing in large enclosures.
  - Pebble bed flow and heat transfer models
- **Nek5000 validation basis**:
  - Ongoing validation effort against TAMU experiments for upper plenum.
  - Ongoing validation against random pebble bed data at TAMU (useful also for FHRs). Verification against available DNS data.
  - Collaboration with vendors.
- **Nek5000 improvements**:
  - Anisotropic distributed resistance and heat transfer models for Pronghorn.



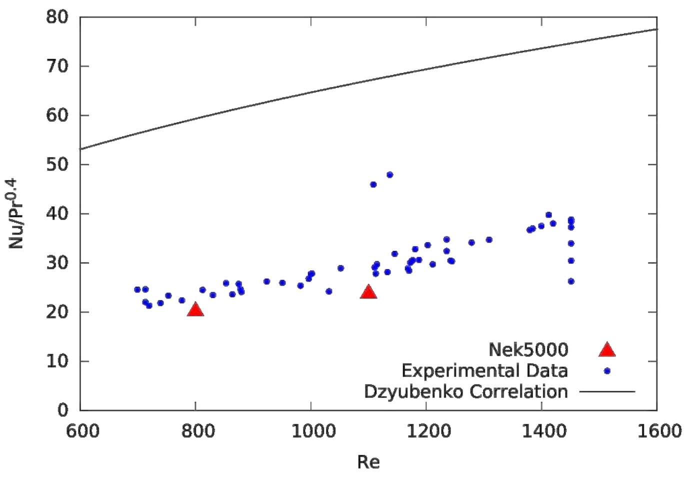
Nek5000 Simulations in the upper plenum of a gas reactor at various Reynolds numbers, increasing from 100 (i) to 1000 (v). Results will be compared against ongoing TAMU experiments.

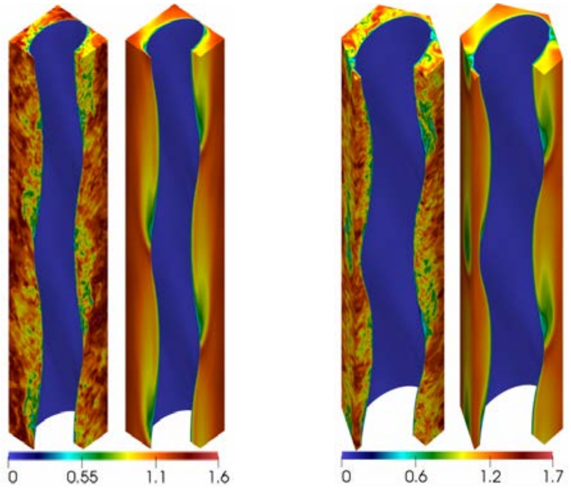


Nek5000 simulations in the TAMU random pebble experiment. Left – PIV experimental results, Right – Snapshot of the velocity field. Comparisons are ongoing.

Nek5000 for FHRs : Challenges and Status

- **Unique T/H challenges:**
  - Low Reynolds number flows encountered in several components.
  - Potential for excessive stress in high temperature components (upper plenum).
  - Salt may freeze in certain reactor transients. Freezing and thaw modeling are necessary.
- **Nek5000 validation basis**:
  - Validation on available experiments for twisted tubes HX (e.g., DRACS) and pebble “beds”
  - Collaboration with vendors.
- **Nek5000 improvements**:
  - Large Eddy Simulation in Nek5000 provides an efficient and accurate mean to evaluate friction and heat transfer.
  - Coupling to SAM for full system analysis (upper plena simulations)
- **Nek5000 Gaps**:
  - Need of data for validation.
  - Salt thaw and freeze models.

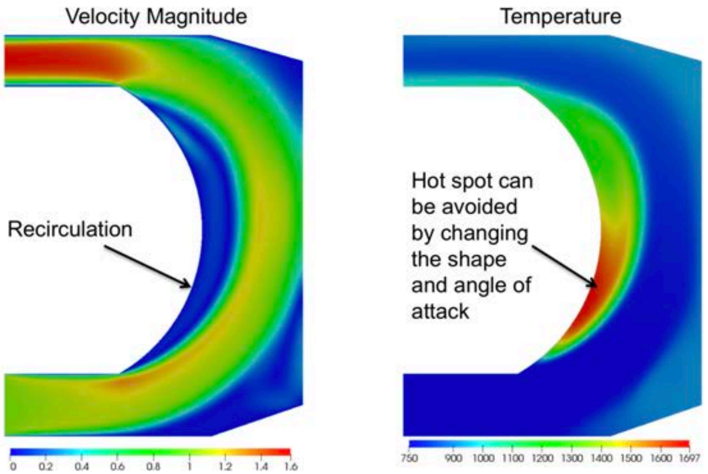




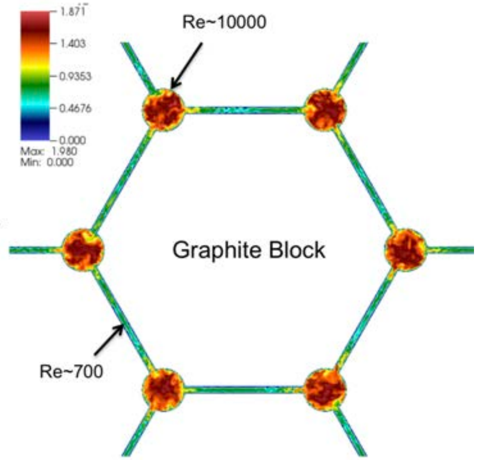
Twisted tube performance evaluation using Nek5000. Top - comparison with an available experiment and correlation. Bottom – Fluid flow in various lattice configurations.

Nek5000 for Molten Salt Reactors: Challenges and Status

- **Unique T/H challenges:**
  - Unique core configurations with potential recirculation and stagnation zones (exacerbated by the high Prandtl number)
  - Delayed neutron precursor drift and associated transport
  - Uncertainty of thermo-physical properties of salt.
  - Potentially very Low Reynolds numbers in some designs.
- **Nek5000 validation Basis**:
  - Limited MSR-specific validation basis. Ongoing collaborations for validation on MSRE data.
- **Nek5000 improvements**:
  - Coupling to SAM for modeling of full system when 3D effects are important (fast MSR core)
  - Modeling of mass transport for DNP and fission products.
  - Efficient Large Eddy Simulation approach provides accurate results at low Reynolds number conditions.
- **Nek5000 Gaps**:
  - Coupling to neutronics needs to be updated to handle DNP drift
  - Coupling to chemistry models for salts
  - Need to extend validation basis



Demonstration of flow in a fast spectrum MSR core (Nek5000). Highlighting the importance of 3D effects on the prediction of the highest structure temperature.



Demonstration - Large Eddy simulation in a representative thermal-spectrum MSR. The cross section may present local laminarization and strong inhomogeneity of the flow field.

Nek5000 for Fast Reactors: Validation Status and Plans

- Substantial validation has already been performed in Nek5000. C- Complete, O- Ongoing, P- Planned.

	TAMU-Wire Warpped Fuel Assembly	THOR	HEDL	ENEA-NACIE	ENEA-CIRCE	CEA-SUPERCAVNA	KTH-TALL/TALL3D	JAEA-PLAJEST	ANL-MAX	JAEA-PLANTDL
BASIC PHENOMENOLOGICAL MODELS										
Wire-wrap bundle wall drag friction	C	O	C	C	C					C
Wire-wrap bundle PIV	C									
Wire-wrap mixing			C							
Wire-wrap bundle heat transfer	C	O	C	C	C					C
Inter-assembly heat transfer										P
Low Prandtl number fluid convective heat transfer				C	C	O	O	C		C
Fluid conduction				O	O		O			C
Thermal-striping								C	C	
Mixed convection				O		O				P
Buoyancy driven flow				O	O	O	O			P
Thermal stratification						O	O			
Pool dynamics				O	O	O	O		C	P
TYPES OF CALCULATIONS										
Single-phase flow trainsient and steady state				C	C		O			C
Transition to natural circulation				P	P		O			P
Coupled system and CFD code simulation							P			P

Nek5000 for FHR/MSR: Validation Status and Plans

- Limited validation already performed in Nek5000. Several Ongoing efforts. C-Complete, O- Ongoing, P- Planned.

	UCB-PBHTE	TAMU-Pebbles	UNM-HX	UW-Flibe NC Loop	OSU-LTDF	UM-HTDF	UCB-CIET	ORNL LSTL	MSRE Water Mockup	MSRE
BASIC PHENOMENOLOGICAL MODELS										
Salt properties				P		P		P		O
Pebble-bed wall drag friction		C								
Pebble-bed convective heat transfer	P	C								
Pebble bed conduction models	P	C								
Pebble bed PIV		O								
Twisted Tube Heat exchnagers			C							
Salt freezing				P				P		
Heat generation in fluid components										O
Radiation heat transfer with salt				P		P		P		O
Species mass transport										O
Tritium transport										
Delayed neutron precursor (DNP) and decay heat precursor decay										O
Delayed neutron precursor and decay heat precursor generation										O
TYPES OF CALCULATIONS										
Single-phase flow trainsient				P	P	P	P	P	P	O
Transition to natural circulation				P	P	P	P	P	P	O
Thermal stratification									P	O

Conclusions

- DOE is developing modern T/H multiscale modeling tools applicable to a wide variety of reactor designs.
- While greatest emphasis to date has been for sodium and gas cooled reactors, substantial capability exists for other reactor concepts

- *Basic capabilities have been demonstrated to simulate advanced reactor LBEs.*
- *Existing capability gaps have been identified and will be given high priority in future code development work*
- *Past and Ongoing comparisons to experimental data are very encouraging however substantial validation work remains*

Questions?

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Source Term Assessment Approaches and Codes for Advanced Reactors

DOE Briefing to ACRS:

Advanced Modeling & Simulation Tools for Advanced Reactors

Background

- Source term definition in 10 CFR 50.2:
  - ”*The magnitude and mix of the radionuclides released from the fuel, expressed as fractions of the fission product inventory in the fuel, as well as their physical and chemical form, and the timing of their release.*”
- Deterministic accident source terms requirements for LWRs in 10 CFR 50.67
  - TID-14844 makes prescriptive radionuclide release assumptions for a LOCA leading to core melt as the bounding event
    - Instant release of 100% of noble gases, 50% of halogens, 1% of remaining solids to the containment
  - NUREG-1465 specifies unique BWR and PWR releases based on scenarios considered in NUREG-1150 and supplemental analyses
    - Prescribed timed (early/late) in/ex-vessel releases accounting for engineered safety features along with uncertainty analyses
- SECY-93-092 sets the regulatory expectations for advanced reactors to rely on more realistic source term evaluations

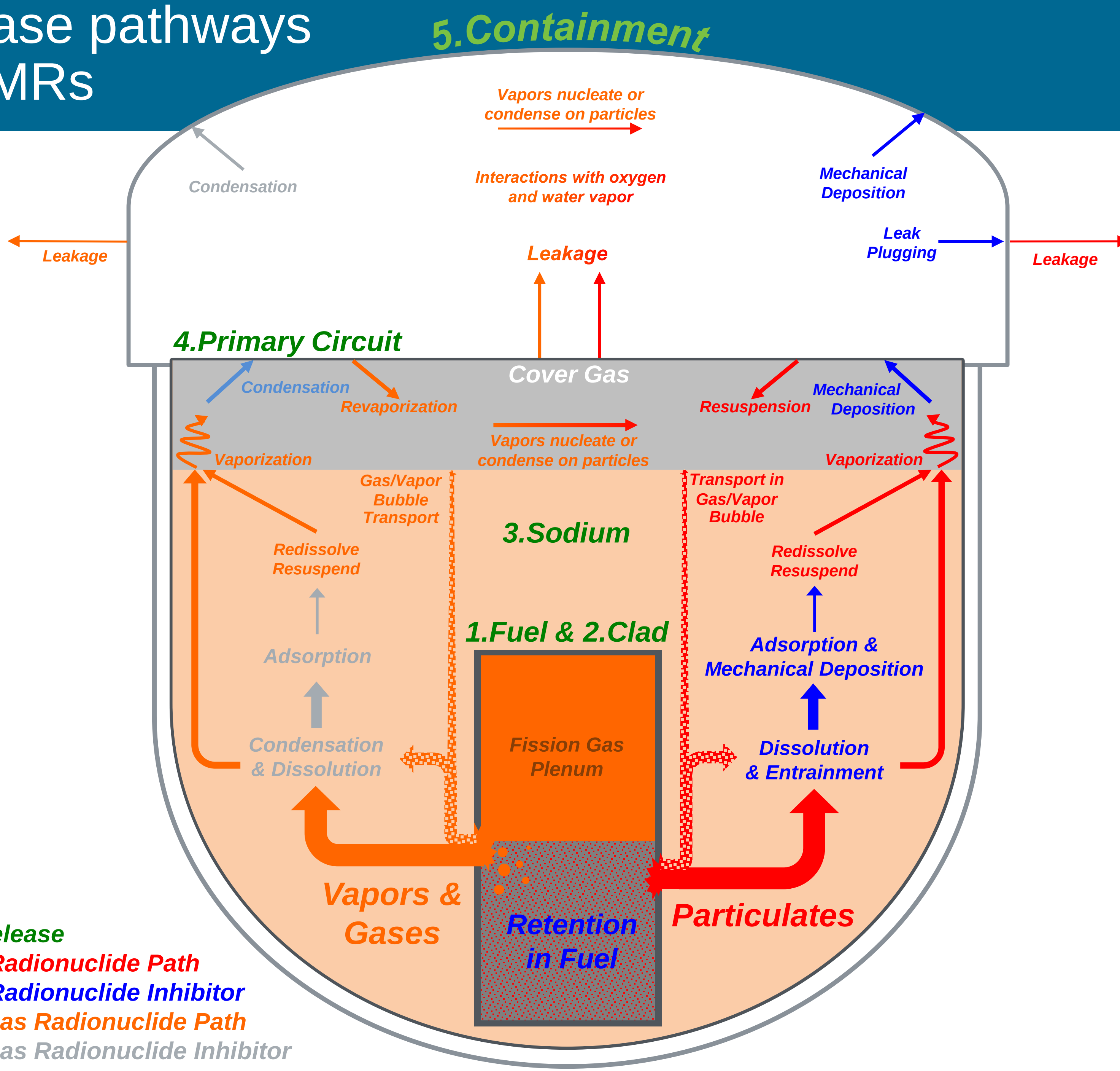
Rationale for MST for Advanced Reactors

- For advanced reactors, source term is not always limited to bounding events
  - For some advanced reactor types, very small releases can be anticipated during even AOOs/DBAs
- Broader spectrum of accidents needs to be considered
  - Potential for “frequent but small” vs. “infrequent but large” releases
  - Accidents that could lead to early vs. delayed releases with different radionuclide discharge and emergency response implications
  - Radionuclide sources other than the fuel in the reactor core
    - Fuel storage, coolant/cover-gas cleanup and chemical processing systems
  - Also to support Levels 2/3 PRA and EPZ reduction requests
- Mechanistic Source Term (MST) Assessments:
  - *Analysis of radionuclide release, in terms of quantities, timing, and other characteristics, resulting from the specific event sequence being evaluated using best-estimate phenomenological models for the transport of radionuclides from their source to the environment through all holdup volumes and barriers, taking into account the mitigation features.*

General MST Approach

Inventory	•Identify radionuclide sources and characterize the potential inventory associated with each source (core, spent fuel, cleanup system, …)
Release pathways	•Identify relevant pathways and phenomena associated with radionuclide transport from their source to the environment
Modeling	•Modeling of the phenomena involved in transport of radionuclides through identified pathways and barriers
Scenario evaluation	•Application of models to a spectrum of accidents (AOOs, DBAs, and BDBAs) for evaluation of release rates and frequency
Regulatory review	•Interactions with the regulator as part of pre-application and license review process

Release pathways for LMRs



Legend
Barrier to Release
Particulate Radionuclide Path
Particulate Radionuclide Inhibitor
Vapor and Gas Radionuclide Path
Vapor and Gas Radionuclide Inhibitor

MST Approach for LMRs

Existing codes
NEAMS Program Tools
Developmental Capabilities
NRC-supported codes

Inventory analysis	ORIGEN, REBUS
Transient scenario modeling	SAS4A, SAM, PERSENT
In-pin radionuclide distribution	LIFE-M, SAS4A, BISON
Radionuclide release from failed fuel	Radionuclide Release Module (RRM)
Radionuclide bubble transport	
Liquid-metal pool radionuclide release	
Cover gas region analysis	MELCOR, CONTAIN-LMR
Containment region analysis	MELCOR, CONTAIN-LMR
Offsite dispersion analysis	RASCAL, WinMACCS

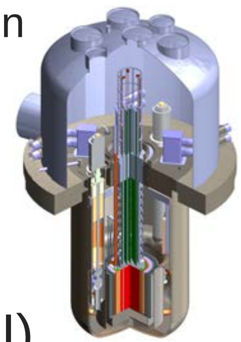
Trial LMR MST Application

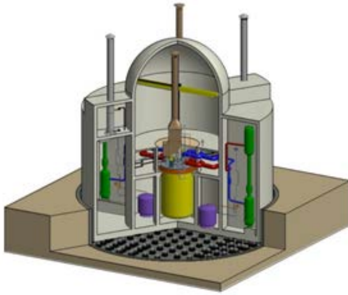
- AFR-100 design
  - Trial MST calculations for a 100 MWe pool type small modular SFR with metallic fuel
  - ANL-ART-49: http://www.ipd.anl.gov/anlpubs/2016/11/131283.pdf
- Two transient scenarios considered as example cases
  - **PLOF+** Long, slow heat-up of core and primary system with fuel failures but no melting
  - **UTOP+** Quick rise in fuel temperatures leading to melting, but with primary system at near-nominal conditions
    - Sequences are typically selected based on a risk-informed approach using PRA
- Conclusions:

Phenomena	***Importance***
Pool Bypass (Bubble Transport)	*Very High*
Fuel Release Fractions (Actinide/Lanthanide)	*High*
Aerosol Deposition/Removal	*Medium*
Reactor Head/Containment Leak Rate	*Medium*
Pool Vaporization	*Low*
Noble Gas Decay Chains	*Low*

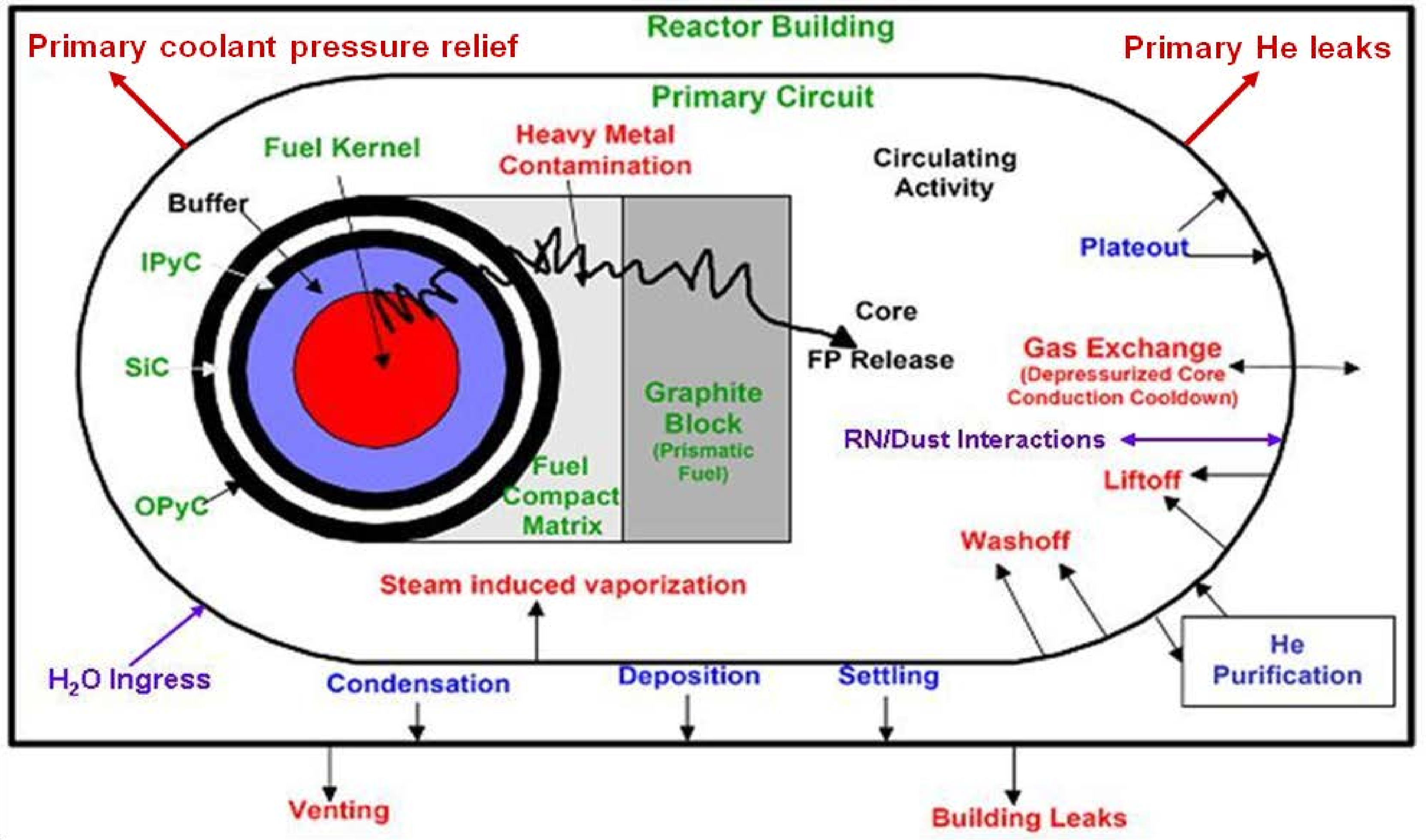
Other LMR MST Applications

- GE-Hitachi
  - MST findings as a major part of PRISM PRA update/modernization effort (2-year collaboration between GEH and Argonne)
- TerraPower
  - Company-funded work at Argonne to repeat trial MST calculation for TWR design
- Korean Atomic Energy Research Institute (KAERI)
  - KAERI-funded effort for preliminary source assessments and experiments are Argonne to support PGSFR licensing
  - Supports development of RRM for metallic fuel
- Fauske & Associates
  - GAIN voucher to Argonne for coupling SAS4A with FATE for LMR source term assessments (initial application to WEC LFRs)
  - Supports development of RRM for oxide fuel
- Two 2018 DOE-NE NEUP awards to UWM and UNM
  - Radionuclide retention tests in liquid sodium and liquid lead

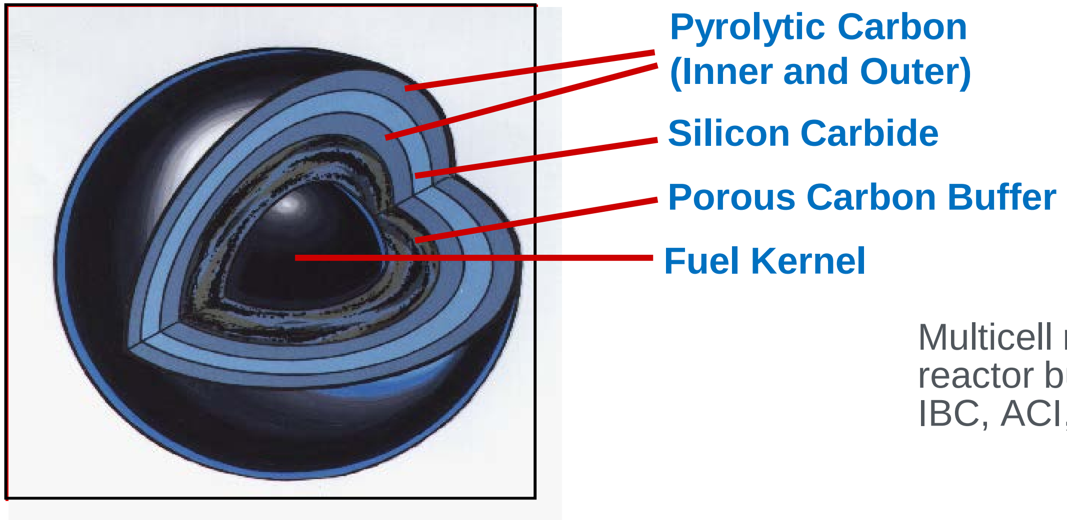


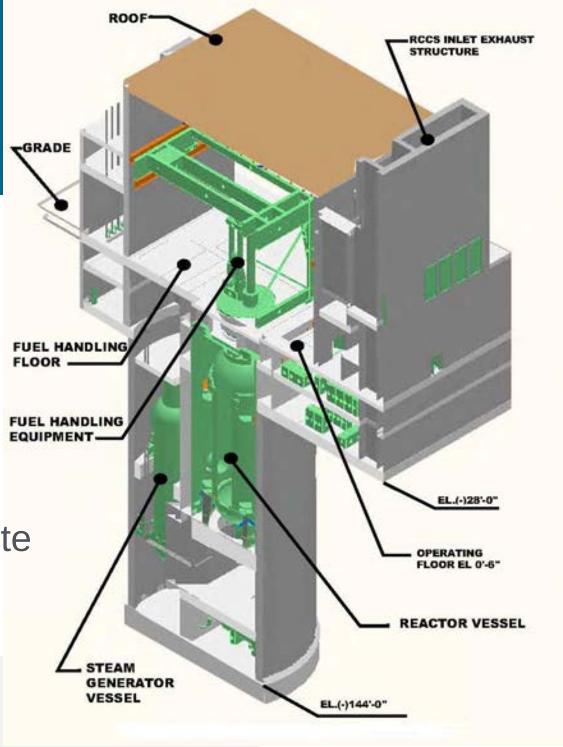


Release Pathways for HGTRs



Multiple Barriers for HGTRs

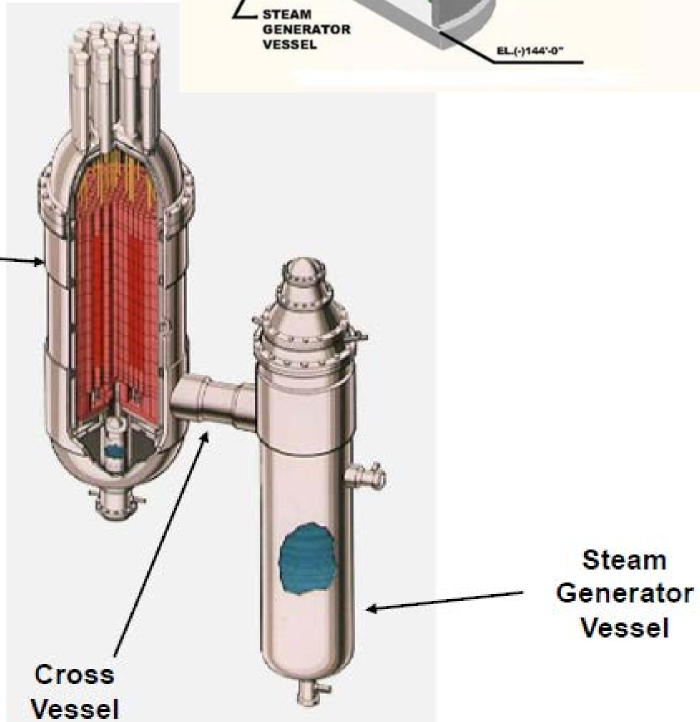




Multicell reinforced concrete reactor building based on IBC, ACI, AISC standards

COMPACTS

FUEL ELEMENTS



Helium Pressure Boundary fabricated based on ASME B&PV Code Section III

MST Approach for HTGRs

- Radionuclide retention within fuel during normal operation
  - Relatively low inventory inside HPB from defective fuel particles
- Limiting off-normal events characterized by
  - an initial release from the HPB depending on the size of leak/break/pressure-relief
  - a larger, delayed release from the fuel at elevated temperatures
- *Functional containment* concept to meet 10 CFR 50.34 requirements and EPA PAGs with wide margin for spectrum of off-normal events
  - Coated fuel particle is the primary barrier to radionuclide release during normal operation (due to initially defective particles) and off-normal events (through diffusion and recoil of radionuclides at elevated temperatures for long transients)

MST Approach for HTGRs

Existing codes
NEAMS Program Tools
Developmental Capabilities
NRC-supported codes

Inventory analysis	ORIGEN
Transient scenario modeling	RELAP, PRONGHORN
Fuel response to scenario studied	PARFUME, BISON
Radionuclide release rates from fuel	BISON, TRISO fuel QA
HPB radionuclide release	MELCOR
Reactor building analysis	MELCOR
Offsite dispersion analysis	RASCAL, WinMACCS

Trial HTGR MST Application

- HTGR Mechanistic Source Term White Paper (INL/EXT-10-17997)
  - https://www.osti.gov/biblio/989901-htgr-mechanistic-source-terms-white-paper
- Scoping Analysis of Source Term and Functional Containment Attenuation Factors (INL/EXT-11-24034)
  - https://www.osti.gov/biblio/1037782

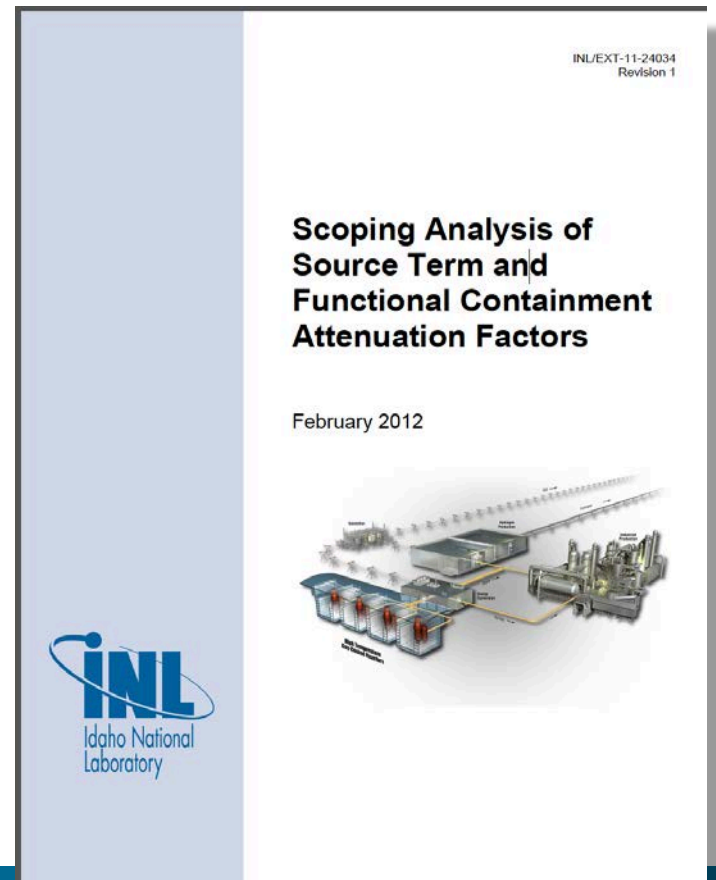
INL/EXT-10-17997
Revision 0

Mechanistic Source Terms White Paper

July 2010

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Idaho National Laboratory



INL/EXT-11-24034
Revision 1

Scoping Analysis of Source Term and Functional Containment Attenuation Factors

February 2012

Idaho National Laboratory

MST Approach for MSRs

- *Functional containment* concept can also apply to MSRs (with dissolved fuel) and FHRs (with solid fuel)
  - For FHRs, coated fuel particle is also the primary barrier to radionuclide release during normal operation and off-normal events
  - For MSRs, molten salt can retain almost all non-gaseous fission products
- Source term will likely be dominated by minor releases during incidents more likely than BDBAs
  - Leaks from molten salt chemical processing system (may be inside or outside the containment)
  - Tritium generated during irradiation of molten salts (especially those containing Li) will require approaches to prevent its uncontrolled release to the environment
    - assess its rate of generation in the core,
    - trace its movement in and out of the core with moving molten salt,
    - monitor its accumulation in critical locations (i.e., cover gas space),
    - establish mechanisms for collection and purge
- For FHRs MST approach and tools used can be similar to those for HTGRs

MST Approach for MSRs

Existing codes
NEAMS Program Tools
Developmental Capabilities
NRC-supported codes

Inventory analysis	ORIGEN
Transient scenario modeling	SAM, Nek5000
Molten-salt chemistry modeling	
Radionuclide release rates from salt	
Cover gas region analysis	MELCOR
Reactor building analysis	MELCOR
Offsite dispersion analysis	RASCAL, WinMACCS

Summary and Conclusions

- Regulatory expectations for mechanistic source term evaluations for advanced reactors
  - For some advanced reactor designs without cliff-edges, source term will include minor release from incidents more likely than BDBAs
  - Also to support EPZ reductions
- Trial LMR and HTGR MST calculations based on a combination of legacy DOE and NRC codes with identified gaps (data and codes):
  - Radionuclide release rates from failed fuel
  - Bubble transport (scrubbing) in LMRs
  - Retention in molten salt (MSRs, FHRs) and liquid metal coolants (LMRs)
- Emerging capabilities can play significant role in analysis of phenomena leading to fuel failure and radionuclide release
  - SAM, BISON, PRONGHORN, Nek5000, and new MSR chemistry modeling tools
  - Can remove the empiricism embedded in the legacy codes
- These capabilities interface with well-established radionuclide tracking capabilities of NRC codes like MELCOR and CONTAIN to support mechanistic source term assessments and Level 2/3 PRA

Questions?

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Concluding Remarks (ATF and Advanced Reactors)

August 21, 2018

DOE Briefing to ACRS:

Advanced Computer Models for Reactor Safety Applications

Notional ATF Code Maturity

	Doped-UO_2	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U_3Si_2	Non-cylindrical metallic fuel
Fuels	BISON	BISON	BISON	BISON	BISON	BISON
T-H	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD	CTF, CFD
Neutronics	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT	Shift, MPACT

Where Green = Mature capability exists, with limited validation

Where Yellow = basic capability exists, but key development required

Where Red = conceptional capability

Notional Non-LWR Code Maturity

	SFR	HTGR	FHR	MSR
Neutronics	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake
Fuels	BISON	BISON	BISON	In progress chemistry code
T-H	Nek-5000, SAM, SOCKEYE	Nek-5000, Pronghorn, SAM	Nek-5000, Pronghorn, SAM	Nek-5000, SAM
Source term	SAM, BISON	Pronghorn, BISON	SAM, Nek-5000, Pronghorn, BISON	SAM, Nek5000