

# **Official Transcript of Proceedings**

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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1 UNITED STATES OF AMERICA

2 NUCLEAR REGULATORY COMMISSION

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4 ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

5 (ACRS)

6 + + + + +

7 THERMAL-HYDRAULIC SUBCOMMITTEE

8 + + + + +

9 TUESDAY

10 AUGUST 21, 2018

11 + + + + +

12 ROCKVILLE, MARYLAND

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

17 COMMITTEE MEMBERS:

18 MICHAEL L. CORRADINI, Chairman

19 DENNIS C. BLEY, Member

20 WALTER L. KIRCHNER, Member

21 JOSE A. MARCH-LEUBA, Member

22 JOY L. REMPE, Member

23 GORDON R. SKILLMAN, Member

24 JOHN W. STETKAR, Member

25 MATTHEW W. SUNSERI, Member

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1 DESIGNATED FEDERAL OFFICIAL:

2 WEIDONG WANG

3 ALSO PRESENT:

4 STEVE BAJOREK, RES

5 JON CARMACK, INL

6 DAN FUNK, DOE NE

7 JESS GEHIN, INL

8 JASON HALES, INL

9 STEVE HAYES, INL

10 SHANE JOHNSON, DOE

11 RICHARD LEE, RES

12 ELIA MERZARI, ANL

13 DAVE POINTER, ORNL

14 EVERETT REDMOND, NEI

15 TANJU SOFU, ANL

16 CHRIS STANEK, LANL

17 JEFF WHITT, Framatome\*

18 RICH WILLIAMSON, INL

19 \*Present via telephone

20

21

22

23

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# CONTENTS

Introduction . . . . .	4
Opening Remarks . . . . .	6
DOE Codes for Accident Tolerant Fuels (ATF) in LWR Safety Analysis	
Introduction . . . . .	22
Fuel Performance Modeling for ATF . . . . .	34
Neutronics and Thermal Hydraulics for ATF . . . . .	128
DOE Codes for Advanced (non-LWR) Reactor Safety Analysis	
Introduction . . . . .	186
Neutronics Analysis Capabilities for Non-LWRs . . . . .	187
Fuels Modeling Capabilities for Non-LWRs . . . . .	224
Thermal-Hydraulic/System Analysis Capabilities for Non-LWRs . . . . .	255
Source Term Assessment Codes and Methods . . . . .	292
Concluding Remarks (ATF and Advanced Reactors)	328
Public Comment Period . . . . .	333
Adjourn . . . . .	347

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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

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1 entire meeting will be open to public attendance.

2 The subcommittee will gather information,  
3 analyze relevant issues and facts, and formulate  
4 proposed positions and actions as appropriate for  
5 deliberation by the full committee.

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

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

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

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

24 Secondly, since this is an information  
25 meeting and it's the first of what I expect will be a



1 couple, at least. There's no intention to write a  
2 letter report with the full committee.

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

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

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

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

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

20 MEMBER BLEY: If you push the button.

21 CHAIRMAN CORRADINI: If you push the  
22 button.

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



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

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

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

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

25 I believe today's briefings will provide



1 the committee a good overview of the current  
2 capabilities and limitations of the codes, and the  
3 analytical enhancements afforded by these codes as  
4 compared to the legacy codes currently used by both  
5 the regulator and licensees.

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

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

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

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

23 A very important strength of these teams  
24 is the multi-disciplined, multi-laboratory composition  
25 of the team membership. In the early days of our



1 program, we established an overarching success metric  
2 centered on creating modeling and simulation platforms  
3 that would be used by industry for both in-house  
4 computational needs and for the development of  
5 licensing products for submission to the Nuclear  
6 Regulatory Commission.

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

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

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

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

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

25 With limited federal budgets at both



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

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

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

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

22 The mere fact that the ACRS requested  
23 today's briefing demonstrates that the Department's  
24 nuclear energy computational efforts are being  
25 recognized by the U.S. technical community, and our



1 modeling and simulation program is on a success path.

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

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

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

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

25 MEMBER MARCH-LEUBA: Shane, Mike has gone



1 over on the procedures for the microphone and the fact  
2 that we speak for ourselves and not the committee. He  
3 forgot to tell you that we like to interrupt, and so  
4 get used to it. I'm going to be the first one to do  
5 it.

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

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

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

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

22 Make them available to industry, let  
23 industry decide whether or not they see merit in the  
24 code, whether they want to use the code moving forward  
25 whether it's for their in-house purposes only, whether



1 it's for, you know, informing where the companies are  
2 going with their development plans or hopefully, to  
3 ultimately be used in licensing space in interactions  
4 with the NRC.

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

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

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

22 But a vendor has to use a license code, I  
23 mean it has to have been reviewed and approved by the  
24 NRC. Certainly, not for everything and they will have  
25 to negotiation but anything that goes into tech specs



1 for the final plan has to have an approved version of  
2 the NCR with it.

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

6 MR. JOHNSON: Correct.

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

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

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

15 MEMBER REMPE: Why not?

16 CHAIRMAN CORRADINI: Well, hang on.

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

19 CHAIRMAN CORRADINI: Why don't we, before  
20 we get to the end game which I was figuring we're  
21 going to get here. But we're here before -- but I do  
22 think, I do think I want to hear from the DOE folks  
23 but I do thing Joy, and Jose are raising a question  
24 that somewhere today we've got to address which from  
25 the industry side who has decided to adopt whatever

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1 for their use in a particular application?

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

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

13 MR. JOHNSON: That's my understanding.

14 MEMBER REMPE: Okay --

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

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

23 Of course, they had a three year limit on  
24 LDRD, so it was for a different task on the code, they  
25 didn't break any laws. But there's been a lot other

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1 money beyond what DOE has put into the code, would it  
2 continue?

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

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

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

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

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

22 The interest level in users for the codes  
23 that we're developing vary in terms of the maturity  
24 level of the concept. And so that's something that we  
25 will discuss, but if existing tools are good enough



1 for near-term accident-tolerant fuel concepts, then  
2 there's less of an interest in using the code itself.

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

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

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

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

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

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



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

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

7 MR. STANEK: Of course.

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

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

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

23 So I think somewhere, whether you do it  
24 one by one or at the end, I think that's important for  
25 us to understand. Particularly, if you're not going



1 to give us the bottom line answer which is A is  
2 adopting X. Okay?

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

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

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

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

22 The requires a mechanistic source term and  
23 how ready those codes are that you're developing for  
24 analyses of mechanistic source terms are to be used in  
25 the licensing area is going to be very important for



1 any early movers of those advanced technologies.

2 Thank you, Mike.

3 CHAIRMAN CORRADINI: Okay.

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

6 CHAIRMAN CORRADINI: You get the last  
7 question.

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

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

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



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

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

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

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

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

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

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

25 CHAIRMAN CORRADINI: No, they're open.



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

2 MEMBER MARCH-LEUBA: Yes.

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

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

9 MR. JOHNSON: Yes.

10 CHAIRMAN CORRADINI: Okay.

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

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

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



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

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

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

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

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

25 Like I said, the amount of material we



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

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

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

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

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

24 MR. STANEK: Right.

25 MEMBER MARCH-LEUBA: But for a small



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

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

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

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

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

25 The user will then very likely, if not be



1 required to perform additional validation for a  
2 specific application and that will vary from  
3 application to application. We'll hear about a lot of  
4 that in the following presentations.

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

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

21 MR. STANEK: Correct.

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



1 same tool?

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

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

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

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

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

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



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

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

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

13 CHAIRMAN CORRADINI: Especially when?

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

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

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



1 opinion.

2 MEMBER REMPE: So I have --

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

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

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

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

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

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



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

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

8 MEMBER REMPE: Okay.

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

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

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

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

25 Or to be reviewed by the NRC and SER



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

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

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

14 MEMBER KIRCHNER: Thank you.

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

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

21 The reason we've done this is that you'll  
22 hear a number of different codenames referred to  
23 during the two presentations this morning. And the  
24 idea is that this table could be referred to as a  
25 guide to associate a code name with a specific



1 capability and its intended use.

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

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

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

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

19 CHAIRMAN CORRADINI: Recent, he went west.

20 MR. STANEK: Recently, in Idaho National  
21 Laboratory.

22 MEMBER REMPE: So I have question that  
23 probably Steve could answer later but whenever I see  
24 something like this you have MARMOT and BISON, but  
25 later like when you're closing slides you only talk



1 about validation of BISON.

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

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

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

9 MR. HAYES: I will talk about that.

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

12 MR. HAYES: I'll explain that.

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

20 MR. HAYES: Yes.

21 CHAIRMAN CORRADINI: Okay, fine.

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



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

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

4 MEMBER MARCH-LEUBA: You can get the  
5 mouse.

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

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

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

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

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

24 One slide on the multiscale, mechanistic  
25 modeling approach that DOE's taking in advanced fuels



1 modeling because this is the approach we've been  
2 working on for nine years and this is the approach we  
3 intend to use for ATF.

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

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

14 We're modifying BISON to address all the  
15 things that we see potentially coming, doped UO<sub>2</sub>,  
16 chrome-coated zirconium, FeCrAl cladding, silicon  
17 carbide cladding, silicide fuel, and non-cylindrical  
18 metallic fuels.

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

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



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

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

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

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

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

25          These are the three teams: Framatome,



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

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

8 So Framatome, primarily in the near-term  
9 is working on chrome-coated Zircaloy cladding and  
10 doped UO<sub>2</sub> concepts for improved thermal-connectivity  
11 and fuel performance.

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

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

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



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

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

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

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

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

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

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



1 the concepts.

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

5 MR. HAYES: Yes.

6 MEMBER BALLINGER: What is it?

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

13 MEMBER BALLINGER: So you pass.

14 MR. HAYES: I'll pass.

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

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

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



1 MEMBER REMPE: Okay.

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

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

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

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

24 ATF-2 is a prototypic PWR condition. So  
25 this is in a pressurized water loop in the ATR. It's



1 designed to test integral fuel and cladding concepts  
2 under PWR conditions.

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

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

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

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

16 MR. HAYES: So ATF-2 when it started at  
17 the end of May, not every concept was ready to take  
18 off at the same time. Westinghouse has coated  
19 cladding concepts in, Framatome has coated cladding  
20 and doped UO<sub>2</sub> in. So that's what's in it today. The  
21 first few rodlets.

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

25 MR. HAYES: So Framatome has all of their



1 stuff in ATF-2 currently. Westinghouse has coated  
2 Zirlo in there now. GE is expected to deliver FeCrAl  
3 cladding test articles in the upcoming year.  
4 Hopefully, by about January.

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

8 MEMBER REMPE: Okay, and then what data,  
9 I think I heard you should have a thermocouple in ATF-  
10 2? That's it?

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

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

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

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



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

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

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

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

7 CHAIRMAN CORRADINI: Okay.

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

10 CHAIRMAN CORRADINI: Okay.

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

15 MR. HAYES: So you see by --

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

18 MR. HAYES: I know.

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

23 MR. HAYES: Exactly, so all the vendors  
24 anticipated doing some testing in Halden, maybe quite  
25 a bit. Obviously, with the shutdown of Halden, Halden

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1 needs to be, these tests need to be redirected.

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

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

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

19 MR. HAYES: Exactly.

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

23 MR. HAYES: You know, I would challenge  
24 that a little bit. The in situ instrumentation is the  
25 preferred way to go. We don't question that. But as



1 we look at where to move things and get the same sort  
2 of data that's not Halden, it's not going to be able;  
3 it's not going to be possible to reproduce everything  
4 that Halden does somewhere else. We may have to skin  
5 the cat in a little bit different ways in some cases.

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

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

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

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

16 MR. HAYES: Okay.

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

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

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

24 MR. HAYES: So we are talking with the NRC  
25 along those lines ,and we dealt with it a little bit



1 in ATF-1 and ATF-2 fabrication of test articles which  
2 in some cases vendors did and some cases labs did, and  
3 in some cases, even universities contributed.

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

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

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

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

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

22 MR. HAYES: So as I've said, it is  
23 possible to have thermocouples in ATF-2 so we can  
24 approach it that way. We also, and I'll speak to this  
25 at the end, we also plan to do thermo-connectivity



1 measurements of irradiated fuel specimens in the hot  
2 cell.

3 MEMBER REMPE: Okay.

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

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

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

15 MEMBER BLEY: As someone wants them to be?

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

19 MEMBER BLEY: Okay.

20 MR. HAYES: And of course what's going to  
21 start up later this year is probably just some  
22 shakeout testing on UO<sub>2</sub> and Zirc. But next year, in  
23 '19, the first ATF concepts will be tested.

24 These will be unirradiated ATF concepts  
25 but the idea is as time progresses rodlets that are



1 condition in ATF-1 and ATF-2 will be tested in TREAT.

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

7 And then --

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

12 MR. HAYES: Correct.

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

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

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

24 MR. HAYES: I do not believe so.

25 MEMBER BALLINGER: Not even the chrome



1 coating?

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

7 MEMBER BALLINGER: None in Europe?

8 MR. HAYES: Well, so Framatome is doing,  
9 has done a lot of doped UO<sub>2</sub> testing in Europe. Okay,  
10 that is true. And Westinghouse may have done some  
11 chrome coated cladding in Europe.

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

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

17 MEMBER REMPE: Later in your talk, I  
18 thought I saw some comparisons of data from the doped  
19 UO<sub>2</sub> but it was not with the cladding for ATF is what  
20 I was kind of wondering.

21 MR. HAYES: That's correct.

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

24 MR. HAYES: Right. So this is an overview  
25 of the irradiation testing that DOE is performing and



1 plans to perform on ATF concepts. There's also LOCA  
2 testing that can be performed outside of the hot cell,  
3 outside of the reactor in a hot cell.

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

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

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

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

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

24 MR. HAYES: For GE?

25 CHAIRMAN CORRADINI: Yes.



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

3 CHAIRMAN CORRADINI: It hasn't been  
4 revealed?

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

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

9 MR. HAYES: I do not know.

10 CHAIRMAN CORRADINI: It had a nice name.

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

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

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

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

25 MR. HAYES: Idaho.



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

3                   MR. HAYES: Exactly.

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

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

8                   MEMBER REMPE: Okay.

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

13                  MEMBER REMPE: Okay.

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

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

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

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

24                  CHAIRMAN CORRADINI: So it's in the ATF-3  
25 plan to do power bursts as well as to do slow-ramp



1 ups and ramp downs? You know what I'm asking?

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

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

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

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

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

20 MEMBER REMPE: You have PALM cycle with --

21 MR. HAYES: Using a PALM-type device.

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

24 MEMBER REMPE: Our actual locating --

25 MR. HAYES: So we're into --



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

3 MR. HAYES: Okay.

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

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

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

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

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

19 It's not clear you can get all the way  
20 there in the same assembly design so GE, I think if  
21 you talk to them, they might say they're looking at an  
22 alternative assembly design to try to save a load of  
23 5 percent.

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



1       happen.

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

7                   MR. HAYES:   And transportation.

8                   CHAIRMAN       CORRADINI:               --       and  
9       transportation.

10                  MR. HAYES:   That's right.

11                  CHAIRMAN CORRADINI:   Okay, fine.

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

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

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

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



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

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

10                  MEMBER REMPE: May not be the second  
11 thing?

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

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

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

20                  MEMBER REMPE: The control rods are going  
21 to stay.

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

24                  MEMBER REMPE: I mean at TMI, as Mike  
25 mentioned the control rods went, so I'm real curious



1 because we used to talk about after the tolerance.

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

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

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

9 MR. HAYES: The last one just so I don't  
10 forget, Framatome is working this area as well so  
11 Framatome has already had some doped UO<sub>2</sub> fuel in  
12 LaSalle for a period of time.

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

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

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

21 MR. HAYES: It was nothing unorthodox.

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

24 MR. HAYES: It was not the ATF cladding.

25 MEMBER REMPE: Okay.



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

2 CHAIRMAN CORRADINI: You did a great job.

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

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

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

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

24 And this remains to be seen, but the  
25 proposition is they may require less data for

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1 validation. We're not saying no data; we're saying  
2 less data.

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

5 MR. HAYES: Exactly.

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

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

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

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

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



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

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

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

13          MR. HAYES: Yes.

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

16          MR. HAYES: Yes and no.

17          CHAIRMAN CORRADINI: -- okay.

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

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

21          MR. HAYES: You're right.

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

24          MEMBER BLEY: Before you go ahead, Steve  
25          --



1 MR. HAYES: Yes.

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

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

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

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

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

17 MR. HAYES: But to be honest --

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

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

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

25 CHAIRMAN CORRADINI: I mean, I think where



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

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

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

11 CHAIRMAN CORRADINI: Then you would  
12 planted.

13 MEMBER BLEY: Maybe a lot yes.

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

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

18 MR. HAYES: I'm not ignoring you.

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

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

25 And the real advance in recent years has



1       been if I know what the microstructure looks like,  
2       even more so than chemistry, if I know what the  
3       microstructure looks like then I can accurately tell  
4       you what the properties of material are going to be  
5       and what the fuel behaviors are going to be.

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

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

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

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

25              And then we build new models based on that



1 understanding which we implement in BISON. Okay? It  
2 is possible to run MARMOT and BISON in a couple  
3 fashion, but that's the main way of doing business.

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

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

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

16 MEMBER BLEY: And a lot of that --

17 CHAIRMAN CORRADINI: So Steve in MARMOT a  
18 lot of it is presumed in advance, like the  
19 microstructure I would assume. So that you can evolve  
20 --

21 MR. HAYES: Exactly.

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

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



1 things.

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

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

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

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

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

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

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

25 MEMBER REMPE: Nothing like it at all.



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

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

5                   MR. HAYES: Pardon me?

6                   MEMBER MARCH-LEUBA: Does it not reproduce  
7 today?

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

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

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

17                   MR. HAYES: Or better.

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

22                   But right now, frankly, if you're saying  
23 you're validated, you have the same problem that you'd  
24 have with FRAPCON that you have to stay between the  
25 upper and lower bounds for where you've validated it

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1 because it sounds to me, and maybe I'm putting words  
2 in your mouth, you can't get all the data you need  
3 from MARMOT to validate those models you put into  
4 BISON.

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

7 CHAIRMAN CORRADINI: But I mean --

8 MR. HAYES: Not for a regulatory  
9 discussion.

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

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

18 CHAIRMAN CORRADINI: Right.

19 MR. HAYES: Exactly.

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

22 MR. HAYES: Exactly, so there is truth to  
23 what you're saying there. The mechanistic models that  
24 are developed using MARMOT and these lower-length  
25 scale techniques, we are implementing them in BISON

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1 and then doing the bulk of our validation at the BISON  
2 level.

3 But someone else could implement those  
4 models in another code.

5 CHAIRMAN CORRADINI: Okay.

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

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

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

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

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

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



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

6           MEMBER REMPE:   Such as.

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

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

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

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

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1           So and if it's capturing margin, how much  
2           margin do you get back, do you think you're going to  
3           get back. Like, for the example, in the infamous  
4           50.46 hit area, how much margin do you think you're  
5           going to get?

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

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

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

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

22          But a tool with enough physics into it  
23          they can do some meaning exploration. That's the way  
24          DOE, this is the way the lab people use it. We use  
25          BISON in some of our advanced fuel development areas



1 like metal fuels for fast reactors.

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

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

8 MR. HAYES: Right.

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

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

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

16 MR. HAYES: Exactly.

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

23 You just need to go pick it up and go have  
24 the conversation with the NRC. We're taking it far  
25 enough to give that vendor confidence. This is really

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1 a tool that can provide me some benefit.

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

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

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

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

18 MEMBER KIRCHNER: So how well --

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

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

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

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

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

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

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

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

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



1 break.

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

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

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

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

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

25 CHAIRMAN CORRADINI: If we get to it



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

5 MR. HAYES: Exactly.

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

9 MR. HAYES: Right.

10 CHAIRMAN CORRADINI: The one that confuses  
11 me is --

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

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

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

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

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

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



1 different?

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

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

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

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

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

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

23 CHAIRMAN CORRADINI: That's fine. Okay.

24 MEMBER REMPE: So you can't do melting but  
25 do you, I mean, fuel starts degrading before it



1 reaches melting temperatures with cladding, you can't  
2 even liquefy and have cladding fuel interactions with  
3 the Zircoloy. Right? Or the ARMOUR or whatever it  
4 is.

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

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

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

21 There's no geometry it can't handle so if  
22 your ATF concept is non-cylindrical, no problem for  
23 BISON. It was built from the very beginning to go  
24 after multiple fuel packs. So the way the models and  
25 the properties and the behavior models are implemented

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1 in the code, it's very easy to introduce new models  
2 that have an application to a particular fuel or not.

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

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

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

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

22 You do not need a high-performance  
23 computer to run BISON. You can run it on your desktop  
24 computer. Most of our developers and users do that,  
25 as long as your problem's simple enough. But if you

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1 want to develop or need to develop complicated,  
2 difficult problem and run it in 3D or something like  
3 that BISON is designed to be thrown out on high-  
4 performance machine and operate very efficiently.

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

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

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

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

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

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

25 MR. HAYES: Oh, yes.



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

6                   MR. HAYES: If someone asks for it.

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

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

13                  CHAIRMAN CORRADINI: So how are you going  
14 --

15                  MR. HAYES: NRC, NRC.

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

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

24                  All tests must pass prior to merging it  
25 with the official version if anything gets flagged as



1 a problem it won't be merged until though programs are  
2 resolved. Again, hitting this issue of NQA-1 of BISON  
3 is regularly per NQA-1 standards, and it's always  
4 satisfactory.

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

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

15 So what we're talking about is for UO<sub>2</sub> and  
16 Zircaloy. You can see her 75 integral and ramp type  
17 experiments are in the assessment database. A 47  
18 LOCUS matching RIAs. I just give you these numbers.

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

23 Now as is already mentioned some vendor's  
24 come along and they have proprietary that DOE, in  
25 general, doesn't have access to. And they do some



1 additional validation, so there are some assessment  
2 reports out there that are proprietary that have  
3 additional data. But what you'll find in here is the  
4 open stuff that the DOE has done.

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

10 Have you had any interference with it?

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

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

22 And so those tend to resolved right away  
23 so even though there's not going to be a frozen  
24 version with a published BISON assessment report until  
25 the end of the year, on any given day of that year the



1 version of BISON that is operating is essentially  
2 validated to that state.

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

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

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

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

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

22 MEMBER REMPE: Okay.

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

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

4 Company X and Y may change the correlation  
5 --

6 MR. HAYES: They may.

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

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

12 CHAIRMAN CORRADINI: Right.

13 MEMBER REMPE: Right.

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

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

21 MR. HAYES: That right.

22 CHAIRMAN CORRADINI: Okay.

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



1 INL published.

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

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

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

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

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

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



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

4 Is it have or is it twice?

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

7 MR. HALES: About the same.

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

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

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

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

21 MR. HALES: I'm Jason HALES from INL.  
22 This answer's going to pretty much a letdown because  
23 I can't answer for FRAPCON. I don't know how it  
24 compares honestly, what I do know is that Steve said,  
25 did he compare BISON results to the experimental data



1 it compares very well and we're comfortable with that.

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

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

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

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

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

24 MR. HAYES: So performance is not measured  
25 on the same scale for every property. So for fuel



1 temperature, you typically look at plus or minus 10  
2 percent. Okay, for fission gas release you typically  
3 look at plus or minus a factor of two. But this is  
4 true for all codes.

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

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

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

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

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

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

24 But over time, you know, those proprietary  
25 and model and behavior models get updated with better



1 models. That doesn't mean you can't still select the  
2 MAP probe data if that's what you want to do.

3 MEMBER REMPE: Oh, okay.

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

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

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

12 MR. HAYES: Yes.

13 MR. HALES: And it is well defined?

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

16 MEMBER MARCH-LEUBA: If it gets approved  
17 now, approved SER, it will have a bunch of  
18 limitations. And yes, if I were you, you can predict  
19 UO<sub>2</sub> doesn't mean you can predict the silicide.

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

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

25 MR. HAYES: Exactly, if all this was to



1 set the stage for our model enhancements for ATF to  
2 say that they BISON we have, and the multiscale  
3 modeling approach we've has borne out good results  
4 applied to UO<sub>2</sub>.

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

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

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

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

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

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



1 performance code.

2 It hasn't reached its final state even  
3 for UO<sub>2</sub> and Zircoloy we're continuing to develop new  
4 and improvement mechanistic models that are going to  
5 improve it.

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

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

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

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

25 Now the HIP ended in 2017, but that



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

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

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

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

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

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

19 MR. HAYES: No.

20 MEMBER REMPE: One of the vendor fuels?

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

23 MEMBER REMPE: Just for me? Okay.

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

25 MEMBER REMPE: Okay, I thought it would



1 be an easy answer.

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

6 We're using the approach that DOE's been  
7 using in the area of fuels for the last nine years.  
8 And it's sort of a four-pronged approach, and that is  
9 any time you start with a new fuel in the BISON  
10 framework, you just stand up basic properties and  
11 model for behavior using anything that you have, a  
12 legacy models, or adapt UO<sub>2</sub> models or there may be  
13 existing models for some of these materials.

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

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

23 And so we run DAKOTA with BISON regularly  
24 to do sensitivity analyses especially when we're  
25 starting in a new fuel. We do sensitivity analyses



1 to help us prioritize what properties or what  
2 behavior models for a given fuel type have the  
3 biggest effect.

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

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

13 So the way the HIP was written and the  
14 way it started it focused mostly on these two  
15 systems. But before the HIP was over, coded,  
16 cladding concepts and doped UO<sub>2</sub> were emerging as  
17 interesting concepts as well.

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

22 MEMBER REMPE: So again I was just trying  
23 to understand what the objective of the high-impact  
24 problem was and it sounds like it wasn't really an  
25 analysis problem it was more trying to expand the



1 capabilities of BISON to address what was perceived  
2 to be an accident-tolerant fuel assisted time.

3 It was more model development --

4 MR. HAYES: That's exactly right.

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

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

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

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

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

21 MEMBER REMPE: And this would hopefully  
22 help you focus?

23 MR. HAYES: We have some tables coming  
24 that try to summarize where we stand for the various  
25 concepts. And not every box is checked on every



1 concept, you're right.

2 Okay, so this is the table that attempts  
3 to give the 30,000-foot view of where we are on all  
4 these categories of ATF features from doped  $\text{UO}_2$ ,  
5 coated cladding, FeCrAl cladding, silicon carbide,  
6 silicide fuel and metallic fuel.

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

11 For some, it's better than others. For  
12 doped  $\text{UO}_2$  fuel, we've spent a lot of time looking at  
13 the fission gas release modifications needed. Much  
14 less so for the mechanical response but we expect  
15 there to be some, so we're not completely there.

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

24 So you can see the yes or no, on the  
25 evaluation, on base irradiations, so we don't have any



1 irradiation data yet on coated cladding or silicon  
2 carbide as a cladding, although, there's a lot  
3 irradiation data on silicon carbide.

4 CHAIRMAN CORRADINI: Was the doped UO<sub>2</sub>  
5 fuel irradiations vendors supplied or you did?

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

8 MR. STANEK: The answer's both, so there  
9 are priorities, as far as we understand there are  
10 proprietary irradiations that have been done on doped  
11 UO<sub>2</sub> as Ron was mentioning, in Europe.

12 But there are open Halden tests that have,  
13 in particular, fission gas release data for doped UO<sub>2</sub>.

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

16 MEMBER KIRCHNER: Just looking at the  
17 right-hand column, it's improved fission gas,  
18 diffusivity for fission gas, are you seeing much later  
19 fission gas release with doped UO<sub>2</sub> fuel?

20 MR. HAYES: We're seeing lower.

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

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

25 MEMBER KIRCHNER: I could see you might be



1 improving your diffusivity model but are you seeing  
2 higher release of fission gas and doped fuel?

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

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

7 MR. HAYES: This is about the model.

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

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

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

18 Or is this DOE decides how much each user  
19 gets?

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

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

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

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

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

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

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

21          Am I understanding this though?

22          MR. HAYES: Similar.

23          CHAIRMAN CORRADINI: Okay, fine.

24          MR. HAYES: Faster and better, similar.

25          CHAIRMAN CORRADINI: So if you were to go



1 to, well, now let me ask my second question. So maybe  
2 I misheard Chris when he said it earlier. Your  
3 industrial support group or NEI support group, I'm not  
4 sure what it is.

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

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

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

17 CHAIRMAN CORRADINI: Oh, okay, fine.

18 MR. HAYES: So that group does not --

19 CHAIRMAN CORRADINI: Okay, I misheard.

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

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

23 MR. HAYES: Exactly.

24 CHAIRMAN CORRADINI: Framatome,  
25 Westinghouse, and GE, which one of them has decided to



1 take BISON as their base tool for their safety  
2 analysis justification for ATF?

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

5 CHAIRMAN CORRADINI: Why?

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

9 CHAIRMAN CORRADINI: Oh, fine.

10 MR. HAYES: -- BISON with.

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

13 MR. HAYES: They have now announced --

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

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

19 CHAIRMAN CORRADINI: So they're  
20 evaluating.

21 MR. HAYES: They're evaluating BISON.

22 CHAIRMAN CORRADINI: Okay. Okay. Thank  
23 you.

24 MR. HAYES: Okay. So that's the high  
25 level overview. And now we're going to have a status



1 on each one of the concepts in particular.

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

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

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

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

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

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



1 But in the area of --

2 MEMBER REMPE: Is that the MARMOT?

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

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

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

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

16 MR. HAYES: There's no MARMOT model.

17 MEMBER REMPE: -- informed modeling.

18 MR. HAYES: Exactly.

19 MEMBER REMPE: Okay.

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

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

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



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

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

6 CHAIRMAN CORRADINI: Oh, thermal  
7 expansion.

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

11 MEMBER REMPE: So --

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

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

19 MR. HAYES: That's right.

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

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

25 MEMBER REMPE: But in some of these



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

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

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

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

11 MEMBER REMPE: Okay.

12 MR. HAYES: -- those considerations.

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

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

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

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1 BISON is predicting it or reproducing it fairly well.

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

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

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

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

22 Chrome-coated cladding, so this was  
23 actually added later in the process than you might  
24 imagine. But there's certainly functional models now  
25 in BISON to model chrome-coated cladding. We're

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1 beginning to get experimental data that we need to do  
2 assessments.

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

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

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

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

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

23 And in these two cases, the coating that  
24 was added was FeCrAl. Now, none of the vendors are  
25 looking at FeCrAl as a coating. Although, MIT has a

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1 research project where they're looking at FeCrAl as a  
2 potential coating.

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

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

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

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

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

25 This is an area where we have lower length



1 scale, you know, mechanistic model development going  
2 on in the area of mechanical properties and creep.

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

8 MR. HAYES: Understood.

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

11 MR. HAYES: We are aware of it.

12 CHAIRMAN CORRADINI: Okay.

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

16 CHAIRMAN CORRADINI: Okay, fine.

17 MR. HAYES: -- this activity.

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

23 MR. HAYES: FeCrAl cladding --

24 CHAIRMAN CORRADINI: Well, that the  
25 industry --



1 MR. HAYES: -- or all of these?

2 CHAIRMAN CORRADINI: All --

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

5 CHAIRMAN CORRADINI: Okay.

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

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

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

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

23 And so this is an area where BISON is  
24 fairly mature. And quite a bit of lower length scale  
25 model development work has been done, especially in



1 the area of thermal conductivity, swelling, fission  
2 gas release.

3 CHAIRMAN CORRADINI: Are there any  
4 experiments on oxidation?

5 MR. HAYES: Of silicide fuel?

6 CHAIRMAN CORRADINI: Yes, I've got --

7 MR. HAYES: Yes, there are.

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

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

13 CHAIRMAN CORRADINI: Okay.

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

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

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

23 So this would be at a center line of a  
24 fuel pellet and the surface of a fuel pellet. And  
25 this is what the thermal conductivity profile would

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1 look like un-irradiated. And you can see degraded to  
2 a certain burn-up level this is what the model  
3 predicts.

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

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

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

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



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

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

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

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

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



1 that are being developed as well.

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

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

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

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

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

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



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

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

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

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

21          So we have already, DOE has taken the  
22          initiative to partner with the Halden staff moving  
23          forward. And they're going to help us with those  
24          issues, instrumentation and how to appropriately  
25          implement them wherever these experiments go. We



1 don't just assume that we're going to get that right  
2 without their help.

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

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

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

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

24 But the bottom line here is fuel behavior  
25 data needed for ATF validation is being generated. I

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1 mean, what you see here is silicide fuel in the hot  
2 cell in Idaho. It's low burn-up. It's at about 10  
3 gigawatt-days per ton. But we're beginning to get  
4 data on it.

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

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

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

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

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

25 I think Shane said in his opening remarks



1 that we don't believe modeling and simulation is going  
2 to replace experiments, not at all. We still need  
3 experimental data. And as someone mentioned or  
4 alluded to earlier, we still need experimental data  
5 that's going to bound operations.

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

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

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

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

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1 happens.

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

6 MEMBER KIRCHNER: Steve, I was --

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

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

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

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

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

19 MR. HAYES: Well --

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

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

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

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

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

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

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

25 MEMBER REMPE: So, and this has been going



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

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

11 MEMBER REMPE: It's --

12 MR. HAYES: -- very well.

13 MEMBER REMPE: Okay.

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

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

23 MR. HAYES: Some, yes.

24 MEMBER BLEY: Can you give me a little  
25 idea about how much of that you've done? And when



1 you've done it, I can think of three possible  
2 outcomes. You do it and look and you say, yes, it  
3 predicted pretty well. Or you look and say  
4 something's off. And you dig in and figure out what  
5 it is. And maybe you change --

6 MR. HAYES: -- on the model.

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

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

14 MEMBER BLEY: I hope so.

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

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

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

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

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

8 MEMBER BLEY: Yes.

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

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

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

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1 to the hot cell.

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

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

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

15 MR. HAYES: Yes.

16 CHAIRMAN CORRADINI: Are we there almost?

17 MR. HAYES: We're there.

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

22 CHAIRMAN CORRADINI: Yes.

23 MR. STANEK: And I think, generally  
24 speaking, even for phenomena that we think we know  
25 exceptionally well, we always seem to find something



1 very fundamental that we didn't understand.

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

6 But what it's really doing is setting  
7 this, allowing us as a, have a springboard into ATF  
8 and advanced reactor fuel to really understand what  
9 those, what that missing physics is, so now we can  
10 focus on those things that we didn't fully understand  
11 --

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

18 MR. HAYES: Oh, sure, sure.

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

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



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

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

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

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

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

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

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

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

23          CHAIRMAN CORRADINI: Briefly.

24          MR. HAYES: Briefly.

25          MEMBER KIRCHNER: Do you see the



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

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

5 (Laughter.)

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

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

12 MEMBER KIRCHNER: Right.

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

16 MEMBER KIRCHNER: Right.

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

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

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1 MEMBER KIRCHNER: Thank you.

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

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

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

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

15 CHAIRMAN CORRADINI: Just one of many.

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

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



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

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

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

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

23           Fuel temperature distributions, also rod-  
24 by-rod, either directly using a code like BISON or  
25 using BISON to generate fuel temperature tables that



1 can go in so we can get direct rod-by-rod.

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

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

11 As I mentioned, it's primarily developed  
12 for LWR's current operating plants. The emphasis,  
13 therefore, has been on zirconium clad UO<sub>2</sub> fuel in  
14 PWRs, primarily for operational performance and safety  
15 issues.

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

20 And then, more on the safety issues,  
21 looking at reactivity insertion accidents, LOCA, and  
22 DNB are sort of the hallmarks of things that we've  
23 been looking at for UO<sub>2</sub> fuels.

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



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

4 MEMBER KIRCHNER: Yes.

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

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

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

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

23 Overall applicability to accident-tolerant  
24 fuel, so these codes, when you look at the neutronics  
25 and thermal hydraulics, they've been developed and



1 demonstrated for LWRs, particularly PWR applications.  
2 The BWR capability is not as matured.

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

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

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

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

23 When it comes to the thermal hydraulics  
24 subchannel, it's generally a bit more cruder. And  
25 this is where we rely more on CFD directly or CFD

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1 informing the subchannel. And I'll give an example of  
2 that.

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

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

10 MR. GEHIN: Right.

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

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

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

19 MR. GEHIN: We would use --

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

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

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

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

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

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

21 MEMBER BLEY: Mic.

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

25 So, normal operation AOOs and selected



1 DBAs --

2 MR. GEHIN: Yes.

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

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

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

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

13 CHAIRMAN CORRADINI: Okay.

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

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

21 MR. GEHIN: Absolutely.

22 CHAIRMAN CORRADINI: Okay, fine.

23 MR. GEHIN: And --

24 CHAIRMAN CORRADINI: Just wanted to check.

25 MR. GEHIN: Yes. Now, we'll talk a little



1 bit about that. We are seeking to develop improved  
2 models. But they're all going to have to be --

3 CHAIRMAN CORRADINI: Okay.

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

6 CHAIRMAN CORRADINI: Okay, thanks.  
7 Thanks, Jess.

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

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

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

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



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

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

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

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

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

25           It lists CFD here. We've used commercial



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

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

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

8 CHAIRMAN CORRADINI: Okay, fine.

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

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

20 MR. GEHIN: That types of thing, the flow,  
21 you know, the impacts of mixing vanes --

22 CHAIRMAN CORRADINI: Okay.

23 MR. GEHIN: -- inflow, things that  
24 subchannel generally doesn't have models to pick up  
25 that type of detail, yet you'd want to try to reflect

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1 that at a whole core level.

2 CHAIRMAN CORRADINI: Thank you.

3 MEMBER REMPE: So --

4 MR. GEHIN: Yes.

5 MEMBER REMPE: -- if, you mentioned  
6 earlier you'd couple to TRACE if you were going to do  
7 the thermal hydraulics. If you do it like an ATWS-I,  
8 would you get rid of the PARCS part of TRACE and use  
9 your stuff that you've developed? And has that been  
10 figured out yet or that's in the future?

11 MR. GEHIN: You can do that. It sort of  
12 depends on what you believe is important and how you  
13 want to do your analysis.

14 For example, the typical analysis for a  
15 LOCA, you usually don't model every rod in the core.  
16 You bound that with a peak rod and maybe average rod.  
17 And that can be done by coupling BISON with TRACE, and  
18 you choose those rods and rod towers.

19 We've been discussing but haven't really  
20 pursued significantly coupling the full rod-by-rod  
21 detail yet with the systems code to do that type of  
22 analysis.

23 But it's something that we'd be interested  
24 in, something that CTF with some, a little bit of  
25 development work could be applied to that type of area



1 as well if you want to do the full detail. It's  
2 really up to the user in that case to decide whether  
3 they want to go after that level of detail.

4 MEMBER REMPE: So there's not a firm plan  
5 on what the approach will be yet.

6 MR. GEHIN: Well, the current -- and I've  
7 got a slide on this. So maybe we'll talk --

8 MEMBER REMPE: Wait till later. That's  
9 fine.

10 MR. GEHIN: I'll tell you what we've been  
11 doing. And I think it's correct to say there isn't a  
12 decided plan on the approach for that. Whereas, I  
13 think that, you know, maintaining connections with the  
14 current methodology but with more advanced tools seems  
15 to be what's being discussed more.

16 Okay. I'm going to talk a little bit of  
17 details about each of the codes. MPACT is a 3D core  
18 pin-resolved neutronics code. So this is optimized  
19 for determining pin-by-pin neutron flux distribution.

20 And what I mean by pin-by-pin is that the  
21 fuel rod, and if you sort of look at the diagram in  
22 the upper right, each fuel rod is modeled in detail at  
23 the rod level for each core. So this is modeled with  
24 transport theory, method-of-characteristics, which is  
25 a general geometry transport, which is why I'm saying

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1 it can be extended to other fuel types so that we  
2 really only applied it to cylindrical.

3 This is applied in a 2D plane across the  
4 whole reactor, where most of the neutronics hydrogen-  
5 80 is. So, if you have differing fuel pins, you have  
6 burnable absorbers, you have control rods, all that  
7 hydrogen-80, if you look on a plane, you'll see that  
8 hydrogen-80.

9 If you do things like put in, you know,  
10 different fuel rods or different fuel assemblies,  
11 those can be directly modeled with this pin-by-pin  
12 capability. And it's a pretty efficient way to do  
13 that.

14 Now, these pins are, of course, coupled  
15 with a 3D coarse mesh solution. And so you can get a  
16 full 3D rod-by-rod solution looking at all the local  
17 hydrogen-80s?

18 As I mentioned, currently models  
19 cylindrical fuel rods without standard approximations  
20 that are made in industry codes. The industry methods  
21 are typically based on nodal methods where you model  
22 the full geometry detail only at the lattice level.  
23 So we model it at the full core level.

24 Pin powers, we compute explicitly. We  
25 don't do pin, we don't need to do pin power



1 reconstruction. We don't homogenize anything.

2 There's a direct feedback calculation.  
3 There's no cross section functionalization. If you're  
4 familiar with that, the typical industry approach will  
5 functionalize the cross section data as temperature,  
6 density, boron concentration --

7 CHAIRMAN CORRADINI: You mean a series of  
8 --

9 MR. GEHIN: -- and make a table. So we  
10 just do this directly. So there's no approximations  
11 on the, you know, the assumed form of those functional  
12 bits.

13 And all of this is to get this rod-by-rod  
14 detail. Because of the problems that I mentioned  
15 here, the areas that we're working on are all rod-by-  
16 rod phenomena that we wanted to capture. And we want  
17 to do that in a way that's beyond the capabilities of  
18 what already exists. Our emphasis --

19 MEMBER KIRCHNER: Can I here, Jess? But  
20 I assume you use N death 7 or whatever.

21 MR. GEHIN: Yes, we use the latest cross  
22 section libraries. I don't want to get too much in  
23 the detail. But if you look at the processing of the  
24 libraries that's done using standard tools, we use  
25 standard resonance processing approaches, a subgroup



1 method that actually is applicable for these types of  
2 problems with the hydrogen-80. But we keep all those  
3 models up to date.

4 I had mentioned the emphasis has been on  
5 PWR development. There are BWR capabilities, but they  
6 have not been developed and validated to the extent of  
7 the PWR capabilities. Those are in progress and  
8 planned to continue.

9 And then, you know, these physics methods,  
10 as I mentioned, are fully applicable to ATF. So, when  
11 you look at transport with fine energy group with  
12 general geometry, there really aren't limitations  
13 there.

14 The limitations or the things that you'd  
15 want to look at is to ensure the neutron cross section  
16 data and the inputs meet your requirements. For most  
17 cases, they're generally acceptable.

18 CHAIRMAN CORRADINI: I guess as I'm --  
19 I'll ask the question I asked about the fuel. So what  
20 industries have adopted MPACT?

21 MR. GEHIN: So it's in an assessment  
22 phase. I'd say it's the same sort of situation.  
23 Westinghouse has been a partner in developing this.  
24 So they're --

25 CHAIRMAN CORRADINI: Well, I guess, I



1 thought you were going to tell me Westinghouse.

2 MR. GEHIN: Yes.

3 CHAIRMAN CORRADINI: But they have not  
4 switched over.

5 MR. GEHIN: I mean, yes, I mean, it's  
6 really their call to decide when they switch over.  
7 They're in an assessment phase.

8 So one of the -- you know, there are  
9 existing tools, of course, they use. And they're  
10 looking at these advanced tools. And one of you  
11 pointed out to determine is there the value there to  
12 invest the --

13 CHAIRMAN CORRADINI: Okay.

14 MR. GEHIN: -- the money into bringing  
15 these tools in.

16 We've worked very hard to make these tools  
17 usable and accepted by industry. But in the end, it's  
18 their decision --

19 CHAIRMAN CORRADINI: Okay.

20 MR. GEHIN: -- whether they do that. And  
21 we've been very fortunate to work with Westinghouse  
22 and other industry organizations to get data and  
23 feedback.

24 We also have an industry council. There's  
25 about 20 members of that, including vendors and



1 utilities, that provide strong feedback as well and  
2 data as well.

3 CHAIRMAN CORRADINI: Okay.

4 MR. GEHIN: In fact, an example of the  
5 data is in the lower right. You know, this is the  
6 typical type of measurements you get as flux maps from  
7 an operating reactor that we then can compare to. You  
8 don't get the detailed pin-by-pin, of course, from the  
9 reactor.

10 But these flux maps, and we've got a lot  
11 of them now for a lot of reactor types, as I have  
12 showed, have been very valuable to understand the  
13 deployments of the codes.

14 CHAIRMAN CORRADINI: So what we're looking  
15 at is a subassembly somewhere in the core and the  
16 little wiggles are the axial variation?

17 MR. GEHIN: Yes. And so what this is,  
18 it's a representation of a quarter core of a PWR.

19 CHAIRMAN CORRADINI: Okay.

20 MR. GEHIN: There are --

21 CHAIRMAN CORRADINI: Okay.

22 MR. GEHIN: -- detectors in various  
23 locations around the core, and these move up and down.

24 CHAIRMAN CORRADINI: Okay.

25 MR. GEHIN: These are flux maps done once



1 a quarter or so. They've been mapped into one  
2 quarter.

3 And this is kind of small and blurry, but  
4 we've got numerous maps where we've compared our  
5 calculations directly to measured results. You can  
6 look at the RMS errors and show that we're getting  
7 very good predictions. So we're pretty comfortable  
8 with that.

9 The Monte Carlo capability, you're  
10 probably familiar with Monte Carlo codes and some of  
11 the more, the ones that are a little bit out, used  
12 more like MCMP.

13 This shift is a Monte Carlo code in some  
14 ways similar to MCMP except it's been designed to  
15 scale on very large computers. And the value to that  
16 is that we can then run enough particle histories to  
17 get statistical uncertainties down at a finer  
18 resolution to areas that are less than one percent or  
19 half percent so we can ensure that it's not the  
20 statistical uncertainties affecting the comparisons.

21 Some of these simulations take, you know,  
22 a trillion-particle histories, which are large scale  
23 simulations. And so the way we've used this code is  
24 to get the best possible answer we can to help verify  
25 the deterministic code.

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1                   And in some cases, you can see here the  
2                   distribution for AP1000 provided evidence that the  
3                   MPACT code, deterministic code, does give good local  
4                   details that can't be measured.

5                   So Monte Carlo is the most direct physics,  
6                   neutronics physics simulation capable of detailed 3D  
7                   geometry without approximation, representation of  
8                   fuel, ex-core geometry. So we use this looking at  
9                   vessel and ex-core measurements.

10                  We can get the detailed isotopics and  
11                  temperature distributions from MPACT to put it into  
12                  this so we can do verifications at state, you know, at  
13                  different burn-up state points as well.

14                  Combined, as I mentioned, with large scale  
15                  computer, this provides the best available means to  
16                  verify more approximate physics models. And it's been  
17                  widely used with that. As I mentioned, we use this to  
18                  verify MPACT for many cases, including the AP1000 case  
19                  showed there.

20                  MEMBER    MARCH-LEUBA:       What   thermal-  
21                  hydraulics have you used for the Monte Carlo?

22                  MR.   GEHIN:       It's   frozen.       So   those  
23                  conditions are frozen. So we run MPACT coupled with  
24                  CTF with fuel temperature either at tables or BISON.  
25                  At a state point, we'll take those conditions, put



1       them in Monte Carlo.

2               There are other programs that are looking  
3       at coupling Monte Carlo to CFD and other things. But  
4       for our purposes for applications, those are beyond  
5       the timeframe.

6               MEMBER MARCH-LEUBA:   So MPACT and CF use  
7       the same TH.

8               MR. GEHIN:   They use the same -- no, it's  
9       -- so, when you run the Monte Carlo calculation,  
10      you're not running a, at least for this application,  
11      not running a coupled neutronics thermal hydraulics.

12              MEMBER MARCH-LEUBA:   Right.

13              MR. GEHIN:   You're freezing the thermal  
14      hydraulics.

15              MEMBER MARCH-LEUBA:   You run --

16              MR. GEHIN:   You run MPACT, CTF --

17              MEMBER MARCH-LEUBA:   Running, but it's  
18      fragment TH and put it into Monte Carlo.

19              MR. GEHIN:   That's right.

20              MEMBER MARCH-LEUBA:   Okay.

21              MR. GEHIN:   So, like I said, there are  
22      programs looking at coupling Monte Carlo and TH, but  
23      that was beyond what we felt we could achieve in our  
24      program --

25              CHAIRMAN   CORRADINI:       From a safety



1 analysis standpoint, are you just -- no, let me ask  
2 the question differently.

3 If I were a vendor or an owner/operator,  
4 am I essentially identifying margin and then deciding  
5 what I can economically do with the margin? I mean --

6 MR. GEHIN: You can do that.

7 CHAIRMAN CORRADINI: -- this is not safety  
8 analysis I guess is what I'm kind of saying in a  
9 backward way.

10 MR. GEHIN: Yes, so this, yes, and so this  
11 can be used to quantify or to help quantify margin,  
12 particularly those associated with physics  
13 approximation.

14 CHAIRMAN CORRADINI: Okay, fine.

15 MR. GEHIN: So it won't --

16 MEMBER KIRCHNER: It's mainly  
17 benchmarking.

18 MR. GEHIN: It won't cover everything.

19 CHAIRMAN CORRADINI: Well, I didn't mean  
20 just this. I meant the whole shooting match, MPACT  
21 with this with --

22 MR. GEHIN: Yes, so it can be. Remember,  
23 some of our scope is operational challenges which  
24 aren't necessarily safety-related --

25 CHAIRMAN CORRADINI: Okay.



1 MR. GEHIN: -- and some are, like RIA and  
2 those areas. And so they won't cover absolutely  
3 everything when it comes to validating those models.  
4 But --

5 CHAIRMAN CORRADINI: So, yes, but I guess,  
6 so let me ask you. You brought it up. Let me just  
7 ask that. So, with the expected, I'm not sure if it  
8 will happen, with the expected new RIA rule, is this  
9 the only way to address the issue?

10 MR. GEHIN: We've been talking with EPRI  
11 and our, and vendors about the use of these tools to  
12 help inform that. I don't think there's any decision  
13 yet --

14 CHAIRMAN CORRADINI: Okay.

15 MR. GEHIN: -- on their point on how  
16 they're going to do it. But we're very interested to  
17 see our tools help on problems like that --

18 CHAIRMAN CORRADINI: Okay.

19 MR. GEHIN: -- if it's possible. But I  
20 can't say whether that's going to be the solution or  
21 not. Okay. All right. I think we're done with that.

22 Here's where I sort of compare and  
23 contrast what we've been working on versus what's  
24 available in the industry, so, again, whole-core,  
25 fully coupled, steady-state, transient thermal



1 hydraulics, fuel performance with neutronics.

2 We removed many of the assumptions in  
3 standard codes, particularly the homogenization,  
4 dehomogenization, local lattice effects, cross section  
5 functionalization, averaging of thermal hydraulics,  
6 those sorts of things.

7 And it's been applied to UO2 concepts.  
8 Sensitivity analysis, as I'll go through in more  
9 detail, on the ATF can be used to investigate some of  
10 the ATF fuel concepts to determine whether more  
11 validation data is needed.

12 The table at the bottom goes through the  
13 different physics model in this capability, the  
14 industry practice, and the DOE code, in this case  
15 VERA, where the standard practice is 3D nodal  
16 diffusion with two energy groups informed by 2D fuel  
17 assembly lattice transport where we do direct 3D  
18 transport with detailed energy groups.

19 The power distributions, thermal  
20 hydraulics, fuel temperatures are typically done at  
21 nodal averages in a industry type calculation. We do  
22 all that fuel pin resolved. So you can just look  
23 where it says fuel pin resolved, fuel pin resolved,  
24 fuel pin resolved.

25 There is a cost for this. If you look at



1 the bottom, target platform for the industry codes  
2 runs on workstations, relatively small systems.

3 Particularly the transport is  
4 computationally, more computationally intensive if you  
5 want to do it at this resolution. So our target  
6 system for that has been 1,000 compute cores, which is  
7 a departmental size cluster.

8 Many of those are available in the  
9 industry. We've been talking with -- or in DOE.  
10 We've been talking with our industry partners about,  
11 you know, we make these machines available. And as  
12 the value of our codes becomes apparent or they decide  
13 there's value, they can invest in machines like this.  
14 They're achievable at this level. So -- okay.

15 COBRA-TF whole-core thermal hydraulics,  
16 this is a subchannel code. This is a thermal  
17 hydraulics subcommittee I believe, so you're probably  
18 familiar with subchannel codes, very engineering --

19 CHAIRMAN CORRADINI: Don't give us a test.

20 MR. GEHIN: Okay. Engineering approach.  
21 CTF is a two-fluid, three-field representation. So it  
22 does single-phase and two-phase flow. For standard  
23 PWR operation, of course, we're primarily using  
24 single-phase flow with sub-cooled boiling.

25 But we've modeled some cases, if you look



1 over on the lower right, main steam line break,  
2 coupling CTF and MPACT that definitely are multi-phase  
3 cases as well.

4 This code has been widely used and  
5 validated for various reasons. We're doing our own  
6 validation as well. I'll talk about that.

7 When we apply, what I mentioned earlier,  
8 when we apply this code, we apply it at what I would  
9 call a fuel rod subchannel, which is the, you know,  
10 the channel that's at the intersection of four fuel  
11 rods.

12 It's been subchannels typically applied at  
13 a, either that level at an assembly or assembly  
14 average conditions or quarter assembly average  
15 conditions. But for the full core we model all 50,000  
16 or so sub-rod channels.

17 CHAIRMAN CORRADINI: Don't go back, but I  
18 should have asked. The neutronics codes that you talk  
19 about SHIFT and MPACT, are they now adopted into  
20 scale?

21 MR. GEHIN: No, they're separate from  
22 scale. There is -- I should take that back. MPACT is  
23 separate from scale. SHIFT is being incorporated into  
24 scale.

25 CHAIRMAN CORRADINI: And what makes the,



1       what's the decision to make it in or out? That's what  
2       I don't understand.

3               MR. GEHIN: To make it what?

4               CHAIRMAN CORRADINI: To decide if it's in  
5       or out?

6               MR. GEHIN: Really from a -- I mean,  
7       that's a decision that would be made by the scale team  
8       on --

9               CHAIRMAN CORRADINI: Oh, so it's really  
10      the scale team.

11              MR. GEHIN: It's available. It's fully  
12      available if there's use there. And so there's no  
13      issue there.

14              CHAIRMAN CORRADINI: Okay, fine.

15              MR. GEHIN: Okay. So I was talking about  
16      the rod channel resolution. Again, this resolution I  
17      mentioned is applied to every rod in the core. And  
18      you can see, for each quarter rod region then you get  
19      a variation there. And I'll come back to that.

20              And for some problems, that's not  
21      sufficient. For some of the problems that we're  
22      working on that's not sufficient. I'll talk about how  
23      we address that.

24              Of course, it's transient and steady-  
25      state. We use it, for example, coupled. If you look



1 at reactivity insertion accident, we model it with  
2 that level of detail as well. And it does have cross  
3 flow model between channels also.

4 As I mentioned, CFD-informed models are  
5 under development. This four azimuthal region around  
6 the rod is okay for many cases. But for some problems  
7 that we would look at, like crud, that's not enough  
8 resolution if you want to resolve the crud layer where  
9 you -- if you've seen crud striping, it's in more  
10 detail than that.

11 In addition, the grid spacer models are  
12 usually represented as losses or approximate models  
13 that can be informed by CFD as well.

14 So the applications, PWR, BWR, steady-  
15 state, and transient, I mentioned the main steam line  
16 break problem. We are applying it to reactivity  
17 insertion accident as well.

18 We're not applying this right now to a  
19 LOCA. Although the code could be extended and applied  
20 to LOCA.

21 CHAIRMAN CORRADINI: So a lot of questions  
22 come to mind. So LOCA, is there something about the  
23 voiding process that then translates back to the BWR  
24 also that is the limit? I'm not sure I understand.

25 MR. GEHIN: You know, and I might have to



1 ask for somebody to help with the answer to this. But  
2 we have not spent a lot of time validating this  
3 current code version for LOCA and applying it to LOCA  
4 to understand all of the issues for that application.

5 So I don't think from a fundamental point  
6 the code can't model LOCA. It's --

7 CHAIRMAN CORRADINI: You just haven't  
8 taken the time.

9 MR. GEHIN: Yes, maybe I'll ask Dave  
10 Pointer, who works on the thermal hydraulics for us,  
11 to see if I gave the right answer or not.

12 MR. POINTER: So I'm Dave Pointer from Oak  
13 Ridge National Lab. And Jess gave the right answer.

14 In the course of CASL, we've actually made  
15 some significant investments to improving the  
16 stability of the multi-phase analysis capability in  
17 CTF.

18 So, in theory, it can be applied to those  
19 problems where you do generate significant void in  
20 ways that we couldn't in the past. But we have not  
21 gone through the next step of beginning to validate  
22 those applications in CTF.

23 CHAIRMAN CORRADINI: Okay.

24 MR. GEHIN: Yes, and so, when we bring up  
25 discussion of LOCA, that question of validation always



1 comes up. And it's on the list. If there's folks  
2 that are interested in applying these codes that way,  
3 we'd definitely be interested in looking at that.

4 CHAIRMAN CORRADINI: Okay. Thank you.

5 MR. GEHIN: So the capabilities here,  
6 again, sort of the bottom line trying to tie it back  
7 to ATF, is the CFD-informed rod-by-rod thermal  
8 hydraulics can be used to model ATF.

9 You know, if you look at the geometry,  
10 particularly the cylindrical geometry applicable, you  
11 may have to take into account surface conditions,  
12 things like that. But the capability, I believe, can  
13 be applied and extended.

14 I'm going to go through a few examples to  
15 show, to emphasize some of the things I was talking  
16 about. And the first one is CFD-informed subchannel  
17 modeling.

18 Some of the problems that we look at, this  
19 four azimuthal regions that you get with CTF is not  
20 sufficient in the models, you know, that used for heat  
21 transfer aren't sufficient. So what we've done is  
22 generated models, fuel assemblies, multiple grid spans  
23 in CFD and calculated detailed flow distributions.

24 When you get these flow distributions, you  
25 can use those to back out, if there's mapped work



1 here, around the rod, you know, the heat transfer  
2 coefficient. And that's what this colored plot shows.

3 If you look along the axial, this is, you  
4 know, on the left-hand side, the axial position on the  
5 rod. And if you take the rod surface and roll it out  
6 into a 2D plot, you see this surface, which gives you  
7 a map of the detailed heat transfer coefficient around  
8 the rod and up the rod.

9 It's impacted. And you can see these  
10 different levels, of course, by the mixing vanes and  
11 those details.

12 So, once you have these heat transfer map,  
13 and it's generally done by a ratio of the actual heat  
14 transfer coefficient to, say, a Dittus-Boelter heat  
15 transfer coefficient that's used in CTF, you can input  
16 that into CTF and get an improved simulation of the  
17 details around the rod, as well as predicting the  
18 overall heat transfer.

19 MEMBER MARCH-LEUBA: So what we're seeing  
20 there, the horizontal lines are the spacers?

21 MR. GEHIN: Yes, these are the spacers.

22 MEMBER MARCH-LEUBA: And then what is that  
23 plume where you're pointing right now?

24 MR. GEHIN: This plume right here?

25 MEMBER MARCH-LEUBA: Yes.



1 MR. GEHIN: Yes, Dave, do you have an  
2 answer for that? I mean --

3 MR. POINTER: So the plume that you see  
4 there is actually an opening in the configuration of  
5 the spacer grid for that particular pin. This is the  
6 central pin in a 5x5 bundle.

7 MEMBER MARCH-LEUBA: So it's on a smoother  
8 symmetry of the --

9 MR. POINTER: It's an anomaly in the  
10 dimple and spring configuration in that particular --

11 MEMBER MARCH-LEUBA: Any properties much  
12 --

13 MR. POINTER: Yes.

14 MEMBER MARCH-LEUBA: -- it doesn't mix.

15 MR. GEHIN: Okay. Thanks, Dave. So we've  
16 applied this to a series of case. I won't go into the  
17 details.

18 But this chart here, this plot on the  
19 right-hand side gives the CTF temperature prediction.  
20 Solid lines are CTF, standard CTF. The dash lines are  
21 with these improved heat transfer coefficients. So we  
22 can a proved simulation. You can also see the error  
23 as you go rod by rod is a lot more uniform.

24 CHAIRMAN CORRADINI: So say that again,  
25 please. I'm sorry.



1 MR. GEHIN: Okay. So this plot gives a  
2 comparison of the difference between CTF and STAR. So  
3 STAR is the reference. CTF is, of course, where we've  
4 input these heat transfer coefficients and done a  
5 calculation of CTF temperature prediction. And --

6 CHAIRMAN CORRADINI: Okay. But I guess I  
7 should have asked my question more specifically. The  
8 Y axis is an error in degrees Kelvin?

9 MR. GEHIN: I believe that's the case --

10 CHAIRMAN CORRADINI: Okay. So now I'm  
11 going to ask the engineering question. Who cares?

12 MR. GEHIN: So, when we looked at --

13 CHAIRMAN CORRADINI: I don't mean to be --

14 MR. GEHIN: No, no, no, it's a good  
15 question because we have the -- when you look at the  
16 application of crud, crud is very sensitive to when  
17 you get at a boron deposition threshold of when boron  
18 deposits and when it doesn't deposit.

19 So, when we did our analysis looking at  
20 the homogenized crud, four regions per rod, we found  
21 that we did not accurately predict the crud deposition  
22 and we had to calibrate that model, because there were  
23 some regions that were right on the edge of this  
24 threshold where temperatures like this mattered.

25 Now, it may be for your problem this



1 doesn't --

2 CHAIRMAN CORRADINI: But your point is  
3 you're close to a threshold. Now I need to know the  
4 answer more carefully --

5 MR. GEHIN: Well, the other value to this  
6 is when you looked at modeling new grid spacers or  
7 incorporating grid spacer designs, certainly you're  
8 going to get data from experimental measurements. But  
9 you're not going to get this resolution of data where  
10 you're going to have to have a model in your --

11 CHAIRMAN CORRADINI: Okay.

12 MR. GEHIN: -- subchannel code to  
13 represent grid spacer.

14 So that's another application where maybe  
15 you're not looking totally at improved accuracy  
16 prediction, but you do need a model to represent the  
17 impacts of those grid spacers. And that certainly has  
18 an impact on crud, DNB, and other areas as well. So  
19 those are the areas where we've really been focused on  
20 this --

21 MEMBER MARCH-LEUBA: So basically that  
22 figure on the right says that when you use the same  
23 heat transfer coefficient in the STAR and CTF, you get  
24 the same temperature.

25 MR. GEHIN: Yes.



1                   MEMBER MARCH-LEUBA:   And if you use the  
2   wrong heat transfer coefficient, you get the wrong --

3                   MR. GEHIN:   I mean, it's not horrendously  
4   wrong, as Mike mentioned, but it does allow you to get  
5   a more uniformed prediction.  If you look at the air  
6   variations, they're much smaller.

7                   And so we think it's one of the keys for  
8   calculating crud.  It may be important for DNB as  
9   well.  Certainly, grid spacer mixing is an effect that  
10  we can capture also.

11                  All right.  CFD evaluation of DNB, so this  
12  is something we've been working on quite a bit on the  
13  hub program to be able to apply CFD directly to  
14  predict when DNB conditions would occur in a PWR with  
15  the idea of being able to supplement experimental  
16  data.

17                  So, typically what's done in industry is  
18  they take a, say, 5x5 rod bundle, do DNB testing on  
19  that, and check things out, particularly when there  
20  are changing fuel designs like grid spacers.

21                  We would like the ability to be able to  
22  inform them on their grid designs that may result in  
23  them having to do fewer DNB tests or find out things  
24  during the DNB test that would change their grid  
25  spacer designs.



1           So we've been incorporating multi-phase  
2   model development to DNB, combining this with more  
3   fundamental measurements on heat partitioning between  
4   liquid and vapor phases, you can see some of the  
5   physics that we've been looking at there, and then be  
6   able to put this into a code like STAR-CCM or NEK5000  
7   to be able to run, basically mimicking what an  
8   experiment for electrical heated DNB test would look  
9   like where you slowly ramp up the power and then you  
10   detect when you actually have, you know, a temperature  
11   excursion indicating DNB.

12           We've been able to get data on this 5x5,  
13   bundled data --

14           CHAIRMAN CORRADINI: This is Westinghouse  
15   data?

16           MR. GEHIN: This is Westinghouse data.

17           CHAIRMAN CORRADINI: Okay.

18           MR. GEHIN: Proprietary data for mixing  
19   vanes and non-mixing vanes. I'm showing the non-  
20   mixing vane case here, which shows basically the  
21   predictions are within plus or minus 16 percent or  
22   better. So --

23           CHAIRMAN CORRADINI: I noticed there's no  
24   axes label. So --

25           MR. GEHIN: Well, sorry about that. But



1 this is a case, the value that we've had working  
2 directly with Westinghouse and some of the other  
3 industry organizations where we may be able to get  
4 access to data. But it is proprietary.

5 MEMBER MARCH-LEUBA: So the points, the  
6 sequence you're putting there are different flow  
7 pressure and power.

8 MR. GEHIN: Yes, I believe that's the case  
9 --

10 MEMBER MARCH-LEUBA: But the same spacer,  
11 right?

12 MR. GEHIN: Yes. So, you know, the  
13 vendors, of course, this is how they validated their,  
14 or developed their own DNB correlations with this type  
15 of data. And so they've given us some of that data.  
16 And then they've actually taken these capabilities and  
17 applying it themselves --

18 MEMBER MARCH-LEUBA: Right, but the value  
19 of this is on the computer you can have a different  
20 spacer and see how it changes.

21 MR. GEHIN: Right. And, you know, one of  
22 the challenge with using CFD for this is applying  
23 single-phase CFD, you know, you can only get so far in  
24 that, and then when you do your test and actually have  
25 two-phase, it may or may not perform --



1                   MEMBER MARCH-LEUBA:   By the condition,  
2   yes.

3                   MR. GEHIN:   Yes.   And so we're trying to  
4   expand the application of CFD for these tests.   At  
5   some point, maybe we can rely on it more.   But we  
6   don't want to -- you know, what we want to really be  
7   able to do is try to better inform these expensive  
8   tests.

9                   And so, of course, this is an area then  
10   for ATF fuels if you're changing things that would  
11   impact flow patterns to investigate impact on DNB  
12   might, at this state of maturity, might be able to  
13   inform where you think data is needed or if you're  
14   comfortable with where things are.   Okay.

15                  MEMBER MARCH-LEUBA:   For ATF fuels, you  
16   just pick the CFD correlation, the DNB correlation to  
17   change.

18                  MR. GEHIN:   I'm not an expert in this  
19   area.   In general --

20                  (Simultaneous speaking.)

21                  MR. GEHIN:   -- experts on that side of the  
22   table.   It's generally driven by the mixing vane, the  
23   geometry.   There could be some surface condition  
24   effects.   But I would not --

25                  MEMBER MARCH-LEUBA:   If the material works



1 differently, the water level would be --

2 MR. GEHIN: Right. And then if you look  
3 at non-cylindrical geometry, of course, there's --

4 MEMBER MARCH-LEUBA: Sure.

5 MR. GEHIN: -- definitely applications.

6 MEMBER MARCH-LEUBA: But for anything that  
7 we are thinking in the near future, if you look from  
8 the outside, the pins look the same.

9 MR. GEHIN: They look basically the same.  
10 You're right. So that's why, if needed, this could be  
11 applied.

12 Transient capabilities, I'll talk about  
13 reactivity insertion accident. So this has been one  
14 of the target problems that we've had, control rod  
15 ejection for a PWR.

16 This is a capability where we've coupled  
17 neutronics, thermal hydraulics with fuel temperature  
18 table model to calculate, you know, the conditions in  
19 the core. This is a four-loop PWR core where there's  
20 a postulated control rod ejection worth \$1.50, which  
21 is, you know, these things are always done  
22 conservatively.

23 And we can get detailed rod-by-rod power  
24 distributions. This figure here shows you that's,  
25 where the ejected control rod is you end up with a

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1 power pulse, if you can squint a little bit at that,  
2 and get an axial power shape.

3 So we get all those details for every rod.  
4 You can identify rods that you may want to look at,  
5 use those as conditions that would go into a fuel  
6 performance simulation as well.

7 We are looking at coupling and working on  
8 coupling BISON indirectly. But it's usable in the  
9 current state as I just mentioned. Of course, this is  
10 also something that can be applied to ATF fuels as  
11 well, and it's fully functional.

12 Okay. Coupling DOE codes with reactor  
13 systems codes, so as I mentioned, for our work we've  
14 been not relying on development of a DOE reactor  
15 systems code. That may come about at some point where  
16 we work on that. But in the timeframe we had, the  
17 vision was to couple with existing reactor systems  
18 codes.

19 So this provides a capability to analyze  
20 flow regimes which CTF has not been validated. And  
21 that's what I meant when we talked about the LOCA,  
22 that while the capability is there, it's not been  
23 validated.

24 And so we've been working with the NRC to  
25 couple, you know, particularly BISON with the NRC code



1 system to look at LOCA. It's been a joint DOE/NRC  
2 effort.

3 TRACE and BISON, which have been coupled  
4 as a demonstration, one, you know, primary reason for  
5 doing this is to show that it can be done. It can be  
6 done in a relatively quick fashion that you can choose  
7 some of these codes that you want to couple. And, of  
8 course, TRACE is the NRC's safety analysis code.

9 The idea here is if this capability could  
10 buy a means to simulate ATF simulation for LOCA as a  
11 -- where other transients, TRACE has been widely  
12 applied to these transients. You've heard about the  
13 state of development of BISON. And so you can bring  
14 those two together.

15 MEMBER MARCH-LEUBA: Does it provide two-  
16 way coupling?

17 MR. GEHIN: It's two-way coupling.

18 MEMBER MARCH-LEUBA: So, but --

19 MR. GEHIN: This is a --

20 MEMBER MARCH-LEUBA: -- BISON provides the  
21 conductivity for TRACE --

22 MR. GEHIN: That's right.

23 CHAIRMAN CORRADINI: Can I just -- I'm  
24 sorry. I didn't mean to interrupt you.

25 MR. GEHIN: No, no.



1 CHAIRMAN CORRADINI: But I'm struggling to  
2 see -- I'm looking at your slides and looking at the  
3 time. I'm struggling to see how this affects -- this  
4 is all interesting. But I'm trying to make the bridge  
5 to ATF, and I don't see a clear bridge.

6 MR. GEHIN: Okay. So the idea, in this  
7 case, the idea on ATF, whether it's for NRC or  
8 somebody else, if you decide BISON is a good code for  
9 ATF --

10 CHAIRMAN CORRADINI: Okay, fine.

11 MR. GEHIN: -- you don't have to abandon  
12 your systems code, which you put a lot of time and  
13 effort in developing. You can use it with BISON as an  
14 example.

15 CHAIRMAN CORRADINI: Okay.

16 MR. GEHIN: So that's the idea.

17 MEMBER REMPE: So you've totally switched  
18 gears with this slide, right? You're not talking  
19 about any of your MPACT stuff with this.

20 MR. GEHIN: That's exactly right.

21 CHAIRMAN CORRADINI: That was about four  
22 slides ago.

23 MEMBER REMPE: Okay. Yes, well, I just  
24 wanted to make sure, because earlier I had asked,  
25 well, are you going to continue using PARCS in the



1 TRACE system. And I think even your last slide talked  
2 about MPACT and CTF, right. But this particular  
3 coupling did not use anything from your earlier stuff.

4 MR. GEHIN: No, no. And, you know, and  
5 so, yes, just to be clear, you know, PARCS is not a  
6 DOE-developed code. It's not in the --

7 MEMBER REMPE: Right.

8 MR. GEHIN: -- that I talked to you about  
9 --

10 CHAIRMAN CORRADINI: But that's okay.

11 MEMBER REMPE: That's okay. But --

12 MR. GEHIN: I'm just, I didn't know where  
13 you were coming from --

14 MEMBER REMPE: Right, I just was curious  
15 because of my earlier question about what the vision  
16 would be and stuff and --

17 MR. GEHIN: Oh, you know, LOCA simulation  
18 does not use neutronics. And so, you know, you get to  
19 the depleted point of the core, then you have a LOCA  
20 event, and you assume your SCRAM. You have the decay  
21 heat. And so this is, you know, it becomes a thermal  
22 hydraulics fuel performance.

23 MEMBER REMPE: But that says, for example,  
24 LOCA. And again, I'm back to ATWS-I. And again, this  
25 just was focused on doing a LOCA or a station

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1 blackout.

2 MR. GEHIN: Well, I knew LOCA, yes, and I  
3 knew LOCA would be a question that came up. And so I  
4 wanted to talk a little bit about what the thinking is  
5 there.

6 MEMBER REMPE: So --

7 MR. GEHIN: That's why I introduced this  
8 slide.

9 MEMBER REMPE: And on this analysis, are  
10 the results documented in one of the reports we were  
11 provided ahead of time?

12 MR. GEHIN: I don't believe we provided  
13 this. We can provide a report.

14 But I'll emphasize, this is a  
15 demonstration, primarily answering the question is can  
16 you take a DOE code that's been developed in the DOE  
17 system and couple it with, say in this case, an NRC  
18 code. You could consider doing the same thing with an  
19 industry code where the end user may want to keep  
20 their own systems code. Can you efficiently take an  
21 outside code and do that coupling? And so that was  
22 the primary purpose of this demonstration --

23 MEMBER REMPE: Okay.

24 MR. GEHIN: -- which was successful. And  
25 this figure down in the bottom is actually a movie,



1 but I think this is a PDF. So --

2 MEMBER MARCH-LEUBA: Yes, it's a PDF.

3 MR. GEHIN: Yes. But that was the point  
4 of it. So, if you're not able to relatively easily  
5 couple these codes, then there's no reason why you  
6 would go beyond that point. So it's really to get  
7 past the first phase of can you do that.

8 MEMBER REMPE: And from -- again, we  
9 didn't see the results of it. But what was better  
10 because you did this? I mean, you've showed you can  
11 easily couple them. But did you get any results that  
12 you couldn't have obtained using their own tools?

13 MR. GEHIN: Well, the, again, the idea  
14 here is if you believe or if an end user would like to  
15 use BISON because they believe BISON is a good tool to  
16 model ATF, it would then provide those capabilities.

17 You would get the fidelity of -- in fact,  
18 we can circle back to that question. You get the  
19 fidelity of TRACE. You apply it to either a single  
20 rod model or however you want to apply it, and then  
21 apply BISON to use its ATF modeling capability is the  
22 vision --

23 MEMBER MARCH-LEUBA: It is a PowerPoint  
24 you can take on the --

25 MR. GEHIN: Oh, is it?



1 MEMBER MARCH-LEUBA: Yes.

2 MR. GEHIN: Oh, you're right. Yes. And,  
3 I mean, this just shows, this is like fully coupled.  
4 It's calculating temperatures. It's calculating void  
5 fractions and in a two-way sense just --

6 MEMBER MARCH-LEUBA: Order of magnitude to  
7 how many person-weeks or person-years or how long does  
8 it take to do this?

9 MR. GEHIN: As far as the coupling?

10 MEMBER MARCH-LEUBA: Yes.

11 MR. GEHIN: I mean, the initial coupling  
12 I think was done relatively quickly. I don't know if  
13 there's somebody, maybe Steve Bajorek --

14 (Simultaneous speaking.)

15 MEMBER MARCH-LEUBA: Because, I mean, I  
16 can do it in FORTRAN, right?

17 MR. GEHIN: Yes.

18 DR. BAJOREK: This is Steve Bajorek,  
19 Office of Research. We started this work I believe in  
20 last October or November. They had the essentially  
21 coupling features done within a couple of days.

22 The very difficult thing is taking TRACE's  
23 adaptive mesh where we look at the fine mesh re-  
24 nodalization, which is moving on a component basis on  
25 the fly, and mapping that into a BISON code, which is

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1 a finite element mesh in 3D.

2 The reason we picked this is this is about  
3 the most difficult coupling exercise we could think of  
4 in trying to take something like TRACE and couple it  
5 over to the MOOSE --

6 MEMBER MARCH-LEUBA: But you're talking a  
7 week, a week of work.

8 DR. BAJOREK: A little bit longer than  
9 that to get everything done with that adaptive mesh --

10 MEMBER MARCH-LEUBA: But it's not ten  
11 years.

12 DR. BAJOREK: Not ten years, no.

13 MEMBER MARCH-LEUBA: Good.

14 DR. BAJOREK: No.

15 (Simultaneous speaking.)

16 MEMBER KIRCHNER: Go ahead.

17 CHAIRMAN CORRADINI: I want to be careful  
18 on time. But I'm going to ask, so now for ATF, this  
19 is interesting. But where is the ATF application?  
20 What am I missing?

21 MR. GEHIN: Okay. So, if you decide you  
22 want to use BISON as your performance code --

23 CHAIRMAN CORRADINI: But these are just  
24 demonstrators of using BISON in lieu of FRAPCON and  
25 FRAP-T.

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1 MR. GEHIN: That's an -- yes, that's  
2 exactly right.

3 CHAIRMAN CORRADINI: Or in lieu of FAST.

4 MR. GEHIN: Yes, or if industry wanted to  
5 take RETRAN coupled with BISON, they --

6 CHAIRMAN CORRADINI: Okay, fine. I get  
7 it.

8 MR. GEHIN: It's a demonstration that you  
9 can do the coupling, because there were questions  
10 about that. And, you know --

11 CHAIRMAN CORRADINI: I know.

12 MR. GEHIN: -- can it be done? You know,  
13 you got a, and the legacy code and you got a new code.  
14 Can you do it?

15 CHAIRMAN CORRADINI: I got it.

16 MR. GEHIN: But you would have to buy in  
17 or, you know, decide BISON is a code that you would  
18 want to use, okay, and specifically focusing on the  
19 thermal hydraulics of LOCA.

20 DOE code applications for source terms is  
21 a question you asked. You know, the answer we had is  
22 we're not working on it beyond design basis accidents.  
23 But there are some things here that can provide inputs  
24 for source term.

25 So we can get, you know, high resolution



1 reactor inventories. These have been well-validated.  
2 These can be used as inventories that provide, you  
3 know, or provide inputs to a code such as MELCOR, get  
4 detailed rod-by-rod. These can be averaged or however  
5 it needs to be. There are validation data from PIE  
6 and reactor operation.

7 We can, since we're using ORIGEN, we can  
8 provide the full detailed isotope set that's  
9 consistent with NRC applications for beyond design  
10 basis accidents.

11 BISON calculates fission gas release.  
12 This also is information that could be useful for  
13 beyond design basis accidents.

14 CHAIRMAN CORRADINI: But here I'm going  
15 to, what little I know I'm going to embarrass myself.  
16 It's not just the fission gas release. It's the  
17 coupling of that to a series of accident scenarios and  
18 the frequency and seeing if I'm going to change the  
19 alternative source --

20 MR. GEHIN: And so --

21 CHAIRMAN CORRADINI: Okay.

22 MR. GEHIN: -- that part we are not doing  
23 just to be clear. I wanted to be responsive to your  
24 --

25 CHAIRMAN CORRADINI: No, no, that's fine.



1 I appreciate that.

2 MR. GEHIN: Yes, and then again, for  
3 transient simulation, some of these, the transients  
4 that I talked about could be used as information  
5 informed beyond design basis accidents as well.

6 As addition, if you want to run a case at  
7 end of cycle, we can deplete out the end of cycle and  
8 provide all those initial boundary conditions that  
9 support beyond design basis accidents. Okay.

10 Let me move on to validation. So the  
11 validation approach involves single and coupled multi-  
12 physics. This chart here, when you look at applying  
13 a coupled system or a core simulation type code are  
14 the typical areas that you look at, critical  
15 experiments.

16 Monte Carlo is usually used as a key part  
17 of this for verifying these approximations, as well as  
18 being able to map between the geometry that your codes  
19 model versus what a critical experiment may be, for  
20 example.

21 Fuel rod PIEs and then operating power  
22 plant data are the sources of data that we have. And  
23 again, Monte Carlo supplements all of this. This is  
24 very typical and standard of what's done with existing  
25 codes.



1 Subchannel validation, if you look at CTF,  
2 I believe we've provided the assessment report for  
3 that. There's the identified phenomenon for  
4 validation. I won't go through the whole list here.  
5 You're very familiar with that.

6 We've got a set of available open  
7 experiments listed on the right for full channel and  
8 subchannel. And in the case of like DNB, we've gotten  
9 access to some proprietary data.

10 Again, this would all be supplemented if  
11 a vendor were to pick up this tool with the remainder  
12 of the proprietary data that they have.

13 Okay. VERA validation, on the plant  
14 level, for existing fuels, there's an assessment  
15 report for this. Again, this has been our emphasis  
16 and, of course, where all the operating data is. So  
17 we've applied it to a large number of PWR plants and  
18 operating cycles.

19 Typically, the comparisons are made for  
20 zero power physics tests. You've got criticality, rod  
21 worth, and then flux maps during power escalation,  
22 operational measurements, soluble boron, and flux  
23 maps, and then our operational transients, start-up,  
24 shutdown, or changes in power during operation such as  
25 maybe a load-follow event where we have data as well.

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1           These plants and cycles listed here, I  
2           won't go into this detail. But they were chosen for  
3           nominal conditions and some of these operational  
4           occurrences like PCI and crud, which is why you'll see  
5           different plants listed.

6           MEMBER MARCH-LEUBA:       You said this  
7           operational data proprietary?

8           MR. GEHIN:   Most of it is, particularly  
9           the fuel data. There are -- some of the cycles for  
10          Watts Bar, the first five cycles we've been able to  
11          get released. But particularly when you get to the  
12          fuel data, that, the compositions and --

13          MEMBER MARCH-LEUBA:   Oh, sure, the fuel  
14          data but --

15          MR. GEHIN:   Yes.

16          MEMBER MARCH-LEUBA:   The fuel data you can  
17          get it --

18          MR. GEHIN:   Yes, so we've gotten this --

19          MEMBER MARCH-LEUBA:   -- but I mean the  
20          plant measurements.

21          MR. GEHIN:   Yes, so we've gotten those  
22          directly from the utilities. They're not public data  
23          usually. Some of the older cycles like I mentioned at  
24          Watts Bar TBA is released. And there's a public  
25          document, and it's been used by others for --



1                   MEMBER MARCH-LEUBA:     You have a DVD  
2                   somewhere with it just in case.

3                   MR. GEHIN:   Yes.   So a lot of, we've been  
4                   able to get a lot of good data on this.

5                   And there are different reactors,  
6                   Westinghouse four-loops, 17x17, 16x16.   But, of  
7                   course, these are all zirconium UO2 fuels.   So we've  
8                   got a pretty good pedigree of how this code performs  
9                   for operational plants that would support a good  
10                  validation case.

11                  Transient, the data there is not as widely  
12                  or as much data for, if you look at reactivity  
13                  insertion accidents for the coupled physics largely  
14                  rely on the SPERT test.   We use that for our  
15                  validation case as well.

16                  I believe you're probably familiar with  
17                  SPERT, a PWR test reactor with a central rod that can  
18                  be ejected to go through a power transient.

19                  And here's an example of a case, generally  
20                  good agreement.   Again, we're modeling this in full  
21                  detail with the DOE codes, resolved fuel geometries  
22                  and thermal hydraulics with CTF with the fuel  
23                  temperature table, so good validation data there.

24                  Now, to the ATF assessments, we've got  
25                  tables that are somewhat similar to what Steve had for



1 BISON. Across the top we have the different fuel  
2 types. And by U metal fuel, this means non-  
3 cylindrical geometry, just to clarify.

4 So we've got geometry, physics models,  
5 materials and nuclear data, validation, have we  
6 performed validation for this and is there design  
7 specific validation data available. And then I've got  
8 some notes below that you can refer to.

9 You can see, of course, for UO2 we have,  
10 all these are yeses. Coated clad yeses, when you get  
11 down to validation performed and validation data for  
12 the neutronics, we don't have that data. But we  
13 believe that applying a coating is well within the  
14 physics capability and prediction capability of the  
15 neutronics code because it's not a large impact.

16 Same is true for doped UO2 or fuel, it's  
17 not a large perturbation. And if necessary, you can  
18 perform sensitivity analysis to confirm that.

19 When you look at the FeCrAl or the iron-  
20 based clads, again the physics models and data are all  
21 applicable. We've not performed specific validation  
22 yet with the codes, although there is previous  
23 operational data with steel clads and, as well as data  
24 that could be generated through LTAs. Sensitivity  
25 studies could help inform that as well.



1 Yes, go ahead.

2 CHAIRMAN CORRADINI: Can you expect a  
3 difference, though? I'm -- it's the doped -- I'm  
4 sorry. I missed that you had the U3Si. But if I look  
5 down the row here about it, it's not the cladding so  
6 much as the fuel constituent, right?

7 MR. GEHIN: We think the cladding, and we  
8 can show this through sensitivity studies. It changed  
9 the absorption properties. But that's all within our  
10 --

11 CHAIRMAN CORRADINI: Okay.

12 MR. GEHIN: I think I'd be comfortable to  
13 say that's within our physics prediction.

14 CHAIRMAN CORRADINI: Okay, fine.

15 MR. GEHIN: You'd want to do a sensitivity  
16 study.

17 CHAIRMAN CORRADINI: Oh, no, that's fine.

18 MR. GEHIN: When you get to the fuel where  
19 you're changing fuel density and things like that,  
20 which I think is, you want to look at more carefully,  
21 we -- and again, where it says no here, we have not  
22 done the validation. The capabilities you see above  
23 this line in general are yes. But we've just not done  
24 --

25 CHAIRMAN CORRADINI: Okay.



1 MR. GEHIN: -- the validation. And in  
2 most cases, we don't have the design-specific  
3 validation data.

4 Now, the one caveat on that, when you look  
5 at the non-cylindrical fuel geometry, we've not  
6 implemented that in the code. The physics models and  
7 the data are applicable. But it's not been  
8 implemented. So that's the state of where we are  
9 there.

10 Thermal hydraulic capability, I think as  
11 Jose mentioned, you know, for all the cylindrical fuel  
12 rods, pretty much the data, you know, or I'd say the  
13 geometry capabilities and the data is applicable. Of  
14 course, for fuel we put not applicable because that's  
15 within the, the cladding doesn't impact that.

16 We've prepared, we've performed validation  
17 for these cylindrical fuel types. And there's  
18 validation data generally available. And where it  
19 says no here, you know, you may be able to convince  
20 yourself that the current cylindrical fuel rod data is  
21 acceptable.

22 For the non-cylindrical geometry, you  
23 know, we've not implemented that. We've not looked at  
24 whether the thermal hydraulic models would change.  
25 The flow distributions would certainly be different if



1       you go to that type of fuel. So that would have to be  
2       investigated. And we've not done validation on that  
3       --

4                   CHAIRMAN CORRADINI: But again, I'm going  
5       to ask this --

6                   MR. GEHIN: Yes.

7                   CHAIRMAN CORRADINI: -- to make sure,  
8       though. And when we're thinking of this, I'm always  
9       thinking of thermal hydraulic coupling back to the  
10      fuels model.

11                  MR. GEHIN: Yes.

12                  CHAIRMAN CORRADINI: Okay.

13                  MR. GEHIN: Yes. Okay. All right. So  
14      conclusion, so the higher-resolution, fully coupled  
15      capabilities are developed and are applicable to ATF.  
16      These are generally done at a higher resolution than  
17      currently available that can be used for, at a minimum  
18      for investigation of impacts and insertion of LTA and  
19      can be checked, you know, against higher fidelity  
20      methods.

21                  You can actually reduce time, in our  
22      experience, in a capability like this you can reduce  
23      the time to perform investigations because the current  
24      industry methods take pre-generation of data. It has  
25      to be tabulated, put into a code. Whereas, if you can



1 just directly simulate something, it's more computer  
2 time rather than the effort spent investigating  
3 challenges.

4 We have a significant validation for UO2  
5 forms. Most of this could be leveraged for ATF. As  
6 I mentioned, the physics we have are applicable. The  
7 data is applicable. And there are sensitivity  
8 approaches or Monte Carlo that can be used to  
9 determine whether you need to do further, get further  
10 experimental data or not. It can be used by industry  
11 or NRC to support, you know, their current tools or be  
12 adopted.

13 The system code, a coupling allows for  
14 evaluation of broader transients. You know, as we  
15 discussed in some detail, we're not developing that  
16 part right now within this activity. There could be  
17 some future activities in DOE that could be applied  
18 there. But we've demonstrated that you can take the  
19 capabilities we have and fairly readily couple those  
20 with systems capability, which is, of course,  
21 important for safety.

22 And I believe that's it. So are there any  
23 questions?

24 CHAIRMAN CORRADINI: Do the members have  
25 any more questions? No? Okay.



1                   So why don't we take a lunch break? And  
2                   we'll come back here, reconvene at 1:15. Okay.

3                   (Whereupon, the above-entitled matter went  
4                   off the record at 12:16 p.m. and resumed at 1:14 p.m.)

5                   CHAIRMAN CORRADINI: Chris, I think you're  
6                   going to lead us off, right?

7                   MR. STANEK: Yes. Just a few quick comments  
8                   to start the afternoon session. In the afternoon  
9                   session we will switch gears from accident-tolerant  
10                  fuel to non-like water advanced reactors. Although you  
11                  have heard this morning during the ATF presentations  
12                  about some of the codes that we will discuss this  
13                  afternoon, there are still other codes that haven't  
14                  yet been introduced, and so as such we've generated  
15                  another version of this table.

16                  As was the case this morning and in the  
17                  interest of time I won't talk about any of the details  
18                  or any of the codes in this table, but hopefully it's  
19                  a useful guide for you as we go through the afternoon  
20                  presentations.

21                  Also, as was the case this morning, one  
22                  idea of this matrix is that it serves as a detailed  
23                  agenda. So first this afternoon we'll hear from Tanju  
24                  Sofu from Argonne National Laboratory, who will  
25                  present neutronics code developments for non-LWRs.



1 Tanju will be followed by Rich Williamson  
2 from Idaho National Laboratory, who will present fuel  
3 performance. Rich will be followed by Elia Marzari  
4 from Argonne National Laboratory. He'll present  
5 thermal-hydraulics.

6 Then our final technical presentation of  
7 the day will again be from Tanju Sofu, who will give  
8 a presentation of mechanistic source terms for non-  
9 LWRs. If there are no questions for me, I'm happy to  
10 turn it over to Tanju.

11 CHAIRMAN CORRADINI: Go ahead.

12 MR. SOFU: Good afternoon. As the first  
13 technical presentation of the session today, I'm going  
14 to cover recently developed neutronics analysis  
15 capabilities for advanced non-water cooled reactor  
16 designs. After a brief background, only one page, on  
17 motivations for developments of these new advanced  
18 modeling and simulation capabilities I will introduce  
19 two neutronics analyses codes, PROTEUS suite and  
20 RATTLESNAKE, to address their validation of the  
21 verification basis and cover some example applications  
22 for SFRs, high-temperature gas code reactors and  
23 molten salt reactors.

24 DOE and NRC have supported development of  
25 numerous neutronics analysis capabilities throughout



1 the past several decades, mainly to support deployment  
2 licensing and operation of water-cooled thermoreactor  
3 concepts.

4 The purpose of this presentation and  
5 presentations that will follow, is not to provide a  
6 comprehensive look at the entire spectrum of  
7 neutronics analysis capabilities, but rather focus on  
8 the recently developed capabilities that aim for  
9 design and analysis of advanced reactor concepts.

10 Legacy capabilities, as well as more  
11 modern Monte Carlo codes, can also support advanced  
12 reactor designs through a varying degree of accuracy.  
13 Therefore, the recent efforts under DOE's Advanced  
14 Modeling Simulation Program focused on providing high-  
15 order, deterministic neutron transport solutions to  
16 compensate for the limitation of these codes.

17 CHAIRMAN CORRADINI: This is an area that  
18 I'm not very familiar with. When you said legacy, what  
19 are you thinking of?

20 MR. SOFU: I'm thinking about existing  
21 codes that could include PARCS for NRC, Scale System  
22 from Oakridge, the 3-D for advanced reactors, sodium  
23 task reactors, and the spectrum of other capabilities  
24 that exist. That also includes Monte Carlo codes,  
25 MCMP, SERPENT, SHIFT we heard about this morning.

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1 CHAIRMAN CORRADINI: So those are what you  
2 would term as legacy. That's what I was trying to get  
3 at. You made the comment ---

4 MR. SOFU: I think I kind of mix those,  
5 legacy as well as state of the art. I think in fact  
6 Monte Carlo codes often provide reference solutions  
7 for us to compare our results with.

8 CHAIRMAN CORRADINI: Okay.

9 MR. SOFU: It did not need to be ---

10 CHAIRMAN CORRADINI: No, I was just trying  
11 to understand what you were referring to. Okay.

12 MR. SOFU: So the unique capabilities we  
13 feel the PROTEUS Suite and RATTLESNAKE can offer  
14 include high-fidelity solutions for complex  
15 geometries, with strong heterogeneities bind with flux  
16 introductions for vigorous treatment of multi-physics  
17 phenomena and transient analyses with deforming mesh  
18 capability, which is an important aspect of fast  
19 reactor design.

20 In terms of impact, improved operational  
21 safety margins through high order and high fidelity  
22 modeling close-to-first principle solutions or  
23 benchmarking with, benchmarking of lower fidelity,  
24 lower order modeling approaches. Again, multi-level  
25 interface with matching levels of fidelity, and by

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1       that I mean providing ten by ten power distributions  
2       to match with CFD-type ten by ten analysis, subchannel  
3       analysis of entire reactor core and finally, enhance  
4       the impact of limited experiments to support reactor  
5       design and licensing.

6               PROTEUS is the first of the two neutronics  
7       codes I will cover today. It is a suite of cross-  
8       section generation capability, three different neutron  
9       transports solvers, and a general perturbation theory  
10      and sensitivity analysis capability all in one  
11      package. It also comes with unstructured, finite  
12      element meshing tools, or complex geometries, and  
13      cross-processing and visualization capabilities.

14             MC-squared-3, the cross-section, multi-  
15      group cross-section generation tool can be used for  
16      both fast and thermal spectrum reactors, including  
17      local heterogeneity effects in a way that  
18      homogenization of the units cell prior to the cross-  
19      section generation is not needed.

20             PROTEUS consists of two highly-scalable  
21      neutron transport solvers for complex geometries.  
22      Again, without any homogenization, these are solvers  
23      based on the method of discrete ordinates and method  
24      of characteristics. They're highly scalable in a way  
25      that they could scale to very large number of

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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.

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1 CHAIRMAN CORRADINI: You have mentioned  
2 now two or three times, is there something unique  
3 about some of these reactors, I think I know it for  
4 sodium, but is there something unique about the other  
5 reactor designs that you need the coupling  
6 characteristic? Because it would strike me this would  
7 make the use of it much more difficult.

8 MR. SOFU: One example would be pebble bed  
9 reactor that the multi-physics coupling could enable  
10 accessing the neutronics effects consistent with the  
11 temperatures of the solutions reactor core.

12 CHAIRMAN CORRADINI: And you'd need the  
13 coupling versus just simply, well, okay. I see your  
14 point. I'll stop there.

15 MEMBER REMPE: Could you elaborate exactly  
16 how you use these codes to support the TREAT restart?  
17 Was it something where you did some calculations and  
18 you provided them to someone from DOE, or how did  
19 these codes help you get the reactor restarted?

20 MR. SOFU: Yes, I think the TREAT restart  
21 effort went through a licensing process not with NRC  
22 but ---

23 MEMBER REMPE: The authorization was DOE.

24 MR. SOFU: Correct. And as part of that, I  
25 think RATTLESNAKE was used as one of the codes that



1 supported the assessment of the reactor core, but also  
2 the RATTLESNAKE's ability to analyze a particular  
3 experiment where in the test channel, the test moved,  
4 there's a different type of fuel, could be accident-  
5 tolerant fuel and coupling the overall TREAT reactor  
6 core response with the experimental fuel pins tested  
7 in the channel, so-called power coupling factors and  
8 things like that is evaluated to a great extent in  
9 very great detail with RATTLESNAKE.

10 In the past, such a power coupling was  
11 done mostly based on intuition. There wasn't much of  
12 a technical basis. You would actually look at the  
13 temperature sensors, what you read input in the test  
14 loop and then try to correlate what was measured  
15 overall reactor response during a transient.  
16 RATTLESNAKE did provide a mechanistic basis for that.

17 CHAIRMAN CORRADINI: But for the re-  
18 licensing of TREAT, for the allowance for TREAT to go  
19 forward and restart.

20 MR. SOFU: Also for experiment modeling.  
21 You see, I think the mission of RATTLESNAKE to support  
22 TREAT operations and experiment design is not over.

23 CHAIRMAN CORRADINI: Oh, okay.

24 MR. SOFU: Its use is going to continue.

25 MEMBER REMPE: So because I have not ever



1       been personally involved with an authorization to  
2       restart a reactor, did you just give them the  
3       RATTLESNAKE calculations, or did you say this is what  
4       we would have gotten with another code and this is  
5       what we got with RATTLESNAKE, and we believe  
6       RATTLESNAKE's better because of X, Y, and Z, DOE  
7       looked at both, I assume it was coming from DOE,  
8       looked at both of them?

9               MR. SOFU: Yes. I wonder if Jon Carmack is  
10       here, would be able to answer that specific question.

11              MR. CARMACK: I'm Jon Carmack, from the  
12       Idaho National Laboratory, sort of. The way I  
13       understand it, Joy, we have to have a code that we  
14       design the experiment packages in TREAT, but the code  
15       also has to be able to model the driver core. And so  
16       RATTLESNAKE is built on the MOOSE-BISON, or the MOOSE  
17       framework to model the core but also provide the  
18       coupling for experiment design. It's going to be used  
19       in the future.

20              I don't believe there's any historical  
21       code that was used to benchmark against, so they've  
22       been doing a bunch of calibration experiments in the  
23       reactor to correlate with that. Dan, you got input?

24              MR. FUNK: I'm Dan Funk, the former manager  
25       for modeling simulation programs in NE. Joy, I just



1 want to make sure we clarify here, I don't believe  
2 that RATTLESNAKE was required in order to get, to  
3 obtain permission and authorization to start up TREAT.  
4 I want to make that clear. But it was useful in  
5 confirming what some of the calculations and  
6 conclusions and authorization basis was, but it was  
7 really pointed more towards the development work at  
8 that point.

9 The desire was to have tools that would  
10 enhance the use of TREAT as we projected would be  
11 needed, and so we're looking at it very critically,  
12 it's proceeding not as fast as maybe some would hope,  
13 but as much as funding will allow. So this is more  
14 forward-looking in some ways. The capabilities are  
15 there but I just wanted to clarify that so that we  
16 didn't give the wrong impression.

17 MEMBER REMPE: Thank you. This helps.

18 CHAIRMAN CORRADINI: So let me make sure I  
19 understand, because I'm --- So PROTEUS, I have to go  
20 back a slide, PROTEUS does the reactor physics and  
21 MCC-3 does the initial ---

22 MR. SOFU: Cross-section generation.

23 CHAIRMAN CORRADINI: Cross-section  
24 generation? And RATTLESNAKE is, at least to a first  
25 approximation, performs the equivalent function of



1 PROTEUS?

2 MR. SOFU: Correct.

3 CHAIRMAN CORRADINI: So, I'm sorry to sound  
4 economical, but why have two?

5 MR. SOFU: I think there are certain  
6 reasons why two, the NEAMS program supported  
7 development of these two capabilities.

8 CHAIRMAN CORRADING: But you're not ---

9 MR. SOFU: Historically, PROTEUS code was  
10 originally supported. The NEAMS program investment in  
11 the RATTLESNAKE development was mostly focused within  
12 the context of TREAT restart.

13 CHAIRMAN CORRADINI: Oh. Okay. I get it.

14 MR. SOFU: I think the RATTLESNAKE has  
15 proven clearly that the good capabilities to support,  
16 especially for thermal reactor analyses, HTGRs and ---

17 CHAIRMAN CORRADINI: I'm jumping, but I'll  
18 jump and ask the question. So if your industry council  
19 comes to you and says, what would you recommend we  
20 consider for our sodium fast reactor or our gas-cooled  
21 thermal reactor or my liquid-fueled MSR, you'd say  
22 either?

23 MR. SOFU: I would say for fast reactors I  
24 would advocate use of PROTEUS, for thermal reactors  
25 RATTLESNAKE. I think that's also consistent with Steve

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1 Bajorek's vision of utilization of RATTLESNAKE to  
2 support pebble bed type concept analyses within NRC.

3 MEMBER KIRCHNER: And could you explain why  
4 one is better for one application and the other's  
5 preferable for the other? You're basically using  
6 transport methods, you're basically using, I would  
7 guess, in-depth trials for cross-sections.

8 MR. SOFU: That's an excellent question. In  
9 fact, I think you could probably do both with both  
10 codes. But the level of validation basis from PROTEUS  
11 is really strong, and I think those are my next few  
12 slides.

13 MEMBER KIRCHNER: Okay, fine.

14 CHAIRMAN CORRADINI: Thank you.

15 MR. SOFU: So in the next pages I'll talk  
16 about the verification and validation basis for these  
17 two codes. It's mostly for PROTEUS, because of its  
18 longer development history, but RATTLESNAKE also has  
19 a very strong V&V basis, and I have a slide on that.

20 So MC-square-3 and PROTEUS solvers have  
21 undergone rather extensive V&V process, and in the  
22 next few slides I included only the validation cases  
23 and only for advanced fast spectrum reactors. But  
24 these two codes have also been applied to numerous  
25 other thermal reactor V&V cases, including the TREATS

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1 experiments, RPI benchmark, OECD NEAs benchmarks and  
2 then ATR benchmark recently. In this slide, I'm  
3 showing the critical experiments conducted at Los  
4 Alamos zero-power reactor, ZPPR and EPR-II  
5 experiments. Those are all US-based legacy  
6 experiments.

7 The BFS experiment that you see, as well  
8 as CEFR startup tests are more recent, and these are  
9 leveraged through international collaborations.

10 BFS in particular is a Russian critical  
11 facility, pretty much the only one that is in  
12 existence today that can support fast-reactor design.  
13 It's located in IPP in Obninsk and used by KRA to  
14 support their PGSFR design, CEA to support their  
15 Astrid design and TerraPower for their traveling wave  
16 reactor design.

17 CEFR is China experimental fast reactor  
18 and analysis of its physics startup test is an ongoing  
19 IEA-coordinated research project. DOE and NRC are also  
20 participants in this effort.

21 The figure you see on the right shows  
22 ZPPR-15 tests of four measurements in comparison of  
23 results for your uranium-235 fission rates, and the  
24 bottom figure is for DFS 761 for uranium-238 fission  
25 reaction rates.



1           This is, this page provides a bit more in-  
2       depth look at the comparisons for one of the tests  
3       listed on previous page, zero-power reactor 6 and 7.  
4       The chart on the right shows reaction rates along with  
5       the radius of the core with two enrichment zones, and  
6       the peak reaction rates are at the core center. This  
7       is only for one of the load configurations and as  
8       shown in the chart, all the results are within the  
9       measurement uncertainties.

10           The table at the bottom shows eigenvalue  
11       predictions for four different load configurations,  
12       all within 80 pcm accuracy with experiment. This is  
13       considered fairly good.

14           MD-squared-3 PROTEUS and PERSENT have also  
15       been indirectly validated against integral tests  
16       performed at EBR-II and ftf. The results of two such  
17       tests are shown in this and next page.

18           In this page, the comparisons of multi-  
19       physics analysis with data from EBR-2 inherent safety  
20       demonstration tests, chart 45 is shown. This test has  
21       been studied as a benchmark exercise in a recent IAEA-  
22       coordinated research project with participants from 12  
23       countries, and the results show predictions by each  
24       participant with respect to test data.

25           As an unprotected, that means un-SCRAMed



1 test, the predictions for time-dependent power relies  
2 heavily on accurate assessment of the complex  
3 reactivity feedback mechanisms following detailed  
4 depletion analysis over several core cycles.

5 Good agreement with test data, what's  
6 shown here is power, temperatures and flow rates, all  
7 indicate validity, however indirect, of neutronic  
8 assessments against data from a very rare integral  
9 test where numerous interconnected phenomena are at  
10 play all at once.

11 CHAIRMAN CORRADINI: This was just the loss  
12 of, the unprotected loss of ---

13 MR. SOFU: It's a station blackout of ---

14 CHAIRMAN CORRADINI: Unprotected station  
15 blackout, okay. But that's a loss of flow test for the  
16 SFR, correct? That's essentially.

17 MR. SOFU: Normally loss of flow implies  
18 you lose the primary pumps only. In that previous  
19 test, the intermediate pumps are also, so it is loss  
20 of flow plus loss of heat sink combined.

21 CHAIRMAN CORRADINI: I see. Okay.

22 MR. SOFU: The other tests that were used  
23 as an indirect validation basis for these codes have  
24 been, the FFTF passive safety demonstrations has so-  
25 called loss of flow without SCRAM test number 13. This

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1 test is a new benchmark exercise, is another IAA-  
2 coordinated research project starting this year with  
3 Argonne, PNNL, TerraPower, MIT and I believe NRC as  
4 U.S. participants.

5 Also as an unprotected or un-SCRAMed test,  
6 the predictions for time-dependent power relies  
7 heavily on accurate assessment of complex reactivity  
8 feedback mechanisms. In the FFTF case, it also  
9 includes the response of GEMS, gas expansion modules,  
10 as novel passive reactivity shutdown device used only  
11 in FFTF.

12 As this benchmark project is just  
13 starting, we are showing only the preliminary results  
14 in comparison to test data but already a reasonable  
15 agreement has been observed for power, temperatures  
16 and flow rates.

17 This space provides a summary of  
18 RATTLESNAKE's verification and validation basis with  
19 several TREAT validation and thermal reactor benchmark  
20 verification cases that have been either completed or  
21 ongoing. Strong TREAT emphasis reflects the  
22 developmental focus of RATTLESNAKE and highlights its  
23 strength as a capability to analyze the accidents with  
24 rapid reactivity changes.

25 I'll quickly go through ---



1                   MEMBER MARCH-LEUBA: Are all of these  
2 benchmarks sodium, or is there any for gas-cooled  
3 reactors?

4                   MR. SOFU: I think there's one gas-cooled  
5 reactor benchmark, HTR-10 benchmark, I had a slide but  
6 Steve asked me to put it in the background.

7                   MEMBER MARCH-LEUBA: You show some bias?

8                   MR. SOFU: It's actually, we need to be  
9 selective. I have to say that pretty much every slide  
10 that you will see in my presentation, also with  
11 Richard and Elia's presentations that will follow,  
12 each page could be a presentation of its own. You can  
13 only present, squeeze so much in short time.

14                  MEMBER MARCH-LEUBA: While I have you  
15 interrupted, the PROTEUS calculation shows the coolant  
16 temperatures. So is PROTEUS a capital thermal-  
17 hydraulic and neutronic?

18                  MR. SOFU: Correct. Essentially, and this  
19 is really not a fully-coupled case in a way that we  
20 use the electronics tools to evaluate the, start with  
21 a fresh core and deplete it to the point where the  
22 tests were performant to several cycles from fresh  
23 core, and then do a sensitivity analysis to evaluate  
24 reactivity feedback coefficients, and those reactivity  
25 feedback coefficients go into codes like SAM, you'll

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1 hear about, to determine the transient response of the  
2 whole primary and intermediate system, and that gives  
3 you the temperatures.

4 But temperatures are intimately connected  
5 to power in a way that if your reactivity feedback  
6 coefficients are not calculated right, then you have  
7 no chance of getting temperatures right or power  
8 right. So that type interconnected phenomena from  
9 integral tests is kind of a unique advantage here.  
10 There are no such tests outside EBR-II and FFTF.

11 There is very limited data coming from  
12 Monju and Phoenix but those are all SCRAM tests. I  
13 don't think this current climate, there probably won't  
14 be any other opportunity to unprotected tests,  
15 especially with advanced reactors. So that's all we  
16 have, and I think we have a good agreement, good  
17 handle on that.

18 MEMBER KIRCHNER: Just to follow up on  
19 Jose's question, is PROTEUS calculating the flow, the  
20 loop conditions, or is that a different code?

21 MR. SOFU: No, that's actually, that's SAM  
22 that you'll hear about later.

23 MEMBER KIRCHNER: Okay. So this is a  
24 combination of SAM and PROTEUS.

25 MR. SOFU: Correct. It's one-day coupling,



1 in other words you evaluate reactivity feedback  
2 coefficients and core power distributions, and SAM  
3 uses that to analyze the transient.

4 MEMBER MARCH-LEUBA: By reactivity you mean  
5 the power reactivity feedback?

6 MR. SOFU: Correct. The reactivity  
7 feedback, I think it's worth showing this slide here,  
8 that net reactivity, what's shown in the top, consists  
9 of several components that could be the temperature  
10 coefficients for the fuel, fuel axial expansion,  
11 metallic fuel as counting unique properties that way.  
12 In fast reactors core can radially expand. The test  
13 spectrum is very sensitive to minor geometric changes.

14 MEMBER MARCH-LEUBA: That's why you need a  
15 thermal-hydraulic calculation, activity times 10.

16 MEMBER MARCH-LEUBA: I think what you're  
17 referring to is spatial kinetics, but ---

18 MR. SOFU: for EDR-II that was not  
19 necessary at all. It's a very small reactor. It's a  
20 mega-watt thermal. Spatial kinetics is not ---

21 MEMBER MARCH-LEUBA: I'll wait until that  
22 slide and then I'm asking.

23 MR. SOFU: So I'll quickly go through  
24 example application of these two codes to sodium fast  
25 reactors and molten salt reactors in HTGRs in next

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1 seven slides. Some of these examples also highlight  
2 the multi-physics use of these neutronics analysis  
3 capabilities.

4 Here, one example of PROTEUS code usage in  
5 combination with the NEK5000, Elia will cover that  
6 that later, was assessment of hot channel factors for  
7 SFRs. The traditional hot channel factor used in SFR  
8 core design are largely based on several decades old  
9 experimental efforts in support of EBR-II, FFTF and  
10 CRBR projects. Their validity for different fuel  
11 assembly designs of next-generation SFRs is  
12 questionable.

13 To address this particular need, coupled  
14 PROTEUS and NEK5000 calculations are used to reassess  
15 a select group of hot channel factors for AFT-100,  
16 which is a DOE design track, a fuel assembly designed  
17 with 91 fuel pins shown on the right.

18 In the coupling scheme, the pin power  
19 distributions shown on the left on a normalized scale,  
20 obtained with MC-squared and PROTEUS for individual  
21 fuel pins in each hexagonal ring are passed on to  
22 NEK5000 for thermal assessments.

23 A preliminary comparison of the legacy and  
24 newly calculated hot channel factors is provided in  
25 this table. Legacy values based on EBR-2 are in red

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1 font and newly-calculated indicated as SHARP in the  
2 table for the name of the multi-physics interface used  
3 for it are in green font.

4 CHAIRMAN CORRADINI: I don't think I  
5 understand. What is SHARP?

6 MR. SOFU: SHARP is essentially coupling  
7 interface between PROTEUS and NEK.

8 CHAIRMAN CORRADINI: So it's the combined  
9 calculation.

10 MR. SOFU: Correct. The top row shows the  
11 parameters for which the uncertainties are considered,  
12 and the first column shows the sub-list of hot channel  
13 factors reevaluated for AFR-100. As seen in the table,  
14 these preliminary results suggest significant  
15 reduction in select hot channel factors, with safety  
16 significance especially since the metallic fuel  
17 performance for fast reactors is often limited by peak  
18 cladding temperature.

19 You can see that in some cases, for  
20 example cladding interval temperature which is  
21 significant parameter of interest for us, the cladding  
22 thickness uncertainty is reduced from 1.03 to 1.018.  
23 The cladding thermal conductivity influenced is almost  
24 like a, cut down by a percentage that is small, from  
25 1.09 to 1.04, and for fuel center line there's not



1 much of a difference but it's not particularly  
2 important parameter for us.

3 It's important to note that even when a  
4 newly-evaluated hot channel factor is on the same  
5 order as the initially assumed value, it still  
6 provides a better justification for its use based on  
7 validated high-fidelity high-order multiphysics  
8 computation scheme. This technique is currently being  
9 leveraged to assess hot channel factors for DOE's new  
10 versatile test reactor project as a new NEUP IRP.

11 CHAIRMAN CORRADINI: So what, maybe you  
12 said and I missed it, what is the legacy code, legacy  
13 tool you're ---

14 MR. SOFU: It's not a tool, it's an  
15 experiment. It's the value used for ATR-2.

16 CHAIRMAN CORRADINI: Oh. But it was  
17 evaluated using experimental data?

18 MR. SOFU: I think mostly hydraulic tests  
19 and such and I'm not quite sure what else.

20 CHAIRMAN CORRADINI: So this is not, okay,  
21 I misunderstood. I thought this was a calculational  
22 comparison.

23 MR. SOFU: It is not. So international  
24 projects, we see a lot of that too. For example, when  
25 India designed their own reactors they often quote the



1 values used in France or in the U.S., whether or not  
2 it is really applicable for their specific fuel  
3 assembly design. There's a lot of uncertainty going on  
4 in hot channel factors which influence core design  
5 significantly.

6 CHAIRMAN CORRADINI: Okay. But, trying to  
7 figure a way to ask this question. So if I turn to  
8 TerraPower, what would they use? If they wouldn't use  
9 the tool that you're offering.

10 MR. SOFU: I think, I really don't know  
11 what they use. I can't say. But I think generally  
12 accepted hot channel factors based on EBR-II  
13 operations are quoted here in red, and most of the  
14 time if you don't have any other way of evaluating  
15 this coefficient, you'd probably rely on that if your  
16 reactor has some similarities to EBR-II, same type of  
17 fuel assembly, same type of operating regime, coolant  
18 outlets, inlet/outlet temperatures and so on.

19 That's usually pretty much what everybody  
20 does, but TerraPower may have their own way of  
21 reevaluating this using their own techniques.

22 CHAIRMAN CORRADINI: So, let me push the  
23 point a little bit more. If I went and I looked at the  
24 PRISM submission and Super-PRISM, or S-PRISM to the  
25 NRC, what did they use? I'm trying to get a direct

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1 comparison as to what tool is being replaced by this  
2 calculational ---

3 MR. SOFU: I don't think there's any tool  
4 that this calculation replaces. Values are mostly  
5 legacy values everybody relies on. The PRISM, because  
6 of its strong similarity to EBR-II, my guess is that  
7 they would be using the red values that you see here.

8 CHAIRMAN CORRADINI: I'm sorry, Walt, I  
9 interrupted you. You were going to say something.

10 MEMBER KIRCHNER: Was PRISM met metallic?  
11 Is that the current concept?

12 MR. SOFU: Yes.

13 MEMBER KIRCHNER: Wasn't it, it was -- at  
14 one time, wasn't it?

15 CHAIRMAN CORRADINI: No, that was CRBR.

16 MR. SOFU: CRBR.

17 MEMBER KIRCHNER: Also FFTF.

18 MR. SOFU: Yeah, I think there would be  
19 greater similarity to FFTF, which one, PRISM? PRISM  
20 would be very similar to EBR-II.

21 Another example of MC-squared-3 PROTEUS  
22 tool kit used for SFR design is demonstration of its  
23 multi-scale modeling capability. The idea here is a  
24 select fuel assemblies from focal assembly or in  
25 addition to that, surrounding six fuel assemblies can

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1 be analyzed with pin-by-pin level of detail while the  
2 rest of the core can be modeled with homogenized fuel  
3 assemblies, which is the figure shown on the left.

4 We demonstrated this capability again for  
5 the AFR-100 design using PROTEUS discrete ordinance  
6 solver, achieving consistent solutions for the focal  
7 fuel assemble for the second and third cases shown at  
8 the bottom row.

9 Applicability of this approach, the  
10 configurations with strong flux ingredients is yet to  
11 be verified, but our ability to model only the focal  
12 assembly with pin-by-pin heterogeneity while the rest  
13 of the core is modeled homogeneously offers a  
14 significant reduction in computing resources and time.

15 CHAIRMAN CORRADINI: I'm sorry, you don't  
16 have to go back. I'm still back with, so I've got, I'm  
17 still struggling with EBR-II. So EBR-II essentially is  
18 actual data, and you're saying that most, because of  
19 the metal fuel concept, most would probably default to  
20 that if they didn't have a calculation. So the  
21 calculation is showing that the heat challenge factors  
22 are lower than what you'd actually assume or measure  
23 for EBR-II.

24 MR. SOFU: I would say properly measured,  
25 but at the beginning of this study, we studied

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1 existing hot channel factors and tried to find  
2 references for them, and references did not exist. So  
3 essentially those values are taken for granted, and  
4 we've been through a similar exercise for comparing  
5 hot channel factors for the joint design of PGSFR  
6 reactor with Korea. It was a big debating point. They  
7 would use one value and our consults would advocate  
8 using another value, and there was no strong basis for  
9 what value would apply the most.

10 In situations like that, you usually go  
11 with the higher hot channel factor because it's more  
12 conservative.

13 CHAIRMAN CORRADINI: Sure. Okay.

14 MR. SOFU: Another example is application  
15 of the codes to molten salt reactors for eigenvalue  
16 evaluation of commercial thermospectrum concept. The  
17 intent was here to use a commercial NSR design as a  
18 test that for our modeling and simulation  
19 capabilities. This case, both 2-D method of  
20 characteristics and 3-D method transport solution  
21 options were compared with Monte Carlo solutions. What  
22 I'm not presenting here, but we also did compare with  
23 the designer's own results, with good agreement.

24 Generally we do the comparisons with Monte  
25 Carlo as a reference solution, but in this case



1     PROTEUS offers sometimes a greater, more detailed flux  
2     solution of small mesh size for coupling with other  
3     analytical tools as needed, such as the CFT solver. It  
4     also gives you a better flux in regions with low flux.

5             These calculations were conducted for  
6     stationary view. Flowing fuel treatment of PROTEUS-  
7     NODAL solver was also demonstrated for the graphite  
8     moderated thermal NSR benchmark problem. Three cases  
9     were considered to evaluate the effect of delayed  
10    neutron precursor drift on neutronics. Reference case  
11    with stationary field, Case A, with slow-moving fuel  
12    with ten seconds transit in the core and five second  
13    outside the core and Case B with fast-moving fuel with  
14    one second in the core and .3 seconds outside the  
15    core.

16            Calculated eigenvalue suggests about 100  
17    PCM impact on eigenvalue in each case with respect to  
18    previous case, due to decay of the first three four  
19    delayed neutron precursor groups outside the core.

20            The impact of the delayed neutron  
21    precursor drift on reactor kinetics will be greater  
22    during transience, and this analysis will be performed  
23    for the transient MSRE benchmark in FY19.

24            For high HTGRs, that's proof of principle.  
25    PROTEUS was used for both prismatic fuel assembly



1 design shown on the left and whole-core image CRG  
2 simulation shown on the right. The accurate modeling  
3 of the large neutron streaming in the control hole  
4 channel, control channel, the large hole at the center  
5 of the left figure, when the control rod is withdrawn  
6 it is a significant challenge requiring high-fidelity,  
7 high-order transport solutions.

8 The whole core simulations on the right  
9 were for MHTGR core assessment of computational  
10 requirements and scalability of the solver. They  
11 looked at all rods out, operating rods in and all rods  
12 in cases. There was no data to compare with, so those  
13 were more like proof of principle calculations to  
14 demonstrate the ability to model complex geometries in  
15 different reactors.

16 Probably the more important pebble beds  
17 HTGR modeling capability comes from RATTLESNAKE, its  
18 utilization in combination with pebble bed tracking  
19 algorithm. Motivation for the high-resolution multi-  
20 physics simulation for pebble bed motion is to support  
21 direct transport calculation with pebble tracking. The  
22 scoot element method is used to provide time-dependent  
23 position of all pebbles for establishing an  
24 equilibrium course.

25 The results shown at the bottom are for a



1 particle tracking transport with nine pebble model  
2 with respect to reference case with SERPENT,  
3 indicating good agreement, and the ultimate goal of  
4 this effort is to have the ability to track the burnup  
5 of individual pebbles as they move down the core  
6 during the cycle.

7 The figures shown on the right are for  
8 HTR-10 simulations, using RATTLESNAKE. The total,  
9 almost half a million tetrahedra, almost 80,000 node  
10 points ---

11 CHAIRMAN CORRADINI: So, I'm listening and  
12 the question keeps on coming back to me. So, I'm back  
13 to industry again. What would X Energy use if not  
14 this?

15 MR. SOFU: I had that discussion with  
16 Martin at a meeting at ORNL two weeks ago. They're  
17 interested in this capability but I believe they have  
18 their own methodology that they're pursuing. I'm not  
19 quite sure what it is, or based on what code. But the  
20 whole idea is understanding the depletion cycle as the  
21 pebble bed core starts moving down in a very gradual  
22 and slow manner is a challenge, is a significant  
23 challenge for them as well.

24 MEMBER REMPE: So I vaguely remember, was  
25 it South Africans, or someone did an experiment now



1 with the real pebble bed reactor but just with some  
2 pebbles to try and validate that they did, were  
3 capable of tracking how the pebbles would go in, and  
4 it was for a core that didn't have control rods in  
5 like a THTR. Is that what you're, or is this just a  
6 proof of principle calculation?

7 MR. SOFU: It's a proof of principle  
8 calculation at this point. Another important point  
9 where we don't have a completion embedded into this  
10 capability quite yet in a way, we're able to  
11 understand the item value calculation, power  
12 distribution in pebble bed with particles moving down,  
13 but we're not able to deplete each pebble as they move  
14 down. That would be the next logical step.

15 MEMBER REMPE: What did the Germans use for  
16 the ABR?

17 MEMBER BALLINGER: The code that the South  
18 Africans were using was called VSOP.

19 MR. SOFU: That's correct.

20 MEMBER REMPE: But what did the Germans use  
21 for the ABR? Did they have a way of tracking this  
22 burnup on a pebble basis?

23 MR. SOFU: I'm looking for who can help us  
24 with that, but to my knowledge I'm not really sure.

25 MEMBER REMPE: I just was curious.



1           MEMBER BALLINGER: I think in Japan they  
2       tried to take VSOP and turn it into a colossal Monte  
3       Carlo code. I'm not sure they were successful at doing  
4       that.

5           MR. SOFU: Yes, if there's a way of finding  
6       out answers to those questions and getting back to  
7       ACRS I'll be happy to do that.

8           MEMBER BALLINGER: There were a couple of  
9       benchmarks on criticality that they had, and I forget  
10      now, I'm losing track of time. There were some  
11      benchmarks on pebble bed criticality height as he  
12      started adding pebbles to the, pebbles to the core.

13          MEMBER REMPE: So, out of curiosity, if you  
14      do have a chance to find out the answer you can send  
15      it to Weidong. That's the federal designated official.

16          MR. SOFU: Absolutely. I have one more  
17      slide here ---

18          CHAIRMAN CORRADINI: So I'm still back  
19      with, I can't get off of EBT-II. I'm trying to  
20      understand the penalty that I incur by taking these  
21      conservative hot channel factors versus a more refined  
22      approach, and then I have, the next question I have in  
23      my mind is, if those were assumed, and I think I asked  
24      you and you said you weren't sure, whether they were  
25      measured or they were assumed and those were



1 considered assumed and conservative enough to proceed  
2 with operation.

3 Can I get away with that with uncertainty  
4 under the current situation or must I have this sort  
5 of precision? Because if I demand the sort of  
6 precision, I look for an experiment to validate it.  
7 And I'm ---

8 MR. SOFU: I think that would be a question  
9 for NRC, actually. But if I were to put regulator's  
10 hat, I would say I would feel more comfortable for a  
11 hot channel factor that has a sound basis as opposed  
12 to a value that is being used because everybody else  
13 using the same thing, and then you don't even know  
14 where it comes from.

15 And if that value is greater than assumed  
16 value, I don't care. That's still my preference. In  
17 other words, have others reestablish the set, high  
18 channel factor set and use that on a consistent basis  
19 even though it turns out to be more conservative than  
20 some number that everybody relies on.

21 MEMBER REMPE: So are these codes being  
22 used to support the design development for the BTR?

23 MR. SOFU: Well, I think I did mention that  
24 all of the NEUP projects this year, Chris' technical  
25 point of contact is to ask university support to use



1       these tools to analyze VTR design to reevaluate hot  
2       channel practice for BTR.

3               CHAIRMAN CORRADINI: The core itself, or  
4       the experiment?

5               MR. SOFU: The core. Oh, it could be  
6       experiment as well. I am sorry, I didn't mean to rule  
7       that out.

8               CHAIRMAN CORRADINI: What was done, maybe  
9       that was, I'm still not there. What was done, or no,  
10      maybe I should ask it differently. On slide 9, when  
11      you were showing the unprotected station blackout or  
12      essentially loss of flow and loss of heat sink, there  
13      was a whole range of calculations. What were the other  
14      contributors using as their tool?

15              MR. SOFU: Oh. So ---

16              CHAIRMAN CORRADINI: I'm still struggling  
17      with trying to understand how this tool relates to  
18      other available tools and what the potential  
19      Applicant, whether it be for sodium in this case,  
20      sodium or gas, would choose to use as their depth of  
21      analysis?

22              MR. SOFU: I can see that this legend is  
23      kind of slow, but TerraPower was using SAS and SAS4A.

24              CHAIRMAN CORRADINI: Was using what? I'm  
25      sorry.



1 MR. SOFU: SAS and SAS4A. NRG, I don't know  
2 what they were using. KIT was using, I think that's  
3 important because KIT was using PARCS and TRACE.

4 CHAIRMAN CORRADINI: Oh, really.

5 MR. SOFU: Yes. I'm sure, KIT, no, PSI, I'm  
6 sorry. What is KIT? KIT is Germany. KIT was using  
7 SIMMER, PSI was using PARCS and TRACE, KAERI was using  
8 MARS-LMR, IRSN was using a code they called, I'm  
9 sorry, my mind is losing. CIA was using SANS, SANS4A  
10 Fukui was using their own JAEA Code.

11 CHAIRMAN CORRADINI: I guess where I was  
12 going with, the only thing I could remember was SAS.  
13 So, another way of saying it is PROTEUS in combination  
14 with SAM is the replacement for SAS.

15 MR. SOFU: For a lot of these participants,  
16 did get the reactivity to feed the coefficients they  
17 used for those codes from Argonne.

18 CHAIRMAN CORRADINI: Oh.

19 MR. SOFU: They did not do the neutronics  
20 part of it. Only a handful of them did. I think Fuqui  
21 did and PSI did, PSI used PARCS for that, so I think  
22 it turned out doing this benchmark was too much to  
23 bite for a lot of the participants so they, some of  
24 them, large number of them chose to only the system  
25 analysis, safety analysis, transient part of it.



1 CHAIRMAN CORRADINI: So from the standpoint  
2 of trying to understand, what goes through my mind it,  
3 they're using their legacy tools to do the analysis.

4 MR. SOFU: Correct. I think I'll just  
5 briefly mention this since I am running out of time,  
6 this was a multiphysics analysis of SFR core  
7 deformation. It's an interesting assessment because it  
8 uses coupled, fully coupled, PROTEUS, NEK5000 and  
9 DIABLO for structural mechanics calculations to  
10 understand how a fast reactor core would radially  
11 expand.

12 It is an important reactivity effect, in  
13 fact in the chart below you see that this is the  
14 highest contributor to net negative reactivity in this  
15 case, but typically that counts for a lot of the  
16 inherent safety features that we obtained.

17 The ability to make that prediction based  
18 on very detailed subassembly by subassembly  
19 representation of the entire core with neutronics, CFD  
20 level of thermal hydraulics and structural mechanics,  
21 is the first demonstration of having a complete  
22 mechanistic way of predicting this for new design.

23 MEMBER KIRCHNER: What would you venture  
24 the uncertainty is on that, and how does it scale?

25 MR. SOFU: There wasn't anything for us to



1 compare with on this. It was more like a proof of  
2 principle type of demonstration. You know, an ideal  
3 application of this would be perhaps apply this to  
4 EBR-II and FFDF transients and analyze, reassess the  
5 core radial extension feedback and then put that back  
6 into the system analysis code to see if you're getting  
7 consistently code.

8 CHAIRMAN CORRADINI: Right. So this is an  
9 unfair question, but we're in the world of unfair.  
10 What is the person-months of effort necessary to do  
11 such an analysis?

12 MR. SOFU: Elia was involved with this  
13 project.

14 MR. MERZARI: Should I answer that?

15 MR. SOFU: I'm guessing maybe a year type  
16 of, maybe a little longer than a year. Go ahead.

17 MR. MERZARI: So this is the Elia Merzari  
18 from Argonne National Laboratory. It's a bit of an  
19 unfair question in the sense that this was a proof of  
20 concept. So the first time that you do something, it  
21 always takes longer. It took quite a bit to  
22 demonstrate. It took about six months to the  
23 calculations you see there, but I would envision that  
24 once we streamline the process, this could take no  
25 more than a few weeks. It wasn't done on millions of

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1 processors, it was done on 120 processors.

2 CHAIRMAN CORRADINI: So, modest amount  
3 compared to others.

4 MR. MERZARI: Yeah. And you saw something  
5 that you need to do a lot of work to find.

6 MEMBER KIRCHNER: Well, it's crucial to use  
7 it as a design tool, because you're going to hit a  
8 point where the size of the core isn't going to give  
9 you enough, your expansion versus your leakage, etc.,  
10 isn't, it's going to limit the size of the module,  
11 essentially. And then you need to assess your  
12 uncertainty and your margin as you push that limit. I  
13 mean, that becomes a fundamental design challenge.

14 MR. MERZARI: Right. And I should mention  
15 that that calculation was a demonstration again. It  
16 was very little sensitivity, it was some sensitivity  
17 but not near as much as we need, and there are several  
18 sensitivities that go into a calculation like that,  
19 means a stage lost regularly through the core. There  
20 are several things that will need to be done for a to  
21 think of full design tool, but I agree with you.

22 CHAIRMAN CORRADINI: Would depletion be one  
23 of them?

24 MR. MERZARI: Certainly the rigid core  
25 expansion depends on fluence.



1 CHAIRMAN CORRADINI: Okay. And that also  
2 would have to have been done. Or needs to be done, I  
3 should say. Needs to be done.

4 MR. MERZARI: We need some calculations of  
5 different states, but you can assume this rate of  
6 fluence as an input to the calculation.

7 MR. SOFU: In radiation swelling of fuel  
8 assembly, the contribution to this expansion is  
9 captured with the DIABLO models. I think the  
10 importance of that particular application is there is  
11 no such comprehensive multiphysics way of evaluating  
12 the core radial expansion for a test reactor prior to  
13 this demonstration.

14 We have codes like NOUVEAU, you may  
15 remember, Mike, but they are generated during the IFR  
16 program very largely on empirical basis. But you get  
17 a code like that, assume applicability for a new  
18 design, is always going to be an open question.

19 CHAIRMAN CORRADINI: So I know we're  
20 running 15 minutes late but it's unfair, is the reason  
21 we didn't see RATTLESNAKE is because it's in the  
22 background slides but there are ---

23 MR. SOFU: No, I think largely I'm the one  
24 to blame for it because I'm more familiar with PROTEUS  
25 and I think the question about including RATTLESNAKE



1 came in the late stages of preparing for this meeting,  
2 so I was able to leverage three or four slides from  
3 Markie Hart, I was grateful to give you what I have.

4 But we recognize its importance for NRC,  
5 especially for division, Steve Bajorek's vision to  
6 utilize that capability as a component of the MOOSE  
7 framework and for HTGR applications, so by no means is  
8 that an indication of its importance.

9 CHAIRMAN CORRADINI: Okay.

10 MR. SOFU: Thank you.

11 CHAIRMAN CORRADINI: On to fuels. We've  
12 used up about 20 minutes of your time, I'm sorry,  
13 Rich.

14 MR. WILLIAMSON: Okay.

15 CHAIRMAN CORRADINI: And we'll try to give  
16 it back to you, maybe.

17 MR. WILLIAMSON: I'm not sure I need the  
18 full time.

19 CHAIRMAN CORRADINI: Okay.

20 MR. WILLIAMSON: Okay, good afternoon. My  
21 name is Rich Williamson, I work and in fact I've  
22 always worked at the Idaho National Laboratory. My  
23 presentation is Fuel Performance Modeling for Advanced  
24 Reactors.

25 Here's the outline of what I brought to



1 present. I have a single slide to begin with. It gives  
2 background information including the objective of this  
3 particular presentation. I have a section of slides  
4 that are the BISON fuel performance code that  
5 essentially duplicate what you saw this morning in  
6 Steve's presentation. I left them in there  
7 intentionally so that the presentation was more  
8 complete, but we'll be able to skip over that section  
9 almost completely. There is one point I want to make  
10 out of those slides.

11 And then really the bulk of what I want to  
12 talk about is application of BISON to two fuel forms,  
13 TRISO and metallic fuel. So that'll be the bulk of  
14 what I have to talk about in summary, conclusions at  
15 the end.

16 As you know and as you've heard already  
17 this morning, DOE is developing modern fuel  
18 performance, modeling tools applicable to a wide  
19 variety of fuel and reactor types, operating  
20 conditions, geometries, and spatial scales. This  
21 capability has been developed for both advanced and  
22 traditional LWR concepts with LWR fuel receiving the  
23 greatest early emphasis, so that the plan has been to,  
24 from the beginning has been to look at both advanced  
25 and traditional fuel but to really demonstrate and

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1 learn by application first to LWR fuel.

2 As Steve pointed out, multi-scale modeling  
3 for us, the coupling device and the norm it provides,  
4 improve mechanistic material models and has delivered  
5 demonstrated results for UO2 fuel and we intend to  
6 follow that same path for advanced fuels.

7 The presentation objective is to provide  
8 a current status of DOE fuel codes for application to  
9 specific advanced reactor concepts as are identified  
10 in the table, which lists the key advanced reactor  
11 concepts against their fuel and coolant  
12 characteristics.

13 The key takeaway from this table, and I  
14 think it's simple, indicates that the DOE fuel  
15 performance codes BISON and MARMOT have demonstrated  
16 capabilities for metallic fuel, applicable to the SFR  
17 concept, and TRISO particle fuel applicable to the  
18 MHTGR and FHR concepts, but at this stage are not  
19 applicable to the MSR concept which employs a liquid  
20 fuel. So the focus then will be on metallic fuel and  
21 TRISO fuel as I mentioned previously.

22 This is the part we skip over. You heard  
23 about MOOSE, BISON, MARMOT, so you know about M.M.  
24 This is almost a duplicate of what you saw before,  
25 details about BISON and what makes BISON different.

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1 CHAIRMAN CORRADINI: You're doing great.

2 MR. WILLIAMSON: I'm at slide 8 already.

3 So, it slows down a bit in a minute. This slide has  
4 already been covered in some depth by Steve as well.

5 The only point I wanted to make is on this  
6 slide, concerning BISON documentation. I wanted to  
7 draw your attention to the link in the third line  
8 there that is a place you can go to get a current set  
9 of manuals. So although the code is, you have to have  
10 a license to get the source code, the manuals and  
11 documentation for the code are available, external  
12 documents, so anyone can go to that site and pick up  
13 those manuals.

14 The other point I wanted to make is it is  
15 an enormous headache to try to keep a source code and  
16 documentation and validation all in step at the same  
17 time and keep everything complete, so we're working  
18 and currently transitioning to a web-based  
19 documentation system that will combine the theory and  
20 user manuals and post more strict requirements on  
21 documentation of new code, but essentially much more  
22 the documentation will exist with the source code and  
23 build from the source code, so when you get the code  
24 you can build the documentation and that forces  
25 developers to keep things much more in lockstep.

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1           Moving on to TRISO particle fuel. This  
2 slide is an effort to in a single slide cover the  
3 capabilities that are currently in BISON for TRISO  
4 particle fuel. I have a similar slide that I use for  
5 LWR fuel and a similar slide that you'll see in a  
6 minute on metal fuel, and the first point I wanted to  
7 make is this box on the left will always be the same.

8           The general capabilities in BISON, finite  
9 element based for a variety of different types of  
10 geometries, fully-coupled thermomechanics, species  
11 diffusion, these capabilities are the same for all  
12 these fuel types and so that's one of the, in my  
13 opinion, one of the real advantages to a code like  
14 BISON, because much of the fundamental capabilities  
15 that you need are there, and it's oftentimes more a  
16 matter of enhancing and adding capabilities to include  
17 in a fuel type.

18           MEMBER REMPE: Rich, I heard earlier today  
19 you took the PARFUME models and put them into BISON.  
20 Didn't PARFUME also have something about the silver  
21 attack on the silicon carbide for accident  
22 temperatures, so does the DOE approach say use BISON,  
23 but then if you need to do an accident, still go use  
24 PERFUME, or do you still have PERFUME that you guys  
25 are using at Idaho, or what's the story?



1 MR. WILLIAMSON: We still have PERFUME. To  
2 my knowledge it's no longer actively supported. The  
3 intent is to move away from PERFUME but there are  
4 capabilities that still exist in PERFUME that are not  
5 in BISON yet, and that's part of our current gap  
6 analysis. That's what we're working on now, too, to  
7 identify the gaps and put our development efforts into  
8 closing those gaps.

9 MEMBER REMPE: What would you use if you  
10 don't start, are you going to try to have an accident  
11 version, like go to MELCORE or something like that for  
12 accident analysis, or what's the plan? Or you haven't  
13 decided yet?

14 MR. WILLIAMSON: Yeah, I guess I would come  
15 down to haven't decided yet, although we don't plan,  
16 as with LWR fuel and ATF fuel that you heard this  
17 morning, there's no intent of going to severe melted  
18 fuel or anything like that.

19 CHAIRMAN CORRADINI: But I think that where  
20 Joy was going is if you take this to different DBAs  
21 and beyond-DBAs, you're going to need to do that to  
22 develop source terms. To develop source terms, you're  
23 going to need a release model. To have an release  
24 model, you're going to have to put it in a construct,  
25 so is the construct PERFUME? That's what I heard you

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1 kind of say.

2 MEMBER REMPE: And you said PERFUME's no  
3 longer supported so I think you got to go to MELCORE  
4 or something, I don't know.

5 MR. STANEK: I think a lot of this will be  
6 described in Tanju's last presentation. I'm not going  
7 to list source term that will go through for each of  
8 the reactor types, how one could generate a mechanism  
9 source term.

10 MEMBER BALLINGER: Can you do UCO as well?

11 MR. WILLIAMSON: No. Not today. We do UO2  
12 only at this stage. The developments that you see here  
13 actually occurred early in BISON's life. This  
14 capability was available in like 2013 and there hasn't  
15 been a huge amount of effort in development since  
16 then.

17 MEMBER BALLINGER: Because I think that's  
18 what does in UCO.

19 MR. WILLIAMSON: Again, that's a gap. And  
20 you'll see when I come to the end of the triso section  
21 that is one of the areas of development for next  
22 fiscal year.

23 CHAIRMAN CORRADINI: So, Rich, maybe I  
24 misunderstood the cartoon. Is the colored cartoon in  
25 the middle the kernel or the compact?



1 MR. WILLIAMSON: In the middle is just the  
2 particle.

3 CHAIRMAN CORRADINI: So, excuse me for  
4 sounding holy god, you're going to nodalize that and  
5 then you got to get 1,000 to 10,000 of those in a  
6 compact and billions of them in a core, or are you  
7 developing some sort of empirical set of calculations  
8 that then would feed into some more macroscopic --- I  
9 guess I misunderstood.

10 MR. WILLIAMSON: I think I have a great  
11 answer to that coming.

12 CHAIRMAN CORRADINI: Okay.

13 MR. WILLIAMSON: So if I don't get to that  
14 then we'll come back to it, but I think I have that  
15 answer and I'll make sure to cover that.

16 So we talked about general capabilities.  
17 Fuel kernel is UO2 to date, and that's principally  
18 because UO2 is already a known quantity for us and so  
19 the UO2 model that we use for LWRs is essentially  
20 applicable to particle fuel although there are issues.  
21 For example, the CO production that is important for  
22 TRISO particle fuel had to be implemented or included  
23 for the TRISO capability.

24 Likewise, gap behavior, with TRISO  
25 particle fuel a gap can form between the inner, the



1 porous pyrolytic carbon layer and the inner pyrolytic  
2 carbon layer and so you have to be able to handle a  
3 gap. We do gaps from the experience in the LWR world  
4 and so gap behavior is essentially there, we just have  
5 to worry about changing the fluid and including some  
6 capability to move mass across the gap.

7 So in essence, the newness of BISON for  
8 TRISO in material models for silicon carbide and  
9 pyrolytic carbon. We've included an irradiation creep  
10 model for silicon carbide and for pyrolytic carbon  
11 anisotropic irradiation-induced strain and irradiation  
12 creep.

13 And these models, Joy mentioned, come from  
14 PERFUME. Our actual source for these is mentioned at  
15 the bottom, but I think you'll find that's true. The  
16 same models that are in this source in 2004 were in  
17 PERFUME.

18 MEMBER BALLINGER: What are you defining as  
19 failure? Are you modeling failure?

20 MR. WILLIAMSON: You're getting to all the  
21 points that we don't do, and that's one of them.

22 MEMBER BALLINGER: Is that, the particle  
23 fuel is inherently probabilistic.

24 MR. WILLIAMSON: Understood.

25 MEMBER BALLINGER: Inherently



1 probabilistic.

2 MR. WILLIAMSON: Understood. And so, again,  
3 when you see my plans for even next year, that's one  
4 of them. The point I need to make again is this is  
5 development that has really lain dormant for a few  
6 years and now with increased interest in advanced  
7 reactors and TRISO fuel, has cranked back up and those  
8 are areas that we will address and have begun to  
9 address.

10 Now I have three examples, and I hope  
11 these lead to an answer to Mike's question. I have an  
12 example of an application device to a 1-D spherical  
13 particle, then a 2-D and a 3-D application. I'll start  
14 with the 1-D case.

15 It assumes spherically symmetric. And  
16 because it's spherically symmetric, it can be done in  
17 1-D. So the mesh you saw was a three-dimensional mesh  
18 which is indeed complex. But if you assume it's one  
19 dimensional, as is done with PERFUME, then the  
20 problems run very quick, typically in under a second.  
21 And so with 1-D, if one assumes spherical symmetry,  
22 then one can run many of these particles and do  
23 statistical analysis, failure analysis in the same  
24 sense that it was done in PERFUME.

25 So this is a 1-D example. It involves the



1 geometry you see here, so a UO2 kernel, porous  
2 paralytic carbon layer and then the typical three  
3 TRISO layers. What we've looked at as far as physics  
4 in this problem is thermomechanics plus cesium  
5 diffusion. We looked at a single fission product  
6 diffusion. There are no issues with adding other  
7 species to that, and then for this example, and this  
8 is just an example calculation, we show, what we  
9 looked at here was really three steps.

10 First an irradiation period that goes for  
11 two and a half years to a burnup of 12 percent as a  
12 step one. Then actually we moved from the core for 100  
13 days in storage to decay, and then to simulate  
14 accident behavior, the particles essentially were just  
15 heated, furnace-heated to 1800 K for 220 hours to see  
16 the effect of an increased temperature.

17 MEMBER REMPE: This is ---

18 CHAIRMAN CORRADINI: This is an experiment?

19 MR. WILLIAMSON: This is a pure example.

20 MEMBER REMPE: This is where I'd think  
21 you'd want to have the silver. Don't they start having  
22 problems like 1600 C is when you start worrying about  
23 the silver?

24 MEMBER BALLINGER: Silver doesn't attack,  
25 it migrates through.

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1                   MEMBER REMPE: Right, okay, so then you  
2 have to worry about it ---

3                   MEMBER BALLINGER: Cesium does a number on  
4 the ---

5                   MEMBER REMPE: But doesn't it start  
6 migrating through at ---

7                   MEMBER BALLINGER: Much lower temperature  
8 than that.

9                   MEMBER REMPE: Yeah. So it seems like  
10 you're kind of missing something.

11                   MR. WILLIAMSON: Yes. And I agree. I agree  
12 fully. We included cesium because we knew that cesium  
13 would move through the silicon carbide layer at those  
14 temperatures whereas it doesn't at operating  
15 temperatures. But yeah, point's well taken. Again,  
16 that species can be added to this calculation.

17                   This, again, is just an example  
18 calculation to demonstrate capability, and there's  
19 lots of results to show. I just showed two. One's the  
20 tangential stress history for both the silicon carbide  
21 and pyrolytic carbon layers. I would just trace the  
22 red curve at the bottom which shows the silicon  
23 carbide layer, and it shows the expected behavior of  
24 that layer moving in a strong compression early in  
25 life because of the compression of the pyrolytic

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1 carbon layers but as the pressure builds in the  
2 particle that stress eventually goes into tension and  
3 then into significantly higher tension during the  
4 accident. So again, just a demonstration of  
5 capability.

6 The plot on the right shows the cesium  
7 concentration, these are radial profiles from the  
8 center of the particle out to the edge and two of the  
9 most curves show basically the cesium distribution  
10 after radiation and after storage, no change there,  
11 and then when raising the temperature much higher,  
12 then you start seeing the cesium diffuse out. That was  
13 the point we were trying to make here.

14 Again, this is in 1-D but run times of  
15 under a second permit rapid analysis if one wants to  
16 look at loss of particles.

17 The second example is now two dimensional,  
18 base spherical particles can occur during  
19 manufacturing as is shown in this micrograph. If one  
20 is okay looking at a single-faceted, aspherical  
21 particle, then this problem can be analyzed in 2-D  
22 axisymmetry. So it's a step up from 1-D, still  
23 computationally reasonably simple but it does permit  
24 one to look at a multidimensional type of effect.

25 So here we looked at the same example,



1 behavior as before, base irradiation followed by an  
2 accident, but now are comparing a spherical particle  
3 to a particle that has a facet, it has a flat spot on  
4 it. The two results that I chose to show are shown  
5 here. The red curve compared to the blue curve is the  
6 stress history in the outer silicon carbide layer, and  
7 you see the aspherical raising, after radiation, much  
8 higher stresses, much higher tensile stresses.

9           You see the same in this contour plot.  
10 This is at the end of the base irradiation and you  
11 see, for this example geometry that we picked,  
12 increases in the tensile stress in the order of a  
13 factor of four by having this facet there. So the  
14 multi-international effects are clearly important and  
15 can be addressed with BISON and 2-D reasonably  
16 efficiently. This problem ran in a few minutes, as I  
17 recall. Six minutes, using eight processors.

18           Moving now to the 3-D. Particles can show  
19 localized thinning of the silicon carbide layer due to  
20 soot inclusions or because of fission product  
21 interactions on that layer, which obviously will  
22 degrade the capability of the silicon carbide layer to  
23 handle the pressure of the particle.

24           So for this, again an example, we simply  
25 added random thinning to the silicon carbide layer as



1 one might see here and simplify the case even more,  
2 just looked at asymmetry of this hole in this whole  
3 particle.

4 And the takeaway from this, as you can  
5 see, the stresses plotted here a region that is not  
6 thin compared to a thin region. You see significantly  
7 higher ensile stresses, significantly higher cesium  
8 fluxes in those regions. So certainly concerns that  
9 come up that can really only be addressed in 3-D.  
10 These cannot be done in 1-D.

11 CHAIRMAN CORRADINI: So maybe you're not  
12 done. I was going to ask the question, are you  
13 finished?

14 MR. WILLIAMSON: Yes.

15 CHAIRMAN CORRADINI: So, you went from 1-D  
16 to 2-D to 3-D, and the real manufacturing of the fuel  
17 you don't know where you are between spherical,  
18 asymmetric and a flaw, so what does one assume from  
19 the standpoint of prescribing the uncertainty range to  
20 do the original calculation before you even do the  
21 extant calc. I'm struggling here.

22 MR. WILLIAMSON: I am too. I really don't  
23 have an answer to that.

24 MEMBER KIRCHNER: You have to do it  
25 statistically, based on the post-production sampling



1 of the kernels.

2 MR. WILLIAMSON: I think so.

3 MEMBER KIRCHNER: Your earlier picture  
4 already shows that most of them are not spherically  
5 symmetric. That's the experience from manufacturing.

6 MR. WILLIAMSON: Others probably know  
7 better than I do about that, you know, but that's ---

8 CHAIRMAN CORRADINI: Okay. So that would  
9 lead me to my next thing. Are, you have the AGR  
10 experiments. Was there pre-analysis so you knew the  
11 range of geometrical conditions of those compacts so  
12 you could then put that into a calculation, then see  
13 what you got post-test for the AGR, I can't remember  
14 which was which. I think AGR-1 was steady stage, R-2  
15 was taken to failure, I don't remember. But is the,  
16 are the AGR experiments the place for validation of  
17 these sorts of analyses?

18 MR. WILLIAMSON: I think so.

19 CHAIRMAN CORRADINI: But they've yet to be  
20 looked at?

21 MR. WILLIAMSON: Correct. I'm about to show  
22 you what validation is done today. And it isn't a  
23 great deal. The only other point I wanted to make on  
24 this slide is now the run times have gone from a few  
25 minutes, so we went from under a second to a few

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1 minutes, now to a few hours on eight processors, and  
2 obviously that could be reduced some with more  
3 processors but now these are much more significant  
4 computations.

5 MEMBER BALLINGER: There were a whole bunch  
6 of benchmark runs, MPR 1, 2, 3 and all that. Are you  
7 aware of those?

8 MR. WILLIAMSON: I thought you were going  
9 to the benchmark, the IAEA benchmark.

10 MEMBER BALLINGER: Well, there's them too  
11 but there was a whole series of benchmark codes,  
12 benchmark runs in the early days that PERFUME was  
13 compared to as well along with others, and they didn't  
14 do too well, primarily because of the probabilistic  
15 nature of the failures. And so them had to do some  
16 stuff to make it work. But those, I don't see those  
17 listed. They're very well characterized.

18 MR. WILLIAMSON: Point well taken. We'll  
19 look at those. We haven't yet.

20 MR. STANEK: Rich, maybe this is a good  
21 point to point out something that Steve went through  
22 very quickly in his fuels presentation today, which  
23 was, it's analogous, which was he showed a 3-D image  
24 of a missing pellet surface, so that's a manufacturing  
25 flaw in UO2 pellet, but the 3-D code like BISON, you

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1 can do an analysis on manufacturing tolerances, what  
2 sort of tolerances can be, what size flaw leads to  
3 what size stress concentration is essentially the  
4 analysis that can be done, which would then inform the  
5 manufacturing tolerance which would then have an  
6 impact on your probabilistic failure assessment.

7 And so, this 1-, 2-, 3-D type of analysis,  
8 I think that's sort of where we're getting at too, is  
9 that yes, failures are probabilistic. Having a handle  
10 on how much of a flow one can accommodate in the fuel  
11 fabrication is something that can't be done with this  
12 type of pressure.

13 MR. WILLIAMSON: Okay. Moving on to V&V,  
14 particle fuel V&V efforts to date consist really of  
15 comparisons to an IAEA benchmark which is entitled  
16 CRP-6. Early 2000, I think, is when that happened.  
17 They, it really was an effort to compare codes on a  
18 series of problems rather than comparisons to  
19 experimental data.

20 So it's not full-on validation, but it's  
21 comparison to codes that are fully validated so it's  
22 a good first step.

23 This IAEA CRP-6 developed a set of fuel  
24 performance codes benchmarked in cases for both normal  
25 operation and operational transience. They ranged in



1 complexity from a simple fuel kernel having a single  
2 elastic coating layer to realistic TRISO-coated  
3 particles under a variety of radiation conditions.

4 As indicated in the table on the left,  
5 BISON has been assessed against analytic solutions and  
6 other particle fuel coats for 13 cases from that  
7 benchmark. I think the total was 16, and at the time  
8 we did this work we did 13 of those 16.

9 Many comparisons can be made from that  
10 chart. I chose to make comparisons here to tangential  
11 stress, which is important for particle integrity.  
12 Comparisons of the tangential stress are shown in the  
13 table on the right, but the simplest cases, cases 1,  
14 2, and 3, they all have analytic solutions and so  
15 BISON comparisons are excellent, as one would expect,  
16 to an analytical solution.

17 But the more complex cases shown in the  
18 bottom table, comparisons are made to a range of  
19 solutions attained by the fuel codes and the  
20 benchmark. Here the solutions are compared to the  
21 range, as you see from that table, the range of values  
22 that came out of the handful of codes that were  
23 involved in the benchmark.

24 About all we can say from this comparison  
25 is that the BISON solutions were always within the



1 range of values computed by the other codes, but no  
2 deeper than that.

3 Continuing with the benchmark comparisons,  
4 results are shown here for three cases that have  
5 increased complexity. For these cases, rather than  
6 compare to all the codes, we chose to compare to three  
7 well-known, reasonably well-validated codes. Those are  
8 PERFUME from the U.S., STRESS the UK, and the ATLAS  
9 code which is the only of those codes that is finding  
10 element from France.

11 On the left, you see comparisons for Case  
12 8, which was an effort to simulate the cyclic particle  
13 temperature experienced during multiple passes through  
14 a pebble bed reactor. You can see the passes, the  
15 effort to simulate that. Predicting the tangential  
16 stress in the inner pyrolytic carbon layer, which are  
17 the curves at the top, essentially overlaid for the  
18 four codes.

19 Then predictions of the tangential stress  
20 in the silicon carbide layer, which are the four  
21 curves at the bottom, nearly overlay. I want to note  
22 that these are what I consider excellent comparisons  
23 are really not unexpected, because this Case 8 of the  
24 benchmark carefully controlled everything about the  
25 calculation they compared. They controlled the



1 geometry, even the material models, and so one would  
2 expect very good comparisons. And I point that out as  
3 we turn to Cases 10 and 11, where that wasn't the  
4 case.

5 For Cases 10 and 11, on the right, these  
6 were based on German fuel experiments. Here  
7 comparisons are made to the tangential stress at the  
8 inner silicon carbide wall, and you see substantial  
9 differences in calculations, particularly for Case 11  
10 which are these four curves that go to higher burnup.

11 These variations have been attributed as  
12 part of the benchmark. Principally the differences in  
13 the fission gas release model, so for this case they  
14 didn't control the gas release and CO production  
15 models and so now you're starting to see the  
16 variations in codes because of the different models,  
17 selections of different models.

18 The BISON fell within the, with our  
19 inherent gas and CO production, this BISON is the red  
20 curve which is in kind of the middle of the pack.

21 MEMBER REMPE: Explain to me they didn't  
22 control the fission gas release model. It might be a  
23 function of temperature or something like that?

24 MR. WILLIAMSON: They didn't specify. So  
25 say for Case 8, they went to the point of specifying,



1 this is the constitutive model, this is the equation  
2 you will use for irradiation creep of silicon carbide,  
3 for example. And so you would expect very good  
4 comparisons if you have constrained your benchmark to  
5 that detail.

6 But this Case 10 and 11, they constrained  
7 some of those details but they let the individual  
8 users then use whatever they have in their code for  
9 fission gas release and for CO production.

10 MEMBER REMPE: So then I would say that the  
11 Case 11 is more typical of what would happen if a  
12 licensee were to come in and say, this is what I  
13 believe will happen with my reactor for this  
14 particular event, and jeepers, man, there's a big  
15 variation, and don't they have to have data to  
16 validate any of these different models for that  
17 burnup?

18 MR. WILLIAMSON: I think so. But I ---

19 MEMBER REMPE: Something we'll have to, the  
20 regulator will have to testify knowing that there's so  
21 much variation there.

22 MR. WILLIAMSON: It's something that we  
23 will shortly learn more about as we move from these  
24 benchmarks into full-on validation where we look at  
25 what data are actually available and start making



1 these detail corrections.

2 MEMBER BALLINGER: Did you separate out the  
3 fission gas release plus the CO production to see what  
4 contributed most to the stress? I suspect it's CO  
5 production.

6 MR. WILLIAMSON: And I would agree. So if  
7 you look at the, there's a paper that describes all  
8 this, and in there we compare the pressures and I  
9 don't remember if they were separated but I would  
10 agree, that's typical. I think that's because the CO  
11 is the bigger component out at those higher burnups.

12 CHAIRMAN CORRADINI: So I'd like us to get  
13 through your talk before we take a break, so are we on  
14 our way?

15 MR. WILLIAMSON: When is break?

16 CHAIRMAN CORRADINI: I'm going to declare  
17 break in 15 minutes. How we doing there?

18 MR. WILLIAMSON: I think easily.

19 CHAIRMAN CORRADINI: Okay, good.

20 MR. WILLIAMSON: I think. I hope so.  
21 Because I'm ready to wrap up TRISO just by saying if  
22 you want to read more detail about anything that I've  
23 talked about on TRISO so far, it's in this paper, this  
24 journal article, and then I want to quickly go through  
25 what our plans are with regard to development. Some of

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1 this has already come up.

2 We started now looking at PERFUME and  
3 BISON to develop this gap, capability gap analysis so  
4 that we know what's in PERFUME and what is needed in  
5 BISON. As Ron pointed out, UCO is an important fuel  
6 for particle fuel, and so that's certainly on our list  
7 as well as more mechanistic CO production. CO's a very  
8 important component, as has also been pointed out, and  
9 we have a very simplistic empirical model there.

10 Then particle failure probabilities have  
11 already been mentioned. We also, BISON with its  
12 discreet fracture capabilities, we're in a position to  
13 look readily at partial de-bonding between layers and  
14 actual silicon carbide fracture, and so we will begin  
15 experimenting with that.

16 MEMBER BALLINGER: Again, that silicon  
17 carbide fracture is also probabilistic, because the  
18 Weibull modulus is way different than for metal or  
19 something, and that Weibull modulus is a function of  
20 how you fabricate the particles. And so there's an  
21 uncertainty on the Weibull modulus which translates  
22 into a big difference in stress and fracture strength.

23 MR. WILLIAMSON: I can only agree. With  
24 regard to validation, talked a bit about that. Our  
25 next step that we started on is to look at the



1 database. We need to better understand the database,  
2 review the NRC HTGR research plan to better understand  
3 the issues, and then during FY19 my intent is to  
4 develop a validation plan for TRISO fuel and begin to  
5 learn the high priority cases from that plan.

6 MEMBER REMPE: The only designer that's  
7 coming forward with a gas reactor right now is X  
8 Energy, is that true? Because AREVA said, we can't  
9 find a customer. They've kind of backed off. Is there  
10 anybody else out there that has a gas reactor? Because  
11 if that's the case my next question is, is it true  
12 that X Energy is using something in scale?

13 MR. STANEK: The answer to the first  
14 question is, in terms of gas reactors, I think you're  
15 correct. But there is an FHR vendor that's also using  
16 particle fuels.

17 MEMBER REMPE: That's true. Okay. And then  
18 I guess they are interested in the BISON suite, is  
19 that true? So you have some, I mean if it's true that  
20 X Energy's doing something else other than BISON, I'm  
21 just kind of wondering ---

22 MR. STANEK: Again, we ---

23 CHAIRMAN CORRADING: He's not going to  
24 answer that question.

25 MR. STANEK: Can't answer that question.



1 MEMBER REMPE: Yeah, okay.

2 CHAIRMAN CORRADINI: He's been instructed  
3 not to answer that question.

4 MR. WILLIAMSON: So I'm going to spend my  
5 last ten minutes on metallic fuel, and I think that is  
6 possible. I have less to say about metallic fuel. It's  
7 at a, there's a lot of capability there to do metallic  
8 fuel but very little validation to this point so not  
9 as much to talk about.

10 Here's the same slide that you saw for  
11 TRISO fuel. The general capabilities, as I pointed  
12 out, are the same for all these codes and in fact for  
13 the type of geometry here, for metallic fuel at least,  
14 the gap is essentially the same. One just needs to  
15 change the gap material from gas to sodium, in this  
16 case.

17 So much of the capability was in place to  
18 both the gap and the general capabilities. The real  
19 work has been in developing material models for  
20 metallic fuel. We're looking at both binary and  
21 tertiary UZr and UPuZr alloys, and you see the list of  
22 capabilities that have been placed in the code.  
23 Temperature dependent, temperature, species and  
24 porosity depending on connectivity, anisotropic  
25 swelling, thermal variation creep, thermal porosity-

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1 based fission gas release and zirconium diffusion  
2 models.

3 Cladding is different for these fuels, so  
4 models have been implemented for both HT-9 and 316  
5 stainless in terms of temperature-dependent  
6 conductivities, thermal and radiation creep. For the  
7 HT-9 there's a failure model that has been implemented  
8 in BISON.

9 Coolant channel, again, borrows heavily  
10 from LWR work. In fact, essentially is the same model  
11 with sodium fuel fluid properties and sodium heat  
12 transfer correlations.

13 I have a single fairly simple example  
14 here. This is a pit from EBR-II. It's modeled assuming  
15 axisymmetry, so this is a 2-D-RZ calculation. Here  
16 we're looking at thermomechanics plus zirconium  
17 diffusion in the fuel alloy, all fully coupled. This  
18 is sodium bonded with sodium coolant channel.

19 And then for this problem to look at  
20 parametric behavior and understand fuel behavior  
21 better, the user looked at variations in fuel alloy  
22 composition and pin power.

23 And just two fairly simple results. Here's  
24 the temperature histories for different fuel  
25 compositions. You see expected behavior in that the



1 fuel temperature rises gradually. That's mostly  
2 because of increasing porosity in the fuel until that  
3 reaches kind of a steady state and then the  
4 temperatures become steady. Similarly, the pressures  
5 as a function of different power rates show the  
6 expected behavior that higher powers mean higher  
7 pressures.

8 In regards to fuel metal validation,  
9 there's really quite a bit of older data out there  
10 from EBR-II and TREAT, and I think FFTF. We're digging  
11 into those databases to better understand what's  
12 available. Cases in progress are listed in the table  
13 at the bottom.

14 Scheduled for completion in FY18 are three  
15 cases from EBR-II and an transient case from TREAT. I  
16 have results from one of those cases, from X447. These  
17 are, I would still term these as preliminary because  
18 we've only seen them in the last few weeks and are  
19 still digesting them but this is a binary fuel at an  
20 average power of 30 kilowatts per meter for about a  
21 year. The multiple rods, these rods were taken out as  
22 Steve mentioned at various points in time to do PIE on  
23 them, in order to get these four data points. That's  
24 what had to be done, is a rod had to be removed and  
25 PIE had to be done to get the fission gas release.

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1 CHAIRMAN CORRADINI: Just a quick question.  
2 Is the manufacturer, the way you make the metal fuel,  
3 going to change the properties one would then use in  
4 the calculation? Because my understanding is the way  
5 they made the EBR-II fuel is not the way TerraPower  
6 would make their current fuel.

7 MR. WILLIAMSON: Steve, you're going to  
8 have to help. Steve is a metal fuels guru, I'm not.

9 MR. HAYES: That's true.

10 CHAIRMAN CORRADINI: And you are?

11 MR. HAYES: Steve Hayes, from Idaho  
12 National Lab. The answer is, metal fuels historically  
13 has been manufactured in lots of different ways, and  
14 you're right, TerraPower proposes doing something a  
15 little bit different but one thing we've been fairly  
16 successful in showing over the years is metallic fuel  
17 performance is relatively insensitive to fabrication  
18 routes.

19 CHAIRMAN CORRADINI: So the property, I was  
20 trying to get at the property ---

21 MR. HAYES: I don't think he needs to  
22 modify many properties, or any, based on fabrication  
23 route.

24 CHAIRMAN CORRADINI: Okay. Thank you.

25 MR. WILLIAMSON: Thank you, Steve. Okay,



1 just drawing your attention to these three plots.  
2 Cladding hoop strain is a function of position, the  
3 sharp drop in both the measurements and in the  
4 calculation correspond to the top of the fuel slug.

5 Fission gas release is shown in the upper  
6 right, and then a comparison of the peak inter-clad  
7 temperature. This is a comparison between BISON and an  
8 estimate that was made by the experimenters. There was  
9 no measurements for this plot.

10 So what we can say at this point is we've  
11 done some very early validation of the metallic fuel  
12 capabilities. The first comparisons are very  
13 reasonable. There's significant work yet to be done.

14 Which brings me to the development and  
15 validation plans for metallic fuel. With regard to  
16 development, there's five bullets there. Our plans are  
17 to improve and/or find an alternate for the fuel  
18 swelling model. Early calculations have shown an issue  
19 with the radial swelling. Our current Zr diffusion  
20 models are applicable to tertiary but must be extended  
21 to the binary. We need to investigate lanthanide  
22 diffusion and fuel cooling and cladding interaction,  
23 sodium infiltration and cladding swelling.

24 There's, I guess what I'd like to leave  
25 the impression is there is a capability to do metal



1 fuel but it's to the point where we can begin doing  
2 detailed assessments by comparison to data. We know  
3 there are areas of development that remain and we are  
4 focused on those. We're building the set of validation  
5 cases for FY19. I list three from EBR-II but there  
6 will be more than that.

7 That brings me to summary and conclusions.  
8 I think I'll just let you read those. I guess I, the  
9 top bullets are, I think, obvious as we walk through  
10 this, and the bottom opportunities for cooperation,  
11 certainly one is to implement fuel behavior models in  
12 vendor or NRC codes. I just wanted to point out that  
13 that effort has begun. As we learn more about material  
14 models or we use MARMOT to create proof of material  
15 models, we're very interested in cooperating,  
16 including those in NRC codes or vendor codes if  
17 there's interest. We have begun that effort and moving  
18 in that direction. Obviously there's the opportunity  
19 to use BISON by the industry or by NRC,

20 CHAIRMAN CORRADINI: Questions by the  
21 committee? Okay, let us take a break.

22 (Whereupon, the above-entitled matter went  
23 off the record at 2:56 p.m. and resumed at 3:13 p.m.)

24 CHAIRMAN CORRADINI: Okay, let's get back  
25 together, and I think now we'll turn to Elia.



1 MR. MERZARI: Yes Mr. Chairman, it's a  
2 pleasure to be here. It's actually an honor to be  
3 presenting, and I'm grateful for the opportunity.

4 CHAIRMAN CORRADINI: I'm not so sure about  
5 that.

6 MR. MERZARI: Can you hear me?

7 CHAIRMAN CORRADINI: We can hear you.

8 MR. MERZARI: Okay, thank you.

9 MEMBER REMPE: We're not sure we believe  
10 you.

11 MR. MERZARI: I'm sure, I know. In fact,  
12 I was sincerely not saying the word pleasure there,  
13 but let me ---

14 CHAIRMAN CORRADINI: But you went further  
15 and you said honored and --

16 MR. MERZARI: Yes, I know.

17 CHAIRMAN CORRADINI: -- now it's on the  
18 record.

19 MR. MERZARI: Yes that's right, it's on  
20 the record. So, in this presentation, I will cover  
21 the capabilities for non-light water reactors for  
22 three thermal hydraulic codes in development of DOE  
23 and it's a lot of material so believe me, I'm aware I  
24 have an accent, and I encourage you to stop me when I--  
25 -when you can't understand what I'm saying but please,

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1 perhaps let's consider limiting the interruptions  
2 otherwise you'll never get to the end of this  
3 presentation but---

4 CHAIRMAN CORRADINI: I have a---

5 MR. MERZARI: --now that I've said that,  
6 you're going to interrupt me more, I'm sure.

7 CHAIRMAN CORRADINI: I have a--no, I was  
8 going to say we've dealt with the Spanish so we can  
9 deal with the Italian.

10 MR. MERZARI: Of course. Okay, sounds  
11 good. Okay, here are the codes I'm going to talk  
12 about: SAM is a component-based system code based on  
13 the MOOSE framework which you read about today,  
14 PRONGHORN is an engineering scale akin to the code,  
15 based again on the MOOSE framework, and NEK5000 is an  
16 open source competition free analytics code. For each  
17 code, I will briefly review the current capabilities  
18 and provide the validation status for each of the  
19 advanced reactor technologies of interest. So, due to  
20 the massive scale separation present in nuclear  
21 reactor flows, a more physical approach is often  
22 desirable.

23 Akin to what you saw this morning in  
24 Steve's presentation, a single-code approach is often  
25 insufficient as modeling scales several numbers apart



1 requires different methods. This reason vests DOE as  
2 the full investment in the development of an  
3 integrated multi-scale suite of tools which spans  
4 scales starting from the plant level with SAM to  
5 engineering scales with PRONGHORN, and finally the  
6 finer scales with NEK5000. You will notice that there  
7 is some level of overlap between these codes which is  
8 introduced by design to facilitate coupling based on  
9 past experience. We recognize that most, if not all,  
10 safety analysis would be performed at the plant level,  
11 but the situation may arise when additional final  
12 scale modeling is needed.

13 I want to make a point. So, we are  
14 collaborating on all of these codes with industry  
15 partners, so I'll follow the orders from Chris not to  
16 mention specific vendors, but there is significant  
17 interest from the industry and so let's not also  
18 undersell that point, very significant interest. So,  
19 you will see--there is a very high probability you  
20 will see some of these codes in--if not in licensing  
21 applications, in commercial certifications. So, what  
22 I want to say here--in this presentation, we will--I  
23 will discuss the capabilities, validation status, and  
24 future plans.

25 We recognize that validation is a key



1 concern. The primary focus the recent year has been  
2 on the validation on liquid metal reactors and high  
3 temperature gas reactors, and these efforts are being  
4 expanded to cover additional reactor types. Again, we  
5 envision that the safety analysis will likely be  
6 conducted primarily with SAM, and potentially  
7 PRONGHORN for gas reactors, especially if 1-D shows  
8 approximations are sufficient. There are, however,  
9 several cases where these approximations may not be  
10 sufficient, and coupling to PRONGHORN or NEK5000 will  
11 be needed, or least desirable. Examples for this  
12 could be the pool monitoring in SFRs and the modeling  
13 of the core in fast spectrum molten salt reactors.  
14 So, the suite offers the flexi---

15 CHAIRMAN CORRADINI: Elia, I'm sorry, say  
16 that last part again please?

17 MR. MERZARI: So, what I'm saying is that  
18 you might need coupling to see if the--or post medium  
19 model for the modeling of--the pool modeling in--for  
20 the pool modeling in SFRs, for instance---

21 CHAIRMAN CORRADINI: Oh, okay.

22 MR. MERZARI: --where thermal  
23 stratification is important, and it's shown to be an  
24 important factor in several transients, or of the  
25 modeling of the core in fast spectrum molten salt

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1 reactors---

2 CHAIRMAN CORRADINI: Okay.

3 MR. MERZARI: --where there are  
4 significant effects as I will show.

5 CHAIRMAN CORRADINI: Okay.

6 MR. MERZARI: The suite offers the  
7 flexibility to combine several approaches to reach the  
8 desired level of resolution and accuracy. Now, I'm  
9 going to dig a little bit more into SAM. SAM is a  
10 component-based system co-developed on the MOOSE  
11 framework. It uses a formulation particularly suited  
12 for advanced reactors in the liquid form, so,  
13 something where the MAC number is--oh I'm sorry, did  
14 I--where the MAC number is low. It may also have some  
15 applicability to gas reactors for components in  
16 conditions that do not require multi-phase or fully  
17 compressible solvers. Some offer significant  
18 improvements over the state of the art, the leverage,  
19 and the flexibility brought in using the MOOSE  
20 environment, including the use of coupling to other  
21 cores such as BISON, to model fuel performance during  
22 transients, and three major areas of improvement that  
23 I've listed here.

24 One is the modeling of large enclosures as  
25 I mentioned in--like large pools where thermal

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1 stratification may be an important phenomenon, the  
2 model--flexible modeling of the core where--going  
3 beyond the single channel approach, and improvements  
4 related to molten salt reactors such as the monitoring  
5 of fuel movement and delaying the precaution rift.  
6 For most of its development history, SAM has been  
7 focused on liquid metal reactors and the majority of  
8 these improvements, as well as its validation basis,  
9 pertain to this reactor type. SAM has been compared  
10 against several reactor transients for EBR-II and  
11 FFTF, and in general, they are shown to provide the  
12 same or better accuracies than SAS4A/SASSYS-1 for  
13 those tests. You also hear this sometimes called SAS,  
14 but it's actually--SAS4A is combined to SASSYS-1.

15 It should be noted that SAS has benefitted  
16 from decades of calibration for those same tests, so  
17 we were able to reproduce that history within SAM.  
18 For example, on the right-hand side of the slide, you  
19 may see a comparison between SAM results for two ETF-  
20 II experiments. It also beat the rejection tests, and  
21 in unprotected loss of flow. The PLOF represent the  
22 actual temperature of one subassembly. It is possible  
23 to notice that the behavior is very similar between  
24 SAM and SAS, and very close to the experiment. I will  
25 present a little more comprehensive table with an

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1 overview of the validation status of SAM for both fast  
2 reactors and other reactor types. Among the gaps  
3 identified for fast reactors is one of those that I  
4 guess I was listening to you before when Jose asked a  
5 question--

6 CHAIRMAN CORRADINI: Uh huh.

7 MR. MERZARI: --which is the lack of  
8 spatial kinetics capability, which may be required for  
9 some transients, in particular, for unprotected  
10 transients for very large reactors with significant  
11 homogeneity.

12 MEMBER REMPE: So just out of curiosity on  
13 the bottom plot, and I know nothing about the tests  
14 you're trying to match against, but it's kind of  
15 interesting SAM and SAS4A are just right on top of  
16 each other but none of them are--SAM isn't closer to  
17 the data, if I'm looking at that plot, right?

18 MR. MERZARI: But--okay, so I guess what  
19 I'm trying to---

20 MEMBER REMPE: Yes, it's like why are we  
21 going through this?

22 MR. MERZARI: I'm sorry, what's the  
23 question?

24 MEMBER REMPE: Why didn't it come any  
25 closer to the real data if you've got a model?



1                   MR. MERZARI: I mean actually, they are  
2 essentially equivalent, that's the conclusion there,  
3 they're essentially equivalent.

4                   MEMBER REMPE: The bottom plot.

5                   MR. MERZARI: The bottom plot, yes. No,  
6 but they're essentially equivalent to each other. I'm  
7 not trying to say they're---

8                   MEMBER REMPE: Supposed to be equivalent,  
9 but you didn't get any closer to the data, is why--  
10 what I'm trying to ask.

11                  MR. MERZARI: Right, so the point here is  
12 trying to match SAS for this particular test, and on  
13 the fact that we have not mentioned exactly the data  
14 there, near the peak, these are largely due to very  
15 large uncertainties for the measurement in that  
16 particular--remember these are like--these are an  
17 unprotected loss of flow.

18                  MR. BAJOREK: Elia, this is Steve Bajorek.  
19 I think part of the reason is when they ran this test,  
20 the thermocouples were biased low at these higher  
21 temperatures.

22                  MR. MERZARI: Right.

23                  MR. BAJOREK: So you had--even though you  
24 see good agreement between SAS and SAM and they're  
25 higher than the data, that's actually where they think



1 they should be.

2 MR. MERZARI: Right.

3 MR. BAJOREK: It's at that high range---

4 MEMBER REMPE: Okay, that's why I was--  
5 that's the answer I wanted. You want to not match the  
6 data, is the answer, okay.

7 MR. BAJOREK: --there was a negative bias  
8 in measurement.

9 MR. MERZARI: I was trying to get to this.

10 MEMBER REMPE: Uh huh, I got it.

11 MR. MERZARI: Thank you, Steve. Okay,  
12 move on. One of the key advancements of SAM for us as  
13 far as the development of advanced modeling options  
14 for inlet plenum or delta pool, which is vulnerable to  
15 thermal stratification. Thermal stratification has  
16 been identified in several gap analyses as a key  
17 future development required for these reactor types.  
18 We have pursued multiple approaches in SAM, we are  
19 implementing and validating a traditional 0-D model--  
20 03--0-D mixing models, while also implementing more  
21 advanced multi-D options including system CFD  
22 coupling. The right approach will depend of course on  
23 the complexity of the transient, as shown in the  
24 figure on the top right. There will also be project--  
25 for loss of heat rejection, a simple 0-D model is

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1 often sufficient. We envision the coupling to CFD to  
2 be used primarily through foreman calibrated 0-D, 1-D,  
3 or in general use for the models. We have  
4 collaborated with several international institutions  
5 in this domain, as this remains an active area of  
6 research and development. This extends to evaluation  
7 as well. In fact, that's where we leverage most of  
8 these international collaborations, to obtain data we  
9 don't have. An example is the 1995 Monju turbine  
10 test, for which--which we used for our early  
11 assessment of CFD system code coupling.

12 Moving to gas reactor capabilities, SAM  
13 has current limited capability for gas reactors and  
14 this is not currently able to handle compressible flow  
15 in transients such as air and water ingress, which are  
16 typically the most challenging accidents to simulate  
17 for gas reactors. However, SAM can be used to simulate  
18 key components such as the reactor cavity cooling  
19 system. In fact--and Professor Corradini will be  
20 familiar with this--SAM simulations have shown a good  
21 degree of accuracy in simulating the behavior of RCCS  
22 systems, and were done in collaboration with the  
23 University of Wisconsin, Texas A&M, and the National  
24 Shutdown Test Facility at Argonne National Laboratory.  
25 You can see at the bottom right that SAM can reproduce

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1 the mass flow rate as a function of the rise of  
2 channel in the facility. You will also note that  
3 there is a significant scatter on that data and this  
4 is a function of the strong sensitivity the RCCS  
5 system has on ambient conditions. That is part of  
6 this work; we develop a novel model for the fitment of  
7 ambient conditions and the effect of ambient condition  
8 system analysis is published in a recent paper.

9 Moving on to MSRs, molten salt reactors  
10 pose unique challenges to system co-modeling, and  
11 several features are unique. These include the fact  
12 that the vast majority of the deposition is in the  
13 coolant, as well as the presence of a fuel circuit and  
14 the delayed neutron precursor drift. The validation  
15 basis for SAM is limited for this reactor type, as  
16 little data is currently available, but an important  
17 collaboration is ongoing with Louisiana State  
18 University for the simulation of MSRE. In the top  
19 right, you may see that SAM is able to reproduce these  
20 behavior for this reactor, and the reason--this is  
21 ongoing work, but these results have been published in  
22 a recent 2018 ENS transaction summary. Recently,  
23 we've added several MSR targeted features in SAM,  
24 including salt properties, delayed neutron precursor  
25 drift, generation and transport, and heat generation

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1 in the coolant as well as point kinetics and coupling  
2 for CFD for fast spectrum systems.

3 At the bottom right, you may see a  
4 demonstration of these features for--of the novel  
5 point kinetics capability in SAM that includes the  
6 delayed neutron precursor drift. This--again, this is  
7 just a demonstration with a very simple loss of flow  
8 transient in a simplified single-channel MSR loop  
9 model. One of the key gaps identified for SAM, and  
10 this you will see, it's recognized as an important  
11 challenge for MSRs is the lack of coupling for salt  
12 chemistry models and codes.

13 CHAIRMAN CORRADINI: Can we hold off  
14 there? So what is the coupling that's missing in the  
15 chemistry models?

16 MR. MERZARI: So, how you get properties  
17 in--as you increase the amount of fission gas  
18 material, fission products inside of the key.

19 CHAIRMAN CORRADINI: Oh, okay. I always  
20 thought eventually--oh no, you've got it up here, thaw  
21 and freeze during overcooling events.

22 MR. MERZARI: Yes, I didn't mention that  
23 because I'm going to emphasize that for FHRs.

24 CHAIRMAN CORRADINI: Okay.

25 MR. MERZARI: They're--it is a key

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1 limitation for FHRs.

2 MEMBER KIRCHNER: That order, could you go  
3 back? I'm still pondering about putting in air and  
4 water mixtures into SAM, do you have to change your  
5 basic equation sets that you're solving?

6 MR. MERZARI: For which one, sir?

7 CHAIRMAN CORRADINI: Where are you looking  
8 Walt?

9 MEMBER KIRCHNER: Under SAM.

10 MR. MERZARI: Which slide?

11 MEMBER MARCH-LEUBA: He's talking about  
12 air and water injection. You see---

13 MEMBER REMPE: Air ingress.

14 MR. MERZARI: Oh okay, so for the air and  
15 water ingress? Okay, if you wanted to do that with  
16 SAM, you would need a multi-phase model or a way to  
17 track two phases.

18 MEMBER MARCH-LEUBA: Plus, you would have  
19 to add the chemistry, I mean, the sodium and water  
20 don't mix very well.

21 MEMBER KIRCHNER: No.

22 MR. MERZARI: No, no, I'm talking about--  
23 that's--the air and water ingress are for gas  
24 reactors. Those are the post-rated accidents  
25 typically for gas reactors.

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1                   MEMBER REMPE:       That's not a coding  
2                   capability is it?

3                   MR. MERZARI:    Yes, that's not a coding  
4                   capability, we don't type that.

5                   MEMBER MARCH-LEUBA: Yes.

6                   MR. MERZARI:    But to do that, we would  
7                   need to track those. I don't think you would need  
8                   necessarily an accurate chemistry model to do that,  
9                   but for air and water ingress, you must be able to  
10                  track two phases separately.

11                  MEMBER MARCH-LEUBA: But---

12                  MR. MERZARI:    Well actually, I mean---

13                  MEMBER MARCH-LEUBA: If you have hard  
14                  graphite---

15                  MR. MERZARI:    Oh sure---

16                  MEMBER MARCH-LEUBA: --and you have an air  
17                  ingress---

18                  MEMBER KIRCHNER: Or a water ingress?

19                  MR. MERZARI:    Yes, certainly there has to  
20                  be--graphite interaction will require some material  
21                  modeling for sure. So as mentioned, the next reactor  
22                  type is the fluoride high temperature gas--high  
23                  temperature reactor. This is the combined,  
24                  essentially features of MSRs and gas reactors. The  
25                  coolant is typically a molten salt while the fuel

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1 remains in solid form. The validation basis for this  
2 reactor type is again limited due to lack of available  
3 facilities, but several collaborations are ongoing  
4 with both vendors and universities. SAM presents some  
5 key attractive features for FHRs, including salt  
6 properties as well as salt thaw and freeze models,  
7 which are currently under development in our  
8 collaborations with the University of Wisconsin, and  
9 may be needed in the case of other cooling transients,  
10 as well as to model the start up. I know they have a  
11 nice group at the University of Wisconsin for natural  
12 circulation, I've seen some very interesting thermal-  
13 hydraulic effects there that would be fascinating to  
14 model with this. We note that SAM has also components  
15 targeted specifically to FHRs, such as flow diodes.  
16 As an example, on the right side you may see a  
17 demonstration of FHR simulation for the P-B FHR design  
18 of Berkeley, and this view states how the flow diode  
19 is used to reach the desired long term cooling state,  
20 so basically, to prevent the flow reversal.

21 And now to the fun part. In this table we  
22 summarized the validation status of SAM for fast  
23 reactors. The table represents, on the rows, the key  
24 capabilities and functions in SAM, while in the  
25 columns, we list a set of specific things we have

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1 identified as sources of validation data, both for ITs  
2 and SETs. The columns in green represent actual  
3 reactors, so it's the ultimate validation basis in a  
4 sense. Each cell is marked with a validation status  
5 letter. C stands for Complete, O for Ongoing, and P  
6 for planned. We note that a considerable amount of  
7 work has been done, but far more is needed and it is  
8 ongoing. We also note that for fast reactors were not  
9 nearly as comparable as--were nearly comparable to  
10 LWRs, a significant amount of data is available; we  
11 won't be as lucky in other reactor types. Any  
12 questions on this slide?

13 CHAIRMAN CORRADINI: So let me--maybe you  
14 said it quickly and I missed it, SAM is not a  
15 derivative of SAS4 and SASSYS, it's essentially a new  
16 formulation for--and then originally for sodium  
17 applications, but now single-phase system application?

18 MR. MERZARI: Right, right.

19 CHAIRMAN CORRADINI: Okay.

20 MR. MERZARI: So, the reason I guess I'm  
21 expecting a question there, why the switch, or why the  
22 change---

23 CHAIRMAN CORRADINI: Well I can guess, so  
24 I was going to hold off, I was going to go a different  
25 direction with my question, but you go ahead and



1 answer that question, that sounds good.

2 MR. MERZARI: I think that's the first  
3 time today that that happened. So no, the reason is  
4 while certainly SAS has decades of experience with the  
5 modeling of liquid metal reactors, it has shown over  
6 the years it is pretty hard to modify and couple to  
7 other codes and difficult to maintain. So the idea  
8 there was to essentially replace at least one part of  
9 SAS--let us remind ourselves that SAS does much more  
10 than simple thermal hydraulics--and make it more  
11 flexible and usable in the longer term. Now, I don't  
12 want to make it sound as SAS and SAM are necessarily  
13 one is a replacement of the other; in fact, SAM and  
14 SAS can be used together. SAS has several models  
15 especially for severe accidents that are needed to  
16 model, for instance, in certain conditions the  
17 unprotected loss of flow. So you can use SAM for the  
18 thermal hydraulics and SAS for all those models that  
19 come in the fuel--in the transient fuel analysis.

20 In this table we summarize the validation  
21 status for SAM for FHRs and MSRs. A lot of nice work  
22 has been done here for these reactor types and  
23 actually you shouldn't consider this table nearly as  
24 complete; we need many more tests and these will need  
25 to happen in the future if these reactor types are to



1       become viable. Again, we note the notable activity--  
2       the notable ongoing work on MSRE.

3               CHAIRMAN CORRADINI: But the similarity  
4       between all of these--well I know you're going to  
5       switch now to PRONGHORN--so the similarity between all  
6       of these is single-phase flow, normal operation,  
7       operational occurrences, and potentially certain  
8       selected design base assessments?

9               MR. MERZARI: Actually, the unprotected  
10       loss of flow show certainly DBAs, but also beyond  
11       design basis.

12              CHAIRMAN CORRADINI: But single-phase?

13              MR. MERZARI: Single-phase, yes.

14              CHAIRMAN CORRADINI: Okay.

15              MR. MERZARI: Well I mean in most of these  
16       designs--in most of these transients, there won't be  
17       a phase change for sodium, for instance.

18              CHAIRMAN CORRADINI: Well okay, but sodium  
19       boiling makes life more interesting and I would expect  
20       I'd see that in a beyond design basis accident  
21       because---

22              MR. MERZARI: You won't see it from  
23       metallic fuel. It's a strong statement, but typically  
24       in--when metallic fuel forms, you will not see sodium  
25       boil.



1 CHAIR CORRADINI: I know what you're  
2 saying.

3 MEMBER REMPE: So back to Walt's question  
4 about air ingress and water ingress, you've said well  
5 for the sodium reactors, I can go to beyond design  
6 basis accidents; aren't you going to beyond design  
7 basis accidents for gas reactors if you're going to do  
8 air ingress and water ingress events? And then, what  
9 are you are going to link to, BISON, that doesn't have  
10 a severe accident model for fuel?

11 MR. MERZARI: So okay, let me separate the  
12 question. So for--let me answer first the sodium  
13 part, so--and then the link to BISON. So right now,  
14 the only code that can really some of the severe  
15 accidents part is SAS4A, and the plan there is to  
16 implement some of those more--the long term plan is to  
17 implement some of the models into BISON and use some  
18 BISON to do those severe accident parts.

19 MEMBER REMPE: Okay.

20 MR. MERZARI: Regarding the gas reactors  
21 question, again, we are not planning to do water  
22 ingress and air ingress with SAM, we are not. So  
23 those are not part of the analysis at the moment. We  
24 may plan to do those with PRONGHORN, but right now the  
25 plans haven't firmed up for that.

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1 CHAIRMAN CORRADINI: But the reason--I'm  
2 still back on sodium boiling--the reason I don't get  
3 it is because with the appropriate reactor design and  
4 feedback, I don't get high enough temperatures or  
5 enough power that will get me to the saturation  
6 conditions.

7 MR. MERZARI: Uh huh.

8 CHAIRMAN CORRADINI: But--okay.

9 MR. MERZARI: No but again, this is an  
10 aspect that the three tests showed in the 70s, and I  
11 think Tanju can perhaps answer this question better  
12 than me.

13 MR. SOFU: So you can certainly postulate  
14 accidents during which sodium could get to boiling  
15 temperature, but we feel modeling that particular type  
16 of transient is not within our immediate plans,  
17 because when sodium boiling starts, you have bigger  
18 worries than just reactivity feedback or fission.  
19 Those temperatures are essentially the trigger for  
20 severe accident conditions.

21 CHAIRMAN CORRADINI: Okay, that's fine.  
22 I figured.

23 MR. MERZARI: So that said, there are  
24 boiling models in SAS, so if that became a concern,  
25 that could be potentially transported to SAM, but that



1 would require some development work. Those models are  
2 not there in SAM today.

3 CHAIRMAN CORRADINI: Okay, I understand  
4 where you're coming from.

5 MR. MERZARI: Okay, switching to  
6 PRONGHORN. PRONGHORN is MOOSE-based engineering lab  
7 analysis tool for advanced reactors. It targets  
8 primarily pebble bed gas reactors but it is extendable  
9 to other designs. So far everything that we've been  
10 doing is for pebble bed reactors. It features an  
11 isotropic porous media modeling formulation, as well  
12 as a more advanced formulation. In its enhanced  
13 formulation, it can combine porous media agents with  
14 other agents to generate a full model of the primary  
15 system in a significant advancement to what was  
16 previously done with these porous media codes for  
17 pebble beds. Moreover, distributing the existing  
18 models for pebble beds developed with NEK5000 can be  
19 implemented in a straightforward manner in PRONGHORN,  
20 and it can also couple to SAM to model on the FCCS and  
21 the overall system transient response. The validation  
22 basis so far is limited; PRONGHORN is a much more  
23 recent code than the other two codes I presented, but  
24 as shown in a recent white paper and shown here at the  
25 top right, PRONGHORN can reproduce while the pebble

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1 temperature is a function of axial and radial  
2 positions in the SANA experiments, which is a classic  
3 validation data set from Germany for pebble beds.

4 CHAIRMAN CORRADINI: So is--I want to make  
5 sure I understand. Two questions; one is what is it  
6 about the physics with PRONGHORN that you've chosen to  
7 use it instead of SAM where you, in your initial  
8 slides, you used the terminology "applicable DOE  
9 engineering-scale code," whereas SAM is useful in the  
10 SFR, PRONGHORN is the choice of your interest, what's  
11 the physics of it do you make the switch?

12 MR. MERZARI: So the--it's not as much of  
13 the physics as a metro scale resolution, so here we're  
14 solving more scales because we are actually modeling  
15 three dimensionally, the old code, if it were porous  
16 media.

17 CHAIRMAN CORRADINI: Oh, as where SAM is  
18 a one dimensional---

19 MR. MERZARI: It's essentially one  
20 dimensional.

21 CHAIR CORRADINI: It's a sodium RELAP for  
22 quantify--I know that would make you upset.

23 MR. MERZARI: It's a sodium/salt RELAP.  
24 I'm okay with that definition.

25 CHAIRMAN CORRADINI: Okay, so it's three



1 dimensional because of the pebbles?

2 MR. MERZARI: Because of the pebbles, and-  
3 -okay of course you could model, for instance, an FHR  
4 with SAM, and instead of modeling 3-D through the  
5 pebbles, you could replace it with a channel model.

6 CHAIRMAN CORRADINI: Okay, I see. All  
7 right.

8 MR. MERZARI: But if you want to add more  
9 detail, especially for the neutronics, perhaps a  
10 porous media model is more effective. What also SAM  
11 is missing is some of the multi-phase tracking  
12 capabilities that we kind of need for gas reactors for  
13 some of the transients and the compressible models.

14 CHAIRMAN CORRADINI: So is it a coupling  
15 between PRONGHORN and the other tool that Tanju was  
16 speaking of, the RATTLESNAKE?

17 MR. MERZARI: Yes, that's available.

18 CHAIRMAN CORRADINI: But that is the  
19 logical connection?

20 MR. MERZARI: Yes, that's the logical  
21 connection.

22 CHAIRMAN CORRADINI: Okay.

23 MR. MERZARI: So those two tools are both  
24 based on the MOOSE framework and they can be coupled.

25 CHAIRMAN CORRADINI: Okay.



1           MR. MERZARI: And they will be used for a  
2 full analysis of these pebble. So--and perhaps this  
3 answers also your question Mike--so this is the  
4 advanced formulation in PRONGHORN--I'm showing an  
5 equation, I know--and it's basically a multi-phase  
6 approach in which the pebble is essentially 3-D;  
7 there's another phase but it is stationary, and this  
8 allows you--there is a fundamental two-phase  
9 capability in PRONGHORN that can be used, for  
10 instance, you can think of the operations regions that  
11 have no pebbles, or the phase goes to zero, so it's  
12 very easy to combine multiple regions with this, and  
13 it can also, this fundamental capability, be used to  
14 track some from an interphase, perhaps to here. So  
15 you can see that the fundamental--the physics in  
16 PRONGHORN is probably more suitable to track some of  
17 the scenarios like air ingress and water ingress.

18           CHAIRMAN CORRADINI: But when you say  
19 water ingress, you mean steam? That's what I  
20 immediately took to be the case; or are you talking  
21 liquid water?

22           MR. MERZARI: For water ingress, I think  
23 what typically is assumed is not steam, it's liquid.

24           CHAIRMAN CORRADINI: Really?

25           MR. MERZARI: No, I'm sorry, steam, steam,



1 yes.

2 MEMBER REMPE: It's supposed to be steam.

3 MR. MERZARI: Yes.

4 CHAIRMAN CORRADINI: Yes, that's what I  
5 thought.

6 MEMBER REMPE: Even if you---

7 CHAIRMAN CORRADINI: So it's a mixture of  
8 compositions in a gas phase? Okay, fine.

9 MR. MERZARI: Yes, but there is still an  
10 interphase and you still need to track it.

11 CHAIRMAN CORRADINI: Right, well a mixing.

12 MR. MERZARI: Yes, yes.

13 CHAIRMAN CORRADINI: I understand, okay.

14 MR. MERZARI: Okay sorry, do you want me  
15 to--

16 CHAIRMAN CORRADINI: I'm good, no, no, no,  
17 you're doing fine.

18 MR. MERZARI: Thank you, good. Okay, so  
19 we present here the validation status of PRONGHORN in  
20 a manner similar to what was done for SAM, you will  
21 note the limited validation basis, which so far has  
22 been completed only for the SANA test. Additional  
23 simulations and benchmarking are ongoing. We note  
24 that there is a potential issue here; some of these  
25 data sets are not available.

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1 MEMBER REMPE: Yet.

2 MR. MERZARI: Yet. Finally, and hopefully  
3 I'm not--how much time do I have?

4 CHAIRMAN CORRADINI: You have about 15  
5 minutes.

6 MR. MERZARI: Okay, that's pretty much on  
7 time. Okay so finally, we introduce NEK5000, a state  
8 of the art, open source computational fluid analytics  
9 code that features both incompressible and  
10 compressible fluid formulations. Thanks partly to  
11 being open source, NEK5000 is easy to integrate and it  
12 features a MOOSE interface, which is part of the  
13 rationale to go toward an open source specific code.  
14 NEK5000 covers a range of resolutions from direct  
15 numerical simulation to large eddy simulation, to  
16 Reynolds-averaged Navier-Stokes, and finally porous  
17 media formulations. What sets it apart from the codes  
18 is that it has a very state of the art capability  
19 which allows it to run very large calculations on  
20 supercomputers as well as models calculations in small  
21 clusters and even laptops.

22 CHAIRMAN CORRADINI: So I want to take you  
23 back to the slide that you had, but you said it  
24 originally where you showed SAM in terms of length  
25 scales, PRONGHORN, and NEK5000, and there was overlap;



1 and you said the overlap was good for what?

2 MR. MERZARI: To couple to different  
3 codes. So I'll give you an example. So, let's take  
4 a pebble bed for instance, you want to model the  
5 pebble bed with a porous media approach---

6 CHAIRMAN CORRADINI: Right.

7 MR. MERZARI: --okay? You kind of want to  
8 move away from the interface between the porous media  
9 and the CFD codes. You don't want the interface  
10 between the CFD codes and the porous media to be right  
11 at the end of the pebble beds; why, because typically  
12 that leads to some instabilities. So if you are able  
13 to extend the PRONGHORN calculation a little bit more  
14 in the open region, the coupling becomes much more  
15 sound. So you couple essentially in the CFD region  
16 rather than at the interface, because that interface  
17 tends to be unstable very often.

18 CHAIRMAN CORRADINI: Okay.

19 MR. MERZARI: Does that make sense to you?

20 CHAIRMAN CORRADINI: I think so. I was  
21 going to go a different direction; my thought was why  
22 have PRONGHORN at all if NEK5000 can do porous media  
23 calculations?

24 MR. MERZARI: So you can do porous media  
25 calculations with commercial software even, you don't



1 even need NEK5000 really for that. The rationale  
2 there is that you really want something optimized,  
3 especially if you plan to couple with neutronics, and  
4 having a well optimized, well established code to run  
5 that particular portion does buy you something.  
6 Actually, if you want a code modeling tool for pebble  
7 beds, I think that's the right strategy, to include a  
8 specific code that is optimized for that.

9 CHAIRMAN CORRADINI: So I'm going to ask,  
10 another similarity, which I'm sure you're not going to  
11 like. So, is NEK5000 just a better fluent?

12 MR. MERZARI: I'll take that; better is  
13 good.

14 CHAIRMAN CORRADINI: I used the word  
15 better so you would agree with me. But it's similar  
16 to, it's essentially---

17 MR. MERZARI: Yes, but---

18 CHAIRMAN CORRADINI: --it's uninitiated.

19 MR. MERZARI: Yes, but you see--yes okay,  
20 I'll take that, but we have access to the source code.

21 CHAIRMAN CORRADINI: Okay, fine.

22 MR. MERZARI: And that matters, it's not--  
23 it's just not---

24 CHAIRMAN CORRADINI: I'm not disagreeing,  
25 but in terms of similarity, there is a--that's an

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1 appropriate analog.

2 MR. MERZARI: It's an appropriate analog,  
3 I like the word better in there but it---

4 MR. SOFU: I think I would add that, I  
5 think that you--with NEK5000, you would get reference  
6 solutions that you can get validation for--RANS-based  
7 approach code---

8 CHAIRMAN CORRADINI: Sure.

9 MR. SOFU: --from commercial code. Order  
10 of accuracy, level of--order of the solutions is going  
11 to be significantly better.

12 MR. MERZARI: Right, that's why you used  
13 the word better, so I---

14 CHAIRMAN CORRADINI: So that he wouldn't  
15 argue with me.

16 MR. MERZARI: So on the better part, the  
17 code is ranked first in several CEA and EA blind  
18 benchmarks--I mean, the blind is important--on CFD  
19 applications to reactor safety. This includes the T-  
20 junction benchmark, which is listed there, which was  
21 a model in thermal striping. Another notable test is  
22 the simulation at the MAX facility, shown at the top  
23 right, illustrating how NEK5000 can reproduce the  
24 measurable velocity of two jets impinging on a  
25 structure, again for applications in thermal striping.

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1 The primary working validation basis for NEK5000 is--  
2 has been focused on fast reactors. As mentioned in  
3 the previous slide, there has been a significant  
4 validation work performed for thermal striping,  
5 including for sodium data sets, such as the PLAJECT  
6 test from GE. Thermal striping is one of the limiting  
7 conditions for liquid metal reactors, as the core  
8 outlet temperature may have significant variations  
9 between assemblies and structures; it may be subject  
10 to significant thermal fatigue.

11 Additionally, I have performed extensive  
12 validation tests for wire wrapped bundles, both for  
13 legacy tests, and including PIV---recent PIV  
14 experiments done at Texas A&M. Again, we envision  
15 NEK5000 and CFD in general to be used primarily to  
16 inform and calibrate SAM for safety analysis  
17 purposes; but NEK5000 may also be used for component  
18 level modeling, and as mentioned previously, we expect  
19 that its coupling to SAM is going to play an important  
20 role in the simulation of thermal stratification in  
21 the upper plenum.

22 Moving to gas reactors, while not as  
23 extensive as for liquid metal reactors, NEK5000 has  
24 received significant validation for gas reactors as  
25 well. We have two ongoing activities here I'm just



1 going to briefly mention; the simulation of the upper  
2 plenum tests, and the simulation of pebble bed tests  
3 at Texas A&M. On the top right of the slide you may  
4 see a NEK5000 simulation of jets of different Reynolds  
5 numbers in the upper plenum mock-up of Texas A&M, and  
6 the bottom right, you may see a NEK5000 simulation of  
7 the flow through a random pebble test. This test is  
8 being conducted right now, we'll have soon comparison  
9 tests, so this is ongoing work. We envision that  
10 NEK5000 will be primarily used to inform PRONGHORN,  
11 and help define distributive resistant models for  
12 pebble flows; for example, to provide closure models  
13 for pressure drop in transfer and distributive  
14 resistance. It mostly will be coupled to PRONGHORN  
15 and SAM to simulate the upper plenum in a coupled  
16 fashion if needed. The chair has disappeared. Okay,  
17 well I'll go on.

18 MEMBER REMPE: You can go ahead.

19 MR. MERZARI: Okay. In the next two  
20 slides I'll summarize quickly, applications for FHRs  
21 and MSRs. In the interest of brevity, I do not dwell  
22 long here. In general, NEK5000 will be used to inform  
23 SAM and PRONGHORN. A good example in the case--is the  
24 case of twisted tube heat exchangers. Available  
25 correlations do not often provide good match in

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1 experiments in the region of interest due to the fact  
2 that typically it exhibits changes for molten salt at  
3 very high Prandtl and very low Reynolds, and there's  
4 very little data in that region. You can see the  
5 figure on the top right is the correlation, for  
6 instance, provides--over estimates the loosened number  
7 by over a factor of two in those--for that test, while  
8 NEK5000 is relatively close to the experimental data.

9 Again, you can see the Reynolds numbers  
10 included are very low, but these are actually some of  
11 the Reynolds numbers that are being targeted by these  
12 designs, and so nothing was changing in the NEK5000  
13 model there. We could match the--we could match very  
14 well the correlation in the region in the validity of  
15 the correlation, but outside of the region of validity  
16 of the correlation, the correlation fails miserably  
17 while the same NEK model gets essentially the right  
18 answer for this particular test. A possible exception  
19 to the rule of using CFD models to conform with SAM or  
20 PRONGHORN is the modeling of the code in fast spectrum  
21 molten salt reactors, which is illustrated in this  
22 figure at the top.

23 In fact, in molten salt reactors there may  
24 be re-circulation regions and these may cause  
25 significant local peaking. The reason for that is



1 that you have very high Prandtl; the fusion doesn't  
2 quite account for any effect in the heat removal, and  
3 you deposit all the heat in a region where no  
4 velocity--where this no velocity and suddenly you have  
5 local idle position, where there is no means for the  
6 heat to escape. So, of course you could take care of  
7 that while removing the--by removing the re-  
8 circulation region, but in a real reactor that might  
9 be actually quite a challenge.

10 I will now present a summary table  
11 concerning the validation basis for NEK5000. NEK5000  
12 is fairly mature--is a fairly mature code for this  
13 class of reactors, and is considered by validation as  
14 being done. As you see, there's quite a few C's  
15 there, and all required features have been  
16 implemented. Nonetheless, some validation work still  
17 needs to be done for these reactor types. The picture  
18 is far less rosy when we get to FHRs and MSRs, as the  
19 NEK5000 validation basis is far more limited.  
20 Significant work has been done, however, for pebble  
21 bed reactors, and there's a lot of work--a lot more  
22 work to be done, and we have an--we mentioned an  
23 ongoing activity for MSRs.

24 CHAIR CORRADINI: Is it the fluid  
25 properties that make--I mean, since NEK5000 is a--I



1 don't want to say standard but we'll say an open  
2 source commercial tool, is it the fluid properties  
3 that make it in a situation where you have to continue  
4 to do validation?

5 MR. MERZARI: Well the conditions are  
6 relatively different, first of all, and so the---

7 CHAIR CORRADINI: Right, I knew that. I  
8 was going to say for the MSR I got it, because you're  
9 essentially producing the heat within and that causes  
10 the feedback you've got to check, but I'd assume that  
11 for these two it would be primarily the material or  
12 the fluid properties.

13 MR. MERZARI: The fluid properties is  
14 relatively--it's the geometry, the complexity, and  
15 certainly due to the geometry boundary conditions, and  
16 in the case of FHRs in particular, the salt and  
17 thermals, which we don't have and we will need to  
18 validate for some of these transients. But, let me  
19 also point out the fact that FHRs and MSRs have very  
20 low Reynolds numbers---

21 CHAIR CORRADINI: Right.

22 MR. MERZARI: --and that poses some  
23 challenges. So for instance, using standard RANS  
24 models in those conditions is questionable at best.

25 CHAIR CORRADINI: But what--if I were the



1 regulator, I would just say well get rid of the  
2 turbulence completely, and let me look at essentially  
3 a laminar calculation as a bound.

4 MR. MERZARI: Well--but, the laminar  
5 calculation, I'm not sure it's a bound.

6 CHAIRMAN CORRADINI: But, what Reynolds  
7 numbers are we talking about? We're talking about  
8 thousands, or at the least---

9 MR. MERZARI: Sometimes hundreds,  
10 sometimes hundreds and it's---

11 CHAIRMAN CORRADINI: But I'm definitely  
12 laminar.

13 MR. MERZARI: Well, I mean, that's the  
14 thing, you might be laminar if you consider a single  
15 channel, but the moment that you add more complex  
16 geometry, you might end up with instabilities and the  
17 flow not actually being stationary.

18 CHAIRMAN CORRADINI: Okay.

19 MR. MERZARI: And that is definitely  
20 questionable. I mean, there's no such thing as a  
21 truly laminar flow, that is completely stable unless  
22 you're talking about a fully developed nice pipe with  
23 the flow well characterized.

24 MR. SOFU: And with that kind of a heat,  
25 if you just focus on flow, the Reynolds number, you

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1 also have to consider the buoyancy effect--

2 MR. MERZARI: Right.

3 MR. SOFU: --associated with a tremendous  
4 heat flux coming from very, very hot surfaces.

5 MR. MERZARI: That's right. So with that,  
6 I conclude. Actually, I think I bought you back five  
7 minutes. The DOE is developing a modern, thermal  
8 hydraulic, multi-scale suite applicable to a variety  
9 of reactor designs. In fact, while emphasis to date  
10 has been mostly for sodium and gas reactors,  
11 substantial capability exists for other reactor  
12 contents, such as MSRs and FHRs. I've shown some  
13 basic capabilities to simulate advanced reactor LDEs,  
14 including an unprotected loss of flow, and more is  
15 available in the reports and papers I've sent you and  
16 I remain at your disposal for further questions. I  
17 realize I haven't covered all that I--all the  
18 possible--I mean, there's a lot material here and I  
19 cannot possibly cover the full status of these codes,  
20 but I'm available for further questions, and I hope I  
21 conveyed to you the right picture, which is in my  
22 opinion, that these codes have received significant  
23 interest from the industry, there is a lot--there is  
24 significant capability there, there is remarkable  
25 progress, and there is definitely potential. Of

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1 course, a lot more work needs to be done, especially  
2 when it comes to validation. Thank you very much.

3 CHAIRMAN CORRADINI: Questions by the  
4 committee? On to the world of source term. Everybody  
5 wake up.

6 MEMBER BLEY: While you're waiting for it  
7 Chris, I asked the question at the wrong time this  
8 morning. We didn't have--well, being that we were  
9 looking at micro structures, but now as we've got  
10 molten fuel and liquids and aerosols being generated,  
11 the chemistry's got to become extremely important.  
12 How is the modeling of the chemistry in this section  
13 of the work you guys have done?

14 MR. STANEK: So, I think the best answer  
15 to that is that's a topic for the next time we meet.

16 MEMBER BLEY: Do you have an actinide  
17 chemist who's working with you on this stuff, or is  
18 that for the future?

19 MR. STANEK: Based on our interactions  
20 with colleagues in the NRC and some of the vendors, we  
21 now believe we have our arms around what the needs are  
22 in modeling and simulation--

23 MEMBER BLEY: Uh huh.

24 MR. STANEK: --of chemistry. We're  
25 working with the Advanced Reactor Technology Program



1 to hone in on what our strategy will be going forward,  
2 so it's still notional at this point, but yes, we have  
3 engaged the radio chemists and the right modeling and  
4 simulation people to develop a needed capability which  
5 frankly doesn't---

6 MEMBER BLEY: But that's off in the  
7 future, so the stuff we're looking at now is without  
8 that except as it shows up in some kind of  
9 correlations that get picked up somewhere?

10 MR. STANEK: That's correct.

11 MEMBER BLEY: Yes. Okay, thank you.

12 CHAIRMAN CORRADINI: Tanju? If it's a  
13 green you're good.

14 MR. SOFU: The last technical presentation  
15 of the afternoon, so--and I'll just jump right into  
16 it. The formal source term definition in the U.S  
17 Regulations is provided in Part 50.2, if you read  
18 there; and then this source definition is closely  
19 linked with the LWR source term requirements in Part  
20 50.67. The first reference there, TID-14844, makes a  
21 prescriptive assumption for release of all--100  
22 percent noble gases, half of halogens, and one percent  
23 of the remaining solids to the containment, assuming  
24 a LOCA leading to a core melt as the bonding event.  
25 The other reference there you see, 1465, also assumes

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1 a LOCA core melt, but it specifies unique EWR/PWR  
2 releases in-vessel, ex-vessel, accounting for the  
3 engineering safety features along with the uncertainty  
4 analysis; and finally, the SECY-93-092 sets the stage  
5 for regulatory expectations for mechanistic source  
6 term evaluations for advanced reactors. And I think  
7 the rationale for a mechanistic sourced term  
8 assessment is that because the source term  
9 requirements will significantly differ for those  
10 reactors mainly because there is no single bonding  
11 event like LOCA determining the source term. In fact,  
12 for some concepts like those that rely on TRISO fuel,  
13 very small releases can be anticipated even during  
14 AOOs and DBAs, and sometimes during normal operation  
15 from defective fuel particles; there's certainly a  
16 circulating activity in the coolant expected.

17 CHAIRMAN CORRADINI: So the reason though  
18 that you--you don't have to go back to the slide  
19 before--but the reason you identified that, this is  
20 for LWRs?

21 MR. SOFU: Correct.

22 CHAIRMAN CORRADINI: So there's no  
23 construct except from a process standpoint for non-  
24 LWRs?

25 MR. SOFU: Correct.



1 CHAIRMAN CORRADINI: Okay.

2 MR. SOFU: So I'm trying to draw a contrast  
3 as to why we would need a more mechanistic sourced term  
4 approach for advanced reactors.

5 CHAIRMAN CORRADINI: Okay. The reason I  
6 asked the question like that is that the background  
7 documents you gave us, I interpreted as more process  
8 discussions than tool discussions.

9 MR. SOFU: Absolutely, yes.

10 MEMBER REMPE: So this isn't really for  
11 you, this is for the folks sitting around the table  
12 here, but it sounds like from your first bullet when I  
13 was looking at this last night, I was thinking about if  
14 we had a new regulatory system and you had top level  
15 regulatory criteria, it sounds to me that your  
16 experience is also suggesting that you shouldn't just  
17 use the--for top level regulatory criteria, 10 CFR 100,  
18 you should also do--use the regulatory criteria for  
19 normal operation; and so when we talked about that a  
20 few weeks ago or a month ago, it sounds like there  
21 might be a gap in what we heard about because they  
22 might need to consider the regulatory criteria for  
23 normal operating releases and AOOs; is that kind of  
24 what you're thinking too?

25 MR. SOFU: I agree, that's correct, and I



1 think the--this licensing modernization project---

2 MEMBER REMPE: That's where I'm coming  
3 from.

4 MR. SOFU: --the NRC is evaluating based on  
5 DOE and NEI initiative sort of sets the stage for that  
6 discussion.

7 MEMBER REMPE: Yes, but are they--in the  
8 discussion we had they did not have all of like, the 10  
9 CFR 20 and 50 releases--thank you--or criteria.

10 CHAIRMAN CORRADINI: I don't--I guess, I  
11 don't appreciate what you're asking, I apologize.

12 MEMBER REMPE: When Former Commissioner  
13 Apostolakis and Karl Fleming were here a few weeks ago  
14 and we talked about that, they did not have all of the  
15 normal operating regulatory criteria in there and they--  
16 -and George, when I brought that up actually said yes,  
17 you're right, this is--basically even if we design to  
18 these top level regulatory criteria that we've  
19 identified, it may not meet all the regulatory  
20 requirements. And so I'm just kind of emphasizing that  
21 because of the guy sitting over there to the left and  
22 doing his letter.

23 MEMBER BLEY: You're wrong.

24 MEMBER REMPE: I'm wrong?

25 MEMBER BLEY: Yes.



1 MEMBER REMPE: Well, years ago---

2 MEMBER BLEY: I'm not doing a letter.

3 MEMBER REMPE: Oh, okay. Well if you ever  
4 do---

5 MEMBER BLEY: Not today.

6 MEMBER REMPE: --okay, if you ever do a  
7 letter on that topic, okay, I just wanted to emphasize  
8 that point. Again, this is off topic, but it's  
9 something I wanted to emphasize. Thank you.

10 CHAIR CORRADINI: Sure.

11 MR. SOFU: So the bottom line is that for  
12 advanced reactor types, you will need to focus on a  
13 broader spectrum of accidents, not just local-type  
14 bonding events, because there could be releases that  
15 are frequent but very small, versus infrequent but  
16 sizably large, but the risk factor will be comparable.  
17 Also, accidents that could lead to early releases  
18 versus delayed releases could have implications on  
19 radionuclide discharge content as well as the emergency  
20 response implications, and we need to worry not only  
21 about the fuel in the reactor core but we need to  
22 concern--probably consider the field and storage for  
23 liquid metal coolant systems. Coolant covered gas  
24 clean up systems could malfunction, they could just  
25 immediately bypass the reactor pool but that could be

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1 right inside the containment, and any failure of that  
2 system could be sourced inside the containment. And  
3 for molten salt reactors--not that I know much about  
4 it, but I'm assuming some chemical processing systems  
5 may or may not be inside the containment--their  
6 malfunction could also lead to significant releases.

7 So the--on top of all that source term  
8 assessment, but also probably the mechanistic approach  
9 to considering a broader spectrum of accidents for  
10 advanced reactor concepts will also be needed to  
11 support PRA in Level 2 and Level 3, as well as  
12 emergency planning on reduction requests. So there are  
13 plenty of reasons to do this mechanistically looking at  
14 a broader spectrum of accidents. What I provide here  
15 is a kind of--a proposed mechanistic source term  
16 definition, and the general approach I present in the  
17 next speech is largely based on this particular  
18 definition.

19 CHAIRMAN CORRADINI: But what I--I've looked  
20 at your slides ahead of time. What I see is process,  
21 so it's mainly a process discussion?

22 MR. SOFU: Right.

23 CHAIRMAN CORRADINI: Okay, okay.

24 MR. SOFU: Here's the approach. The first  
25 step is an inventory assessment; and then you need to



1 understand the release pathways depending on what  
2 you're considering as the source. We need to model the  
3 phenomena in volt and release pathways, we need to  
4 evaluate specific scenarios, not just bonding events,  
5 and of course, last step is the regulator will take a  
6 look and say we agree or don't agree. So the inventory  
7 step, there can be significant differences for each  
8 reactor type, but even sometimes for each design. For  
9 a traveling wave reactor that targets an ultra-high  
10 burn-up fuel, for example, versus for a heat pipe based  
11 micro-reactor with very, very low burn-up, an inventory  
12 will be significantly different, even with the same  
13 type of metallic fuel, for example.

14 For the release pathways shown here at the  
15 second step, I have example diagrams for them for SFRs  
16 and MHTGRs in coming pages. For modeling and scenario  
17 evaluation, approaches that could be utilized can rely  
18 on NRC and the recently developed DOE capabilities  
19 you've heard this afternoon. That's something that  
20 we've performed in trial mechanistic source term  
21 calculations for SFRs and MHTGRs. That's the release  
22 pathway diagram for a liquid metal reactor in general.  
23 We've done a trial calculation based on this diagram  
24 for NSFR under the DOE program. The green color shows  
25 primary barriers for release of radioactivity, and

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1 obviously in this case we are focusing on fuel in the  
2 core. We consider the fuel matrix itself as a barrier  
3 because depending on the accident sequence, it could  
4 hold the solid fission products within the fuel and  
5 then they're not--other than small chunks that could  
6 get into coolant channels--may be stayed in the matrix.  
7 And also depending on the accident scenario, for  
8 example, a very long loss of heat sinks type of  
9 accident versus a very rapid transient overpower, what  
10 radionuclides are released at what rate will differ  
11 significantly.

12 So I'm showing--the first step is retention  
13 of the fuel, and then once you lose the integrity of  
14 the cladding, depending on the accident, you will have  
15 fission gas immediately released to the coolant, but  
16 some particulates and even molten fuel could get  
17 released if this a rapid transient leading to fuel  
18 melting. There's a complex phenomena absorption,  
19 condensation, dissolution, retention in the fuel, but  
20 probably more a more important unknown, which I will  
21 highlight later on is along with the fission gas  
22 release, some of the solid chunk fuels could be  
23 scrubbed to the cover gas space with the bubbles. And  
24 if the cover gas space between the sodium pool and the  
25 cover gas interface, there would be vaporization,

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1 condensation, re-vaporization, and some vapors could  
2 nucleate on, and--or condense on the particles.  
3 Typically, there would be a design leakage rate from  
4 cover gas space to the containment space, and then a  
5 similar phenomena takes place inside the containment,  
6 and then leakage from the containment. Those are sort  
7 of release pathways for a typical accident--multiple-  
8 failure accident that could lead to a large-scale fuel  
9 failures in NSFR.

10 An approach--the mechanistic source term  
11 approach for liquid metal cooled reactors is therefore  
12 it will involve first, inventory analysis, and then  
13 transient scenario modeling. We need to understand  
14 in-pin radionuclide distribution before the failure or  
15 at the time of the failure; radionuclides released from  
16 the failed fuel, some of those released chunks of  
17 molten fuel could be carried through the bubbles--  
18 fission gas bubbles--to the cover gas space, and some  
19 of them could be retained inside the liquid metal pool  
20 and released to the cover gas space at the surface, the  
21 free surface. We need to analyze the cover gas region  
22 for radionuclide tracking, containment region, and  
23 finally the off-site dispersion analysis. So, these  
24 are the capabilities that could be leveraged to  
25 perform--to implement such an approach.

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1           An inventory analysis could be done with  
2   ORIGEN, or in a radionuclide group basis using REBUS,  
3   for fast spectrum reactors. Transient scenario  
4   modeling could be done with SAS4A traditionally, but we  
5   can also leverage our newest capabilities, SAM and  
6   PERSENT to help with this process. Interim  
7   radionuclide distribution are typically handled with  
8   the fuel behavior codes, if you have such capabilities  
9   in legacy codes, like METAL and SAS4A, but BISON, if  
10   Rich gets his way, we'll be ready to provide such  
11   capability in a short few months. Rich is shaking his  
12   head. And for radionuclides released from the fuel, we  
13   do not have a currently existing capability but we're  
14   developing a module to do that type of job coupled with  
15   SAS4A and SAM within the context of some international  
16   collaborations; I have a slide on that.

17           And then for--really, once we know what  
18   gets to the cover gas space, what goes to the  
19   environment, then those implications could all can be  
20   taken care of on the NRC codes like MELCOR. CONTAIN-  
21   LMR used to do a specific sodium-fire type of modeling  
22   for liquid metal coolant and sodium coolant, but I  
23   think with DOE support, CONTAIN-LMR capabilities are  
24   now incorporated into MELCOR so we won't even need  
25   that.



1 MEMBER REMPE: Yes, it's--is it--it's not  
2 NRC supported anymore is it?

3 MR. SOFU: CONTAIN-LMR, probably not, yes.

4 MEMBER REMPE: So--but again, you're saying  
5 now we're going to put it in MELCOR?

6 MR. SOFU: It is already in MELCOR.

7 MEMBER REMPE: So--yes, okay.

8 MR. SOFU: So, as you see that I don't have  
9 green boxes showing a radionuclide bubble transport and  
10 liquid-metal radionuclide release; those are identified  
11 as gaps. We did perform---

12 MEMBER REMPE: I'm sorry, if you're still  
13 on, go ahead.

14 MR. SOFU: We did perform a trial  
15 calculation to find out what the status of theses codes  
16 for a simple application. We again focused on AFR-100  
17 design, and performed the trial calculation. The  
18 report is publicly available; there's a link here that  
19 you can access. You can see the two scenarios, one is  
20 a protected loss of plus, loss of flow, plus in the  
21 sense that plus is very degraded decay integral  
22 capacity, otherwise you won't get fuel failures with  
23 those accidents; and the other one was an unprotected  
24 control rod withdrawal leading to a quick rise in the  
25 fuel temperatures and leading to fuel melting.

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1           So the consequences of these two accidents-  
2           -duration and consequences are quite different. What  
3           we found out at the end--what we are missing is, as I  
4           highlighted before, a pool bypass for bubble transport,  
5           and fuel release fractions, which is the radionuclide  
6           release module that I mentioned in the previous slide.  
7           Professor Corradini?

8           CHAIRMAN CORRADINI: No, I was just going  
9           say I do these as--well, you said examples but, one  
10          would have to know the--estimate the likelihood of  
11          these scenarios coupled with what would be the release  
12          and look for the--I don't want to have to say the worst  
13          combination--but the limiting combinations. So, these  
14          are just examples; there could be a wide range.

15          MR. SOFU: Examples, and I think the sub-  
16          bullet here that I included based on Richard Lee's  
17          comment on my slides, these sequences---

18          CHAIRMAN CORRADINI: He had a comment? I'm  
19          shocked.

20          MR. SOFU: He did send a comment. So these  
21          sequences are typically, normally for a design selected  
22          based on a--using PRA.

23          CHAIRMAN CORRADINI: Okay, that's okay.

24          MR. SOFU: But we really didn't do PRA in  
25          this case.



1 CHAIRMAN CORRADINI: I was looking at your  
2 slide four and I guess my interpreting of slide four as  
3 you were walking down the path is you'd have to look at  
4 the ensemble of things that could go wrong and their  
5 ultimate result and look at that--what are the dominant  
6 ones that you then would have to look is. Okay,  
7 because that's what they did for the BWR and the PWR to  
8 result in 1465.

9 MR. SOFU: Absolutely. Definitely.

10 CHAIRMAN CORRADINI: Okay.

11 MR. SOFU: I think you're absolutely right  
12 about that.

13 MEMBER REMPE: Your trial calculation, did  
14 it include using MELCOR or CONTAIN or something?

15 MR. SOFU: Yes. Trial calculation, I did--  
16 I believe it did use CONTAIN--I'm sorry--MELCOR.

17 MEMBER REMPE: Okay. And it used BISON or  
18 some other -- it used, like, all these other codes that  
19 was on this slide earlier?

20 MR. SOFU: Trial calculation used, I believe  
21 ORIGEN, SAS4A. This module is developed as part of  
22 that trial calculation and MELCOR. So, for these  
23 missing steps, we just assume, whatever released from  
24 the field somehow reached to the cover gas.

25 So, that would be a very conservative



1 approach, because I think you would have significant  
2 retention of some radionuclides in the sodium coolant  
3 that we didn't take advantage of.

4 MEMBER REMPE: Was it a linked calculation,  
5 where you -- or did you just get output and put it to  
6 the next --

7 MR. SOFU: Pretty much, those were  
8 sequential calculations. You would get the results  
9 from one analysis and then, perform assessments with  
10 the other codes.

11 So, these were -- and I think, at some  
12 point, when you reach to this particular step, it more  
13 like a spreadsheet type calculation, goes into --  
14 connects to MELCOR and input, MELCOR input deck.

15 MEMBER REMPE: At this point, is this a  
16 better approach than just trying to put some models and  
17 have a sodium reactor MELCOR? I mean, what's the  
18 benefit?

19 MR. SOFU: This question has come up during  
20 our discussions with NRC and also Sandia. My  
21 suggestion is trying to develop all these capabilities  
22 somehow capture in MELCOR would be reinventing the  
23 NEAMS program all over again.

24 It would be, in theory -- and I think one  
25 suggestion, I don't remember, I think, who came to



1 Argonne with, I think it was Randy. Yes. So, Randy's  
2 suggestion was, can we have surrogate models that  
3 capture the behavior of a particular reactor type,  
4 based on running these models and understanding their  
5 consequences?

6 That's certainly a possibility, but it  
7 would be far from being mechanistic or general enough  
8 that every time you change your reactor design or have  
9 a different reactor type, molten salt, so that you need  
10 to continue developing surrogate models within MELCOR  
11 to achieve that goal.

12 MEMBER REMPE: I'm just remembering the old  
13 days, the RELAP and things like that, and people said,  
14 can't we get the important things, because you need to  
15 do multiple sequences and --

16 MR. SOFU: Yes. But for light water  
17 reactors, MELCOR actually does extend to scenario of  
18 elevation phase. It has those capabilities. But  
19 they're really very LOCA and light water reactor  
20 hardwired approaches.

21 MEMBER REMPE: I thought they actually -- I  
22 don't know if they've done anything for the sodium  
23 reactor, but for the gas reactor, they did and try and  
24 do something with PARFUME a few years ago, for the --

25 MR. SOFU: Okay.



1 MEMBER REMPE: -- NGNP stuff and so, I  
2 thought they had tried to do that already. And --

3 MR. SOFU: Yes.

4 MEMBER REMPE: -- again, you've got  
5 something that's actually interacting, instead of this  
6 sequential thing, which might --

7 MR. SOFU: Right.

8 MEMBER REMPE: -- be more expensive to run.  
9 I don't know, it's just a thought.

10 MR. SOFU: I think my takeaway from this  
11 particular slide is the MELCOR has well proven  
12 radionuclide tracking capabilities, within cover gas  
13 and containment space.

14 If somehow, provide that link, what  
15 radionuclides are reaching to that interface, cover gas  
16 and containment space, MELCOR would be the best tool to  
17 understand the consequences of accidents.

18 And we have the capabilities to feed that  
19 information into MELCOR. I understand strong desire to  
20 do everything with one code, but I would -- my personal  
21 thought is that this would be too big of an effort.

22 MEMBER REMPE: Okay.

23 MR. SOFU: All right. So, this trial MST  
24 calculations, mechanistic source term calculations for  
25 liquid metal reactors found a lot of attraction.



1           We've used that capability in our  
2           collaboration with GE-Hitachi, as an art program funded  
3           project as part of their PRA modernization effort. We  
4           repeated that for TerraPower's TWR design and also for  
5           KAERI's PGSFR design.

6           We recently received a voucher from DOE to  
7           work with Fauske and Associates, as well as  
8           Westinghouse, to apply this capability to a lead-cooled  
9           fast reactor concept. And that also supporting the  
10          development of this radionuclide release module from  
11          oxide fuel.

12          And finally, we have two recent awards,  
13          NEUP awards to University of Wisconsin and New Mexico,  
14          to do tests with sodium and liquid lead, to assess  
15          radionuclide retention characteristics of those  
16          coolants, that will provide really useful information,  
17          useful data, for radionuclide release module.

18          MEMBER REMPE: Why the oxide fuel thing with  
19          Fauske and Associates? My understanding is, the sodium  
20          fast reactors are all going with metal. Is there a  
21          vendor or a design also staying in oxide?

22          MR. SOFU: This is a lead-cooled reactor.

23          MEMBER REMPE: Oh, it's a lead, okay.

24          MR. SOFU: They are focusing on oxide fuel  
25          initially. I think, eventually, they want to have



1 nitrite fuel, but --

2 MEMBER REMPE: Okay.

3 MEMBER KIRCHNER: So, you probably can't  
4 answer my question. What are you seeing in terms of  
5 results?

6 Getting down to the bottom line, someone,  
7 someplace, has to make a decision on emergency planning  
8 zones. They're not going to be able to look at the  
9 infinite number of combinations of scenarios.

10 So, are you finding some commonality in  
11 your work that would suggest that you're seeing versus  
12 the EPA protective action guidelines or what's the  
13 practice in LWR industry? Are you finding some  
14 scaling, based on --

15 MR. SOFU: Yes. So --

16 MEMBER KIRCHNER: -- technology and choices  
17 and power level, obviously, is a big factor?

18 MR. SOFU: Correct. So, what we are seeing  
19 that, first, we need to push the envelope of those  
20 accidents for liquid metal applications to a point  
21 where we need to have some fuel failures.

22 It's hard to get to that point with a lot  
23 of those concepts, because they're inherent in passive  
24 safety characteristics, passive direct gain  
25 characteristics. So, we have to --

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1                   MEMBER KIRCHNER: That has not been  
2 demonstrated, that a postulate --

3                   MR. SOFU: Postulated.

4                   MEMBER KIRCHNER: -- filling in?

5                   MR. SOFU: Correct.

6                   CHAIRMAN CORRADINI: The postulate being,  
7 what, Walt?

8                   MEMBER KIRCHNER: That these reactors do not  
9 --

10                  MR. SOFU: But --

11                  MEMBER KIRCHNER: -- the fuel rod.

12                  MR. SOFU: Correct. But we have two  
13 unprotected tests coming from EBR-II and FFTF that  
14 demonstrates inherent safety principles and using  
15 capabilities validated with these tests, for similar  
16 designs.

17                  We have fairly good confidence of inherent  
18 and passive response of EBR-II and FFTF designs. So,  
19 that is one that these designers are taking advantage  
20 of.

21                  So, just to jump to your question, however,  
22 oftentimes, when we analyze, really, above and beyond  
23 the spectrum of accidents, we probably would normally  
24 fall under the residual risk category of events, but we  
25 nevertheless have to go there, because you need to have



1 fuel failures to do the source term assessment.

2 Generally, retention in fuel, retention in  
3 sodium, cover gas, and containment space is sufficient  
4 to minimize the dose concerns well below the regulatory  
5 limits. So, that could probably support reduction of  
6 those emergency planning zones, consistent with that  
7 measurement.

8 But again, in my approach that I said, let  
9 me just jump there, the regulatory review is the final  
10 step that we're, of course, we don't want to short-  
11 change.

12 It all boils down to how NRC would receive  
13 these calculations. These trial calculations are,  
14 essentially, studies that inform the design, not  
15 necessarily intended to support the license  
16 application.

17 From here on, I will go really fairly  
18 quickly, because I'm going to repeat a similar pathway  
19 for HTGRs. And this pathway, release pathway analysis,  
20 was prepared as part of NGNP project. As you see, at  
21 the core of it is a TRISO fuel, much, much, much larger  
22 than what it is.

23 But also, it's part of a graphite block and  
24 what's shown here is the helium pressure boundary and,  
25 finally, around it, surrounding it, is another barrier,

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1 is reactor building.

2 And several phenomenon are highlighted  
3 here, steam-induced vaporization, circulating activity  
4 inside the -- from defective TRISO particles. Plate-  
5 out, lift-off, wash-off.

6 And if you have a breach, you can have  
7 either the helium leaks or helium breaks, that could  
8 lead to release of this high pressure through venting  
9 to the environment.

10 So, multiple barriers for HTGRs, at the  
11 center is the TRISO fuel, with multiple layers. And  
12 then, fuel compacts and fuel elements, the graphite  
13 block is another barrier. And helium pressure  
14 boundary, as long as you maintain it intact,  
15 circulating activity is not necessarily a concern.

16 Finally, the reactor building, which is not  
17 a traditional containment structure for modular HTGRs,  
18 because if you do lose the pressure in the helium  
19 pressure system, then I think it vents the helium  
20 first, outside to the environment.

21 But once that initial puff is released, you  
22 have the ability to seal this reactor building, to  
23 retain the fission products, following that initial  
24 phase of an accident.

25 So, during normal operation, relatively low

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1 inventory of fission products inside the helium  
2 pressure boundary is expected from defective fuel  
3 elements.

4 And limiting event is considered to be the  
5 loss of helium pressure boundary integrity, leading to  
6 a slow or sudden pressure loss and larger delayed  
7 release of fission products from the fuel at elevated  
8 temperatures, if, indeed, temperatures get elevated.

9 As indicated earlier, a lot of the  
10 statistical analysis really don't just assume, based on  
11 tests performed, I think they just assume at a certain  
12 temperature, certain failure rates.

13 So, those releases from failed fuels at  
14 certain temperatures is based on those correlations.  
15 It doesn't have a lot of BISON modeling there, I  
16 believe.

17 So, the functional containment concept  
18 introduced in NRC's Reg Guide 1.232 and in the  
19 criterial of MHTGR 16, it allows taking credit for  
20 coated fuel particles as the primary barrier.  
21 Therefore, the reactor building is not leak-tight and  
22 therefore, it's not a conventional containment  
23 structure.

24 And here's the MST Approach, very similar  
25 steps. Inventory analysis, transient scenario



1 modeling, fuel response to scenario studied,  
2 radionuclide release rates from the fuel, and then, the  
3 helium pressure boundary radionuclide release, reactor  
4 building analysis, and offsite dispersion analysis.

5 Codes are more or less the same. Again,  
6 inventory analysis could be done with well-established  
7 capabilities in ORIGEN. And in NGNP project, I believe  
8 RELAP was used as the scenario, transient scenario  
9 modeling. But capabilities of PRONGHORN could be  
10 leveraged to make that assessment.

11 Certainly, BISON and, definitely, PARFUME  
12 models will give us the fuel response, as well as  
13 radionuclide release rates from the fuel at elevated  
14 temperatures. I put this here, I think a lot of that  
15 release rates is going to be coming from test data.

16 CHAIRMAN CORRADINI: I was going to ask  
17 about that line, because I thought, I'm going to pick  
18 on Rich, what I thought Rich said was that BISON is not  
19 in a position to do that line.

20 That there would have to be something,  
21 PARFUME, modified PARFUME, PARFUME in MELCOR,  
22 something. Am I misremembering?

23 MR. WILLIAMSON: So, if I understood what  
24 you just said correctly --

25 CHAIRMAN CORRADINI: The line that says



1 radionuclide release rates from fuel, under, I'll call  
2 it, beyond design-basis conditions, I thought BISON  
3 wasn't in that position, yet.

4 MR. SOFU: Not yet.

5 CHAIRMAN CORRADINI: At all.

6 MR. WILLIAMSON: Well, yes, I guess I'm  
7 hesitating a little bit because we certainly, for a  
8 given particle, can -- in fact, the prong that I showed  
9 that had a cesium release, we certainly can and have  
10 already demonstrated the capability to predict release  
11 from an individual particle for a specific species.

12 So, we're in a position to do that, to do  
13 that for a host of radionuclides. Statistically, we  
14 haven't done that yet.

15 CHAIRMAN CORRADINI: Okay. But -- can you  
16 go back?

17 MR. SOFU: Sure.

18 CHAIRMAN CORRADINI: So, well, okay. So,  
19 let me ask the question a little differently. So, that  
20 middle line is not just from the fuel, but everything  
21 that kind of got dusted up in operating the reactor  
22 inside the primary system, as well as what would be  
23 released from the fuel, yes?

24 Because if I have any sort of transient  
25 response that I have to blow down, I have to know any



1 sort of material that got accumulated from its  
2 operation. And that's not in any of these, as I  
3 understand it.

4 MR. SOFU: As a scenario modeling?

5 CHAIRMAN CORRADINI: But that's the flow,  
6 that's not the fission product deposition that was  
7 there because of --

8 MEMBER REMPE: Lift-off.

9 CHAIRMAN CORRADINI: -- because of lift-off.  
10 Dust, I've got a gas reactor --

11 MR. SOFU: Oh, yes, I see --

12 CHAIRMAN CORRADINI: -- with a bunch --

13 MR. SOFU: -- what you mean, yes.

14 CHAIRMAN CORRADINI: -- of dust. And now,  
15 I punch a hole in the gas reactor and the dust comes  
16 out. So, I have to know, what are the radionuclides in  
17 the dust. That's what I guess I'm getting at.

18 MR. SOFU: I kind of take comfort in the  
19 fact that these calculations were performed for the  
20 modular HTGR as part the NGNP project. There are --

21 CHAIRMAN CORRADINI: Yes, but --

22 MR. SOFU: -- two reports here.

23 CHAIRMAN CORRADINI: But you showed me these  
24 two reports, but these are the ones that I thought were  
25 more process than calculational. Am I misremembering

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1       which ones we were sent?

2               MEMBER REMPE: No, you're correct. They did  
3       peer -- or they had an expert panel on the gas reactor  
4       one, to evaluate where the uncertainties were. And it  
5       wasn't a calculation.

6               MR. SOFU: No, no, I mean, obviously, this  
7       wasn't a kind of license application in that sense, but  
8       --

9               CHAIRMAN CORRADINI: No, no, I understand.

10              MR. SOFU: But it --

11              CHAIRMAN CORRADINI: But I --

12              MR. SOFU: -- did identify --

13              CHAIRMAN CORRADINI: -- didn't disagree with  
14       the process --

15              MR. SOFU: Yes.

16              CHAIRMAN CORRADINI: -- all I guess I was  
17       getting at was, is that there are pieces in your  
18       listing here that go beyond what --

19              MR. SOFU: Yes.

20              CHAIRMAN CORRADINI: -- the red names are.

21              MR. SOFU: I agree with you --

22              CHAIRMAN CORRADINI: Okay.

23              MR. SOFU: -- the steps could be rearranged  
24       and expanded, it's just essentially -- the purpose of  
25       me drafting this, I apologize if it doesn't fit your



1 vision, but, essentially, leverage some codes that  
2 could fulfill certain roles, identify the codes, most  
3 of them.

4 CHAIRMAN CORRADINI: No, no, it's fine, I'm  
5 not worried about that, I was just trying to make my  
6 point. So, if you went to, let's pick on somebody, if  
7 you went to X Energy --

8 MR. SOFU: Yes.

9 CHAIRMAN CORRADINI: -- what are -- forget  
10 about what the codes are, do they have the same process  
11 path? In other words, how are they going to make their  
12 case, if they were to come into the regulator?

13 MR. SOFU: So, I'm assuming, in their case,  
14 the limiting scenario would be losing the helium  
15 pressure. And at that point, they will have a  
16 circulating activity already and that could be released  
17 to environment directly, because they may not have a  
18 containment structure that will hold that pressure.

19 So, with that accident, I think you will  
20 immediately have some dose consequences of, offsite  
21 dose consequences associated with helium puff, with  
22 circulating activity reaching to the environment.  
23 Detectors will sound and --

24 CHAIRMAN CORRADINI: Right, but --

25 MR. SOFU: -- you'll have to --



1 CHAIRMAN CORRADINI: -- you're going much  
2 further than I am, so that's good. So, now, let me  
3 push the point. Has the industry shared with you guys  
4 their approach to any of this?

5 MR. SOFU: No.

6 CHAIRMAN CORRADINI: Okay.

7 MR. SOFU: Those are sort of DOE proposals,  
8 based on some trial calculations are done for SFRs, and  
9 what NGNP did for MHTGRs.

10 MEMBER BALLINGER: But you had to previously  
11 -- the blue TRISO fuel QA, in order for you to claim  
12 that that's the primary barrier and that you don't need  
13 a conventional containment, you have to have previously  
14 -- you have to demonstrate that your coated particles  
15 meet a certain QA spec --

16 MR. SOFU: Correct.

17 MEMBER BALLINGER: -- ahead of time.

18 MR. SOFU: Correct.

19 MEMBER BALLINGER: So, that is up top.

20 MEMBER KIRCHNER: It would seem to me,  
21 pragmatically, for the case of the HTGR, which is  
22 rather unique, because you're going to have this  
23 problem of blowing down the primary system and the  
24 planned buildings for the structure can't withstand  
25 that.

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1 CHAIRMAN CORRADINI: Well, they --

2 MEMBER KIRCHNER: So, they're going to vent.

3 CHAIRMAN CORRADINI: They could, but they're

4 --

5 MEMBER KIRCHNER: They could, but --

6 CHAIRMAN CORRADINI: -- they've designed --

7 MEMBER KIRCHNER: -- the cost is --

8 CHAIRMAN CORRADINI: -- it not to.

9 MEMBER KIRCHNER: No, the cost would be  
10 prohibitive. So, or it could be prohibitive. So, the  
11 approach currently is to vent. So, it seems to me,  
12 yes, you could do all this detailed analysis to try and  
13 calculate what the circulating inventory is and what  
14 the plate-out is and so on.

15 Pragmatically, wouldn't you just define a  
16 tech spec for what you can withstand in terms of that  
17 circulating and deposited inventory?

18 CHAIRMAN CORRADINI: And demand --

19 MEMBER KIRCHNER: Ensure that the fuel is  
20 manufactured so that you, based on your analysis, with  
21 your detail models, you're not going to have a problem.  
22 And then, from that, figure out what the offsite dose  
23 is. And then, that's going to tell you what your EPZ  
24 diameter is, right?

25 CHAIRMAN CORRADINI: So, your point is, work

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1 the problem backwards?

2 MEMBER KIRCHNER: Work the problem  
3 backwards, yes.

4 MEMBER REMPE: You need to consider a  
5 spectrum.

6 MEMBER KIRCHNER: And I would think the same  
7 with the LMR scenarios as well. Otherwise, to go from  
8 alpha to omega, from the very beginning with every  
9 single transient that you have in your PRA space, even  
10 if the codes are running very efficient, it's an  
11 enormous undertaking.

12 MEMBER REMPE: But don't you have --

13 MEMBER KIRCHNER: I think one is  
14 underestimating where you should put the effort and  
15 where mechanistic approaches are most valuable.

16 My own biases, that your codes for the  
17 detailed analysis, at a smaller component level, are  
18 probably much better V&V'ed than MELCOR, at the very  
19 macroscopic level, where you're actually then worried  
20 about release.

21 So, I would divide the labor in a way that  
22 I would bound what I start with in estimating the  
23 releases. And then, I would inform the design of the  
24 reactors with your detailed modeling capability, to  
25 convince yourself you have adequate margin.

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1 MR. SOFU: That is --

2 MEMBER BALLINGER: And hope --

3 MEMBER KIRCHNER: Not to get there.

4 MEMBER BALLINGER: And hope that the QA  
5 requirements don't strangle you.

6 MEMBER KIRCHNER: Well, that may be unique  
7 to the particle fuel.

8 MR. SOFU: I agree, that could certainly be  
9 an approach, a valid one as well. But normally, we  
10 don't necessarily analyze every single sequence. But  
11 what you do, in LMR case for example, I analyze the  
12 accidents, which you need to analyze to understand  
13 their consequences.

14 MEMBER KIRCHNER: Sure.

15 MR. SOFU: You would very quickly identify  
16 the bounding ones for which you would then proceed to  
17 --

18 MEMBER KIRCHNER: Proceed further.

19 MR. SOFU: -- source code evaluation.

20 MEMBER KIRCHNER: Okay.

21 MR. SOFU: You have to look at the spectrum  
22 for Chapter 15 purposes anyway. And in Chapter 15, if  
23 you run into sequences where, with uncertainties  
24 included, you will expect some fairly sizable fuel  
25 failures. That's the one to look at, not necessarily

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1 the whole spectrum.

2 MEMBER REMPE: Because, in your vision,  
3 Walt, what about air ingress and water ingress --

4 MEMBER KIRCHNER: Well, that's another --

5 MEMBER REMPE: -- events?

6 MEMBER KIRCHNER: -- class that they would  
7 have to analyze --

8 MEMBER REMPE: Yes, you've got --

9 MEMBER KIRCHNER: -- for HTGR.

10 MEMBER REMPE: -- to be able to --

11 MR. SOFU: Absolutely.

12 MEMBER REMPE: -- rule it out and I --

13 MR. SOFU: Absolutely.

14 MEMBER KIRCHNER: Yes, that's --

15 MEMBER REMPE: -- yes.

16 MEMBER KIRCHNER: The initial puff may not  
17 be the more demanding problem for the HTGR.

18 MR. SOFU: So, I hope you recognize that,  
19 with these questions, you're putting me in a spot where  
20 I'm trying to find solutions for a specific reactor  
21 type or specific company.

22 Those are just initial puff shows a pathway  
23 and code capabilities that could support a real  
24 application. I would have loved to be part of a  
25 project like that, but this isn't my role under Shane's

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1 program.

2 And finally, for molten salt reactors, we  
3 don't have a diagram similar, a pathway phenomena  
4 diagram for MSRs. They also come with a greater  
5 variety of design choices.

6 They could have solid fuel, they could have  
7 dissolved fuel, they could be fast spectrum, they could  
8 be thermal spectrum. So, it is anticipated that the  
9 functional containment concept can also apply to MSRs  
10 with dissolved fuel, as well as the TRISO fuel.

11 So, owing to high fission product retention  
12 capacity of molten salt, source term may be less of a  
13 concern from fuel dissolved in the coolant.

14 That's kind of counterintuitive to folks  
15 who are not really immediately familiar with the  
16 technology, because they consider that, well, if you're  
17 worried about core melt, then here you are, you have  
18 already molten fuel. But I think the fission product  
19 retention capacity of the salts is significant.

20 More of a concern could come from effluence  
21 of the salt chemical processing system, maybe. And  
22 also, maybe the tritium generated in the core, which is  
23 a kind of very elusive species, as we all know.

24 I kind of drafted this proposed mechanistic  
25 source term approach for MSRs, not that I know much

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1 about it, but I think I can safely say that, what's  
2 immediately missing for such a source term assessment  
3 would be molten salt chemistry modeling, for which,  
4 even under NEAMS sphere, we don't have a whole lot to  
5 offer, other than plans, currently. And also,  
6 radionuclide release rates from salts, to the cover gas  
7 space and such.

8 But still, we can leverage scenario  
9 evaluation phase of it, because like SAM and Nek, and  
10 these two codes are being already utilized to some  
11 molten salt vendors, adopted as part of their design  
12 process.

13 And again, another takeaway from my  
14 presentation is just dependable reliance on use of  
15 radionuclide tracking capabilities of MELCOR and  
16 offsite dispersion analysis with codes like RASCAL and  
17 WinMACCS.

18 Those are just samples, there are  
19 alternatives available, but they would do the job under  
20 it.

21 That's my conclusions. I know that I'm  
22 running out of time, let me see if -- the takeaway from  
23 this slide, perhaps, there are some gaps in our trial  
24 calculations identified.

25 One of them is, radionuclide release rates



1 from the failed fuel and this bubble transport of some  
2 solid and liquid phases to the cover gas space. And  
3 chemistry modeling and retention in molten salt for  
4 molten salt concepts and FHRs.

5 And we do believe that the emerging DOE  
6 ModSim capabilities you've heard today in codes like  
7 SAM, BISON, PRONGHORN, and Nek5000, in combination with  
8 the radionuclide tracking capabilities of MELCOR, can  
9 be leveraged to remove the empiricism embedded in  
10 traditional codes, MAP, MELCOR, for advanced reactors.

11 CHAIRMAN CORRADINI: Okay.

12 MEMBER REMPE: So, as you rethink this or as  
13 you continue to think along this, like, this last  
14 bullet talking about you're going to support a Level  
15 2/3 PRA --

16 MR. SOFU: Yes.

17 MEMBER REMPE: -- you've got to do  
18 uncertainties. And so, if you do this sequential  
19 thing, that's going to be really a pain to deal with,  
20 if the codes aren't linked, with, like, MELCOR.

21 MR. SOFU: Correct. But I think, as I  
22 answered to Walter, Dr. Kirchner, that you don't  
23 necessarily follow the full source term assessments  
24 text for every single accident in your PRA tree.

25 You identify the bounding events and then,

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1 follow the path, complete the source term assessments  
2 for the rest of them, I think.

3 For concepts like LMRs, that's an easier  
4 ordeal, because not all accidents will lead to fuel  
5 failures and you don't need to do source term  
6 assessment for cases where you don't have a fail  
7 failures.

8 For an HTGR, this would be a bigger task to  
9 tackle, because you may actually have statistical  
10 releases from gazillions of TRISO particles. Even for  
11 DBAs, and sometimes AOOs, I mean --

12 MEMBER KIRCHNER: Even original startup.

13 MR. SOFU: Exactly.

14 MEMBER KIRCHNER: You always have --

15 MR. SOFU: That's true. So, for that, I  
16 think it's -- you're right, that's a bigger challenge  
17 to do the whole sequence for every single thing you can  
18 think of for an HTGR.

19 But nevertheless, for HTGR, during NGNP  
20 project, DOE's approach was complete reliance on  
21 mechanistic source term assessments for AOOs, DBAs, and  
22 BDBAs.

23 MEMBER REMPE: It's just something to think  
24 about, and I'm not sure what you'd do for the molten  
25 salt one.



1 MR. SOFU: Yes. Correct.

2 CHAIRMAN CORRADINI: Other questions? Okay.  
3 Chris, you're our cleanup.

4 MR. STANEK: Okay. Well, let me start by  
5 thanking everyone for their attention today, their  
6 feedback, engagement. That feedback and engagement,  
7 for us, is extremely useful, as we continue to slowly  
8 evaluate our code development priorities.

9 Let me maybe start by making an off-the-  
10 cuff observation from the day, which is that I think  
11 today was semi-painful, but perhaps necessarily so, as  
12 a first step, in terms of what we hope is an ongoing  
13 discussion.

14 But we thought it was necessary to provide  
15 a 30,000-foot view of all of the codes that are under  
16 development. And so, our approach today was really to  
17 present a pure informational meeting, at least that's  
18 how we interpreted the guidance, maybe inaccurately so,  
19 but that's how we went about today.

20 And so, what that meant was that we  
21 presented the DOE codes in something like a vacuum. We  
22 didn't talk about how they compared to other codes, how  
23 they might interface with other codes, and we didn't  
24 talk about how users are using the codes or might be  
25 using the codes.



1           And I don't want to be presumptuous, but  
2 I'm probably not being presumptuous, because one of  
3 Chairman Corradini's first questions, but my assumption  
4 is that our approach has left you wanting some of those  
5 examples.

6           And so, now that we have all this  
7 sufficient, let's say, background information on the  
8 table, I think hopefully we've successfully made you  
9 conversant in DOE codes, that the code names now, when  
10 we say them or someone else says them, that you  
11 understand what those codes are and what they can and  
12 can't do.

13           Now, with that background information and  
14 now that we've gotten through that, as an idea, if  
15 there was to be a next briefing, perhaps it would be  
16 valuable to focus on some examples, let's call them use  
17 cases, of where the codes are being used or potentially  
18 being used.

19           My thought here is that the timing of such  
20 a next meeting, again, I'm being presumptuous, but the  
21 timing might be opportune. We're, especially in the  
22 advanced reactor part of this, we are working closely  
23 with vendors who are having their own conversations  
24 with the NRC, and so, they don't want us to be out in  
25 front of their conversations with the NRC.



1 But as they begin to talk to the regulator,  
2 we can more naturally have conversations using very  
3 specific examples that I think all of us are somewhat  
4 frustrated up here that we're not able to talk about in  
5 great detail, but perhaps going forward, we can begin  
6 to do that.

7 In terms of a summary, a prepared summary,  
8 all we wanted to do was to very quickly ascribe a  
9 notional maturity to the codes you saw today. This is  
10 what we interpreted as the formal request from the  
11 ACRS.

12 And the maturity level of each code was  
13 discussed in some detail in the previous presentations,  
14 but here, we refer back to those tables we started the  
15 day with, where we've tried to distill the information  
16 that was presented in the presentations that you heard,  
17 to give you a sense of a notional or a relative  
18 maturity level of each of these codes for a specific  
19 application.

20 And so, here, this is a non-rigorous way  
21 of doing it, but hopefully, in an attempt to distill it  
22 to a meaningful sort of way, something that leaves you  
23 with a sense of where at least we think things are.

24 And so, where we've color-coded the code  
25 name in green, that means that a relatively mature



1 capability exists. It doesn't mean a complete  
2 capability, and the validation might be limited, but we  
3 think those codes are applicable at this time for those  
4 specific applications.

5 Where the code names are in yellow, there,  
6 we have a basic capability, but there's some key models  
7 that require additional development.

8 And finally, for codes that are in red, the  
9 code is still conceptual or in its initial formative  
10 phases.

11 So, what you can see from the ATF set of  
12 codes, by and large, we feel that the codes that are  
13 being developed are fairly mature and applicable to  
14 accident tolerant fuel.

15 This is my last slide, but for non-LWR  
16 reactors, the DOE codes are, let's say, reasonably less  
17 mature. Reasonably meaning that we haven't spent as  
18 much time working on them.

19 I think we're accelerating our maturity  
20 level quickly, but compared to the maturity level for  
21 the accident tolerant fuel, for the advanced reactors,  
22 as you heard today, we have capabilities that are  
23 applicable to each of the advanced reactor designs.

24 In each of those areas, we have interested  
25 industry members, but we are well aware of the



1 necessary development that needs to happen and we're  
2 working hard on that.

3 And you also heard, in the previous  
4 presentations, mention of a chemistry code that we're  
5 -- that's an urgent need that we are rapidly addressing  
6 in real-time.

7 So, that was just intended to be a quick  
8 snapshot of everything that you heard during the day  
9 and, hopefully, sort of bubbles this up to a level that  
10 is somehow digestible.

11 And I think any of us are happy to answer  
12 any further questions. But in the case there are none,  
13 again, I thank the ACRS for the opportunity today to  
14 present this, and again, the feedback received is, for  
15 us, extremely valuable. Thank you.

16 CHAIRMAN CORRADINI: Good. Well, thank you.  
17 I think, we're going to go around, so here's the  
18 process. We want to have public comments, first and  
19 foremost. And then, we want to go around the table.

20 But I'm going to start off by thanking  
21 Shane and all the myriad contractors that went through  
22 this, because we started this by a phone call after I  
23 got asked by the Chairman, so how are those DOE codes,  
24 are they ready for prime time? My response was, we'll  
25 check it out.



1           So, I want to thank all of you for all the  
2           effort you've put in, it was quite a lot.

3           Okay. So, why don't we first ask if there  
4           are comments from the audience here, while we get the  
5           outer phone line open.

6           MR. BROWN: Bridge open.

7           CHAIRMAN CORRADINI: Oh, the bridge is open?  
8           Well, why don't we -- if the bridge is open, let's take  
9           the public comments from the phone first, if I could do  
10          that. So, hold on, everyone.

11          Is anybody out on the line that wants to  
12          make a comment, please?

13          MR. WHITT: Jeff Whitt is on from Framatome,  
14          just to make a brief comment, just express our support.  
15          We've had an opportunity to work with both CASL and  
16          NEAMS in the development of the codes and support it.

17          And I know that was a question that was  
18          asked early this morning, there is an interest and a  
19          desire for using of these tools for future design and  
20          confirmatory work against license codes.

21          And I would say, generally, I would not  
22          discount the future use of DOE codes in licensing,  
23          where that seems to be the right, applicable approach  
24          for some of the advanced fuels or some of the other  
25          advanced concepts.

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1                   So, we are appreciative of DOE coming and  
2                   making this presentation and letting us listen in and  
3                   be a part of it. So, we just want to express our  
4                   support and thank you.

5                   CHAIRMAN CORRADINI: All right. Thank you.  
6                   Are there any other comments on the phone line? Okay.  
7                   Hearing none, could you close, put it on mute, please?  
8                   Close the line? Everett, you had a comment?

9                   MR. REDMOND: Sure, thank you. Everett  
10                  Redmond, Nuclear Energy Institute. I also chair the  
11                  NEAMS Industry Council. Just wanted to give a little  
12                  bit of an overview there.

13                  The Industry Council is comprised of the  
14                  chairs of the three technology working groups, molten  
15                  salt, high-temperature gas, and fast reactors, as well  
16                  as representatives from EPRI and some relationship to  
17                  CASL.

18                  I want to thank also everybody here for  
19                  their interactions today and thank DOE for the work  
20                  putting together the presentations. There was a lot of  
21                  conversation about interacting and understanding who's  
22                  doing what with what codes.

23                  Obviously, as Chris said, that's more for  
24                  the developers to outline that, but there will be some  
25                  interactions in the next few months, in terms of with



1 staff from some of the developers.

2 But one thing I would highlight is that  
3 NEAMS has done some training sessions in the past, with  
4 some folks in industry, Molten Salt Reactor Working  
5 Group, for example.

6 So, you're getting a lot of interest from  
7 the industry in these codes. Exactly how much they  
8 ultimately get used is up to the developers, but there  
9 is great interest, I want to emphasize, on the part of  
10 the community out there. Thank you.

11 CHAIRMAN CORRADINI: Thank you.

12 MR. LEE: Richard Lee from Research. Since  
13 my name was invoked in his view, I wanted to tell you  
14 the comments I get. First is that I said the NRC  
15 source term releases to the containment and to the  
16 environment.

17 So, when we do severe accident analysis or  
18 source term, I do not use the FRAP code, because there  
19 has no role whatsoever in my analysis. Okay? So, I  
20 don't see why it should be linked to BISON whatsoever,  
21 because it is not talking about steady state or has  
22 anything to do with AOO or anything. So, that's one  
23 thing.

24 And then, if you see the two sequence that  
25 was cited, and my comment is that you really need to



1 have the PRA to tell us these are the risk significant  
2 sequence.

3 And the same way we did when NRR asked us  
4 to synthesize the high burnup fuel and the MOX fuel,  
5 okay? Dana Powers went and looked at all the sequence  
6 of PWR and BWR, to make sure we capture all the risk  
7 significant sequence, before we synthesize analysis and  
8 produce a revision to the NUREG-1465.

9 CHAIRMAN CORRADINI: Thank you. Other  
10 comments? Okay. Let's go around the table. So, I  
11 have two questions for the Committee. One is, are  
12 there any lasting comments they want to make from  
13 today's presentations?

14 And also, I'd like to take notes as to,  
15 since this is an information meeting and we're clearly  
16 going to need to have others, what direction would you  
17 propose that we go for our next Subcommittee meeting,  
18 which will also be information?

19 Because as Chris said, we really got a lot  
20 of information in a relatively short amount of time  
21 from a whole range of tools that DOE's developed for  
22 both ATF and for advanced reactors. So, I'm look at  
23 you, Ron.

24 So, question one is, any other comments  
25 about today. Question two is, and now what?



1 MEMBER BALLINGER: I'm sure everybody's  
2 going --

3 CHAIRMAN CORRADINI: Green light.

4 (Laughter.)

5 MEMBER BALLINGER: I'm sure everybody's  
6 going to say this, but I appreciate the update on  
7 things. I'm familiar with some of these things, but  
8 having it all in one place is a good idea. I'm  
9 heartened to see that you've now expanded the animal  
10 groups to include snakes, range animals, and now, fish.

11 (Laughter.)

12 MEMBER BALLINGER: I'm not sure what else  
13 you can do, maybe some insects or something.

14 CHAIRMAN CORRADINI: Don't challenge him.

15 (Laughter.)

16 MEMBER BALLINGER: But with respect to going  
17 forward, I think the idea of picking some really  
18 important, what you consider important, of the  
19 concepts, the ones that are the most likely to, with  
20 divine intervention, I suppose, be going forward and do  
21 some examples, like has been suggested.

22 MEMBER BLEY: Yes, sir, I do have a few  
23 comments. First, same thing, it was a great day. It's  
24 one of the better meetings I've sat through, I enjoyed  
25 it, and the discussions. It's kind of wonderful to

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1 extend the state of the art and examine these  
2 interesting phenomena.

3 Bottom line, for me, at the top is, I've  
4 just heard bits and pieces about this whole program and  
5 these large computer code developments, with some  
6 worry. I gained some confidence today in hearing how  
7 they're being used and still retaining the need for  
8 data and experiments, that's helpful.

9 On the goal of this whole business, early  
10 today, Chris pointed out that in response to  
11 Congressional direction, which I guess is -- we don't  
12 have any Fukushimas here, DOE issued this report on the  
13 program back to Congress in 2015.

14 Early in that report, you say, with respect  
15 to the goals, kind of two parts. One is, they can  
16 tolerate loss of active coolant in the reactor core for  
17 considerably longer time.

18 Indeed, if that ends up being true, that  
19 would help us a lot, in the area of risk. I haven't  
20 heard anything yet that hints at that and most of the  
21 work hasn't been up at that end of the problem.

22 The kinds of things that contribute to  
23 risk, though, you need minutes to hours to do anything  
24 about. So, I haven't heard things that make me think  
25 you're going to buy that kind of time.

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1           The other part is, while improving, you  
2           want to do that while you're improving fuel performance  
3           during normal operations, operational transience, as  
4           well as design-basis accidents and beyond-design-basis.

5           Everything except beyond-design-basis, it  
6           sounds like that's coming together pretty well. I  
7           haven't heard much that makes me think you're covering  
8           the beyond-design-basis events yet.

9           And on the mechanistic source terms, I  
10          guess I'll just harp a little, and it seems like you're  
11          on the right track here, getting the chemistry as right  
12          as you can in that area, allowing for uncertainties,  
13          because there are strange reactions going on very fast,  
14          with daughter products that come and go, it's going to  
15          be pretty messy.

16          So, being able to account for uncertainties  
17          in that chemistry is going to be important, if people  
18          are going to really buy into this and think it's  
19          convincing.

20          Tanju said something I like to hear from  
21          people working this area, is, every time he said  
22          something, it was depending on the accident scenario,  
23          barriers may or may not be useful. And that's crucial  
24          and too often, people don't recognize that. But I  
25          guess that's what mechanistic source term is all about.



1 I hope folks consider that there might be  
2 other simplifications beyond what Walt suggested  
3 earlier, that might be helpful.

4 In other areas, we found that you can  
5 collapse many of the PRA scenarios into classes that  
6 look the same for what's coming next. And in this  
7 area, I hope that's possible. Usually, there are  
8 simplifications like that, there can be. You have to  
9 test those. But that's kind of the whole gamut.

10 Where we go next, anything you bring will  
11 be interesting to me, but I think examples would be  
12 useful. And I just picked up the papers you pointed us  
13 to and I look forward to looking at those. So, thanks  
14 a lot for today.

15 CHAIRMAN CORRADINI: Matt?

16 MEMBER SUNSERI: So, I can't express this  
17 anymore eloquently than Dennis did, so I'll just leave  
18 it as, I found that the strategy that you developed is  
19 a lot more developed, or farther along than I had  
20 anticipated and the progress you're making on maturing  
21 these codes is -- my confidence level is well raised  
22 also.

23 So, I'll just leave it at that. I thought  
24 all the presentations were well done and the presenters  
25 were well prepared.



1           And since I'm the operational guy here at  
2           the table and this is kind of outside my area of  
3           expertise, I'll leave it to those more qualified than  
4           me to judge where we should go next. Thank you.

5           MEMBER REMPE: So, I'd like to add my thanks  
6           for coming here and discussing it. It helps. I guess,  
7           I'm back to the question I raised at the beginning of  
8           the day.

9           Yes, I understand you're enthusiastic about  
10          your research and you believe you're going the right  
11          way, but I -- no one has yet, I mean, I've heard, oh,  
12          they're going to be coming in, and that will be  
13          interesting to see, but no one is yet willing, in the  
14          ATF program, to come in and say, I want to use one of  
15          these for qualifying the fuel.

16          So, I'd like to see something like that.  
17          And I actually think there's a lot to be learned from  
18          such a thing like that.

19          And I understand, industry says, well, I  
20          can do it cheaper if I use my own code, but maybe they  
21          ought to be encouraged with some funding to do that and  
22          get some confidence that these codes are better, if  
23          that's -- we've spent a lot of years developing these  
24          codes, so let's use it.

25          And so, again, it's beyond ACRS making such



1 recommendations, but it sure seems like that that's an  
2 important thing to do.

3 With respect to NRC and the next step, I  
4 actually think it would be good to have a Subcommittee  
5 meeting where we hear from the staff, not only the  
6 folks that are doing the accident tolerant fuel or the  
7 advanced reactors, but also research, see some actual  
8 comparisons to see, are these codes really better?

9 Again, when we asked about that earlier, I  
10 believe we were told by the person from INL, well, my  
11 job isn't to look if it's better, just it matches the  
12 data, but I don't know if it's better than FAST is.  
13 And so, I think we need to have some folks do that, to  
14 get some confidence, too. And I guess I'll leave it at  
15 that.

16 MEMBER MARCH-LEUBA: I thought that was  
17 Mike's job.

18 (Laughter.)

19 MEMBER MARCH-LEUBA: Okay. Yes, well, I'm  
20 very impressed by the DOE team. I think you guys have  
21 done a fantastic job over the years, and today of  
22 course. And I'm especially impressed by the tools that  
23 we have seen. I mean, something like MPACT, it's a  
24 dream calculation. I mean, I see it and I love it.

25 However, I'm concerned about the complexity



1 of the new tools and the user base that -- the DOE team  
2 has been working on this for the last 12 years and you  
3 know how to use it. But those tools are not for you,  
4 are for everybody else.

5 And I suspect that the large vendors may be  
6 able to take advantage of it, but I'm worried about the  
7 small companies, which are the ones that really need  
8 these tools.

9 The ones that are going to design the new  
10 reactors, how are they going to be able to do something  
11 like this, especially if it takes 10,000 cores to run  
12 the calculation like this? I can't -- wait until we  
13 are through and then -- I think that the process is, we  
14 talk now.

15 MR. SOFU: I think, the 2,000 -- when you  
16 are trying to develop capabilities that doesn't exist  
17 elsewhere, it automatically pushes you to a particular  
18 domain of complexity that you're trying to do things  
19 that doesn't exist. If you repeat existing capability,  
20 then you're not really adding any value.

21 But it's interesting that a lot of what we  
22 developed under NEAMS program is adopted earlier by  
23 small companies, as opposed to large ones that already  
24 have their developed capabilities. They're not  
25 interested in that. So, it's the other way around. I

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1 just wanted to make mention of that.

2 MEMBER MARCH-LEUBA: So, for the future, I'd  
3 like to see, I mean, if you know of examples where  
4 companies already taking advantage of this or have  
5 plans for doing it, it would be fantastic if we could  
6 have some of those examples, instead of going into the  
7 nitty details of how you calculate the power on node  
8 27.

9 And in that line, what I would like to see  
10 is a plan of application of these methods for ATF.  
11 Obviously, we haven't done it, but go through how would  
12 I resolve the accident tolerant fuel with this method?  
13 What would I do that would be useful and that would  
14 save me money on the testing?

15 CHAIRMAN CORRADINI: Walt?

16 MEMBER KIRCHNER: Thank you all for the  
17 presentations. For me, it's very enjoyable. I started  
18 my career at Los Alamos doing advanced code  
19 development, so it's, for someone like myself, it's  
20 interesting to see how much progress has been made.  
21 So, I congratulate you on that.

22 Since the slide is up, I would suggest,  
23 you've heard some thoughts already on source term, I  
24 think this is a difficult problem, from end to end, to  
25 do the source term estimates.



1           So, I would have in my back pocket or my  
2           thinking or my strategy, whatever you want to call it,  
3           a way to bound these problems. Dennis spoke eloquently  
4           to certain aspects of this. The chemistry challenges  
5           can't be underestimated, especially for some of the  
6           more advanced concepts.

7           So, I would have concern there and I would  
8           want to have Plan B, because you're not going to have  
9           the level of maturity in the PAR space that we have in  
10          the LWR, backed up by all their experience. Certainly,  
11          not early on. And so, I guess, a caution there, is  
12          what I would put out. And thank you, again, for the  
13          presentation.

14          As to the future, yes, I'd be interested in  
15          hearing more. I think, hearing more attacking specific  
16          problems may be useful. And I know that perhaps  
17          involves vendors, then, and actual designs, but that's  
18          probably where the rubber hits the road, in terms of  
19          applying these codes. And with that, thank you.

20               CHAIRMAN   CORRADINI:   So,   I'll   thank  
21          everybody, but you've been thanked enough. So, let's  
22          just move on from there. I guess, what took me by  
23          surprise today was Chris's starting comment, which the  
24          industry advisory group didn't want to let us know who  
25          are potential adopters.



1                   So, that -- because one of my first  
2                   questions is, okay, who are your users? So, I've got  
3                   to come back to that question. So, if it's still of  
4                   the belief that there is a potential set of users that  
5                   don't want to be identified, I would think the next  
6                   step, for me, would be user needs.

7                   I'd like to hear from industry, what are  
8                   the user needs? So, Everett said he's got his advisory  
9                   group, if they don't want to say, I'll use BISON, I  
10                  want to hear from them, I think I want to hear from  
11                  them, what do they need in a tool that gets them to the  
12                  end game?

13                  And then, if we were to talk about it that  
14                  way, I would flip it and go to the NRC and say, if  
15                  they're the users, what do they need to get it to the  
16                  end game? That kind of goes a little bit with what I  
17                  think Jose was after, which is plan for application of  
18                  ATF.

19                  I think the one thing that Walt mentioned,  
20                  and Dennis mentioned, which is, simpler is better.  
21                  Somehow, I would like to work the problem backwards,  
22                  what is the simplest way to identify the limiting  
23                  source term?

24                  And if you can do that, that simplifies all  
25                  the preliminary analysis and gets me to that source



1 term, rather than complexity. Because these are very  
2 interesting tools, but they're complicated. And I'm  
3 wondering if the industry is hesitating because they  
4 view them as complicated, or maybe they're not familiar  
5 with them and, therefore, that's -- so, I think, for  
6 me, the next step would be to try to hear what the  
7 users need. Not necessarily who the users are, because  
8 I sense you're not going to be allowed to trot them out  
9 in front of us to write down and certify, but at least  
10 to hear what they need. What are they looking for in  
11 a tool that they can use for their safety analysis?

12 I guess, that's where I would like to go in  
13 the future. So, maybe we can find a way to marry that  
14 together with another Subcommittee meeting. I would  
15 think, since this one took four months, the next one  
16 might take a few months. So, why don't we start  
17 talking about, between -- I originally called Tom and  
18 Tom called Chris and Chris called, and so, we can talk  
19 about it and see where we go from there, okay?

20 MR. STANEK: Sounds good.

21 CHAIRMAN CORRADINI: I don't have anything  
22 else. Any other members have anything else?  
23 Otherwise, we're adjourned. Thank you very much.

24 (Whereupon, the above-entitled matter went  
25 off the record at 5:12 p.m.)



# 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 <sub>2</sub>	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U <sub>3</sub> Si <sub>2</sub>	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

1. Steve  
Hayes

2. Jess  
Gehin

		Doped- UO <sub>2</sub>	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U <sub>3</sub> Si <sub>2</sub>	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





# 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  $\text{UO}_2$  Fuel
  - Cr-Coated Zirconium Cladding
  - FeCrAl Cladding
  - SiC Cladding
  - $\text{U}_3\text{Si}_2$  Fuel
  - Non-cylindrical Metallic Fuel
- Validation for Accident Tolerant Fuels
- Summary and Conclusions



# Accident Tolerant Fuels



## Development and Testing

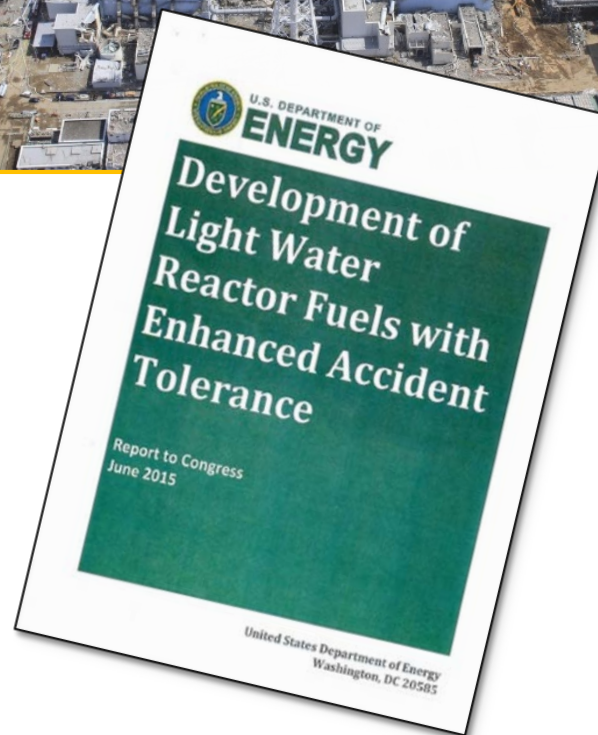


# Congressional Direction and Development Plan on ATF

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.

## 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  $\text{UO}_2$  for improved thermal conductivity and performance



## ■ General Electric



- Iron-based cladding
- ODS variants for improved strength



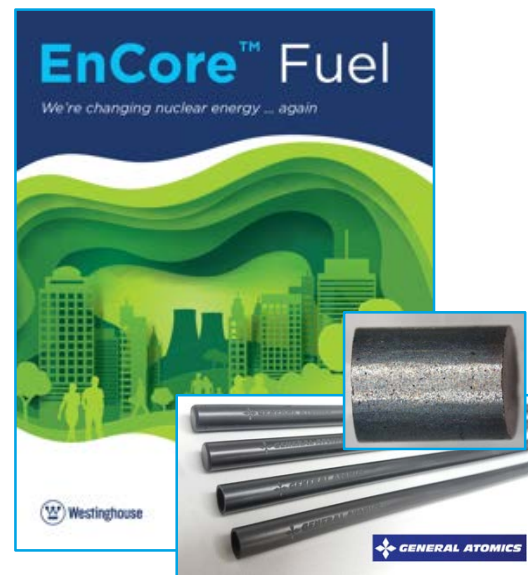
GE imagination at work



## ■ 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

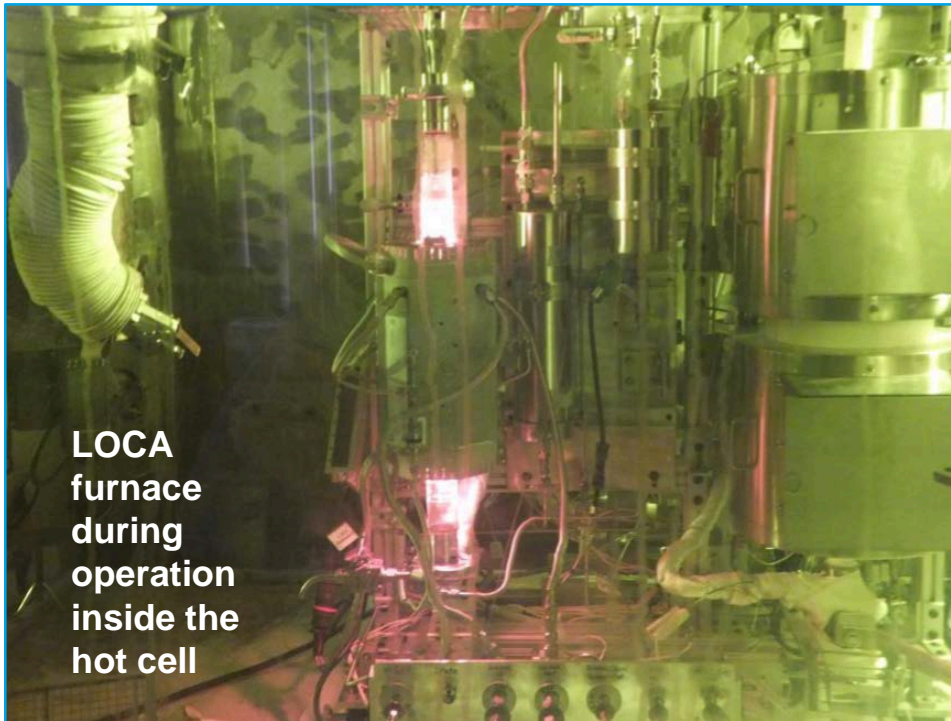
Halden testing must  
be redirected



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	Prototypic	Focused	Focused	Mature concepts	Mature concepts
	Many Compositions	Cladding and Integral Fuel Concepts				
	Nominal conditions	Nominal conditions	Off-normal conditions	Nominal conditions	Nominal conditions	Off-normal conditions
Fuel	UO <sub>2</sub> *, U <sub>3</sub> Si <sub>2</sub>	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  $5^{\circ}\text{C/sec}$
- Temperature up to  $1200^{\circ}\text{C}$
- Capable of water quench





# 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

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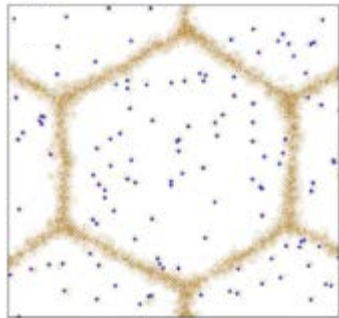
Multiscale, Mechanistic Modeling of Nuclear Fuels



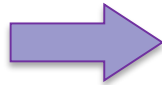
# Multiscale, Mechanistic Modeling of Nuclear Fuels

- **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 where experimental data is sparse, and 3) may require less (or different) experimental data for validation

## Atomistic simulations

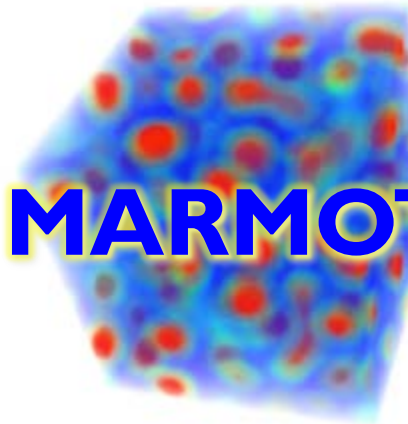


*Atomistically-informed parameters*



- Identify important mechanisms
- Determine material parameter values

## Meso-scale models



**MARMOT**

- Predict microstructure evolution
- Determine effect of evolution on material properties and fuel behaviors

## Fuel performance models



**BISON**

- Predict fuel performance and failure probability

Degrees of freedom, operating conditions

Mesoscale-informed materials models



# The Bison Fuel Performance Code

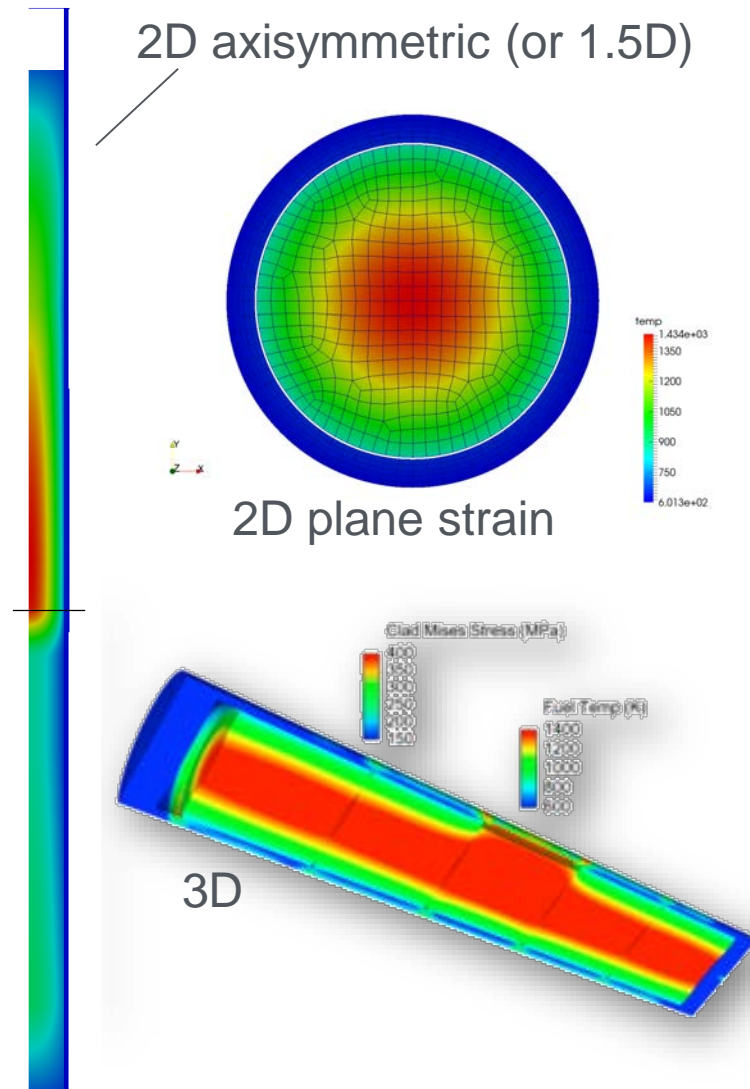
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- 1) Overview
- 2) Verification
- 3) Validation



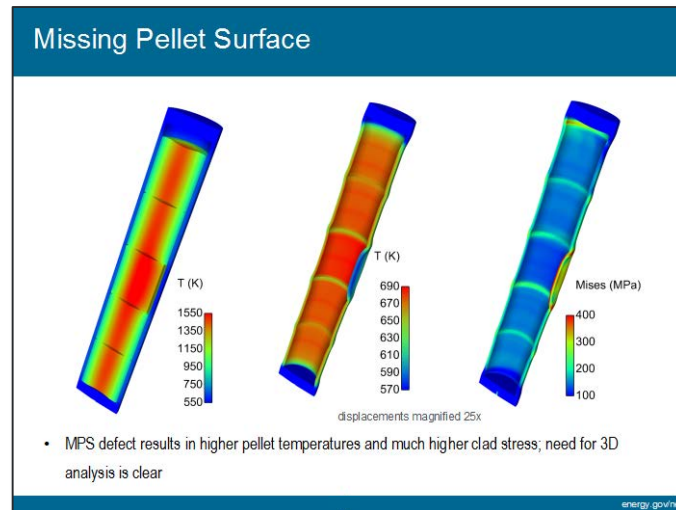
# BISON Fuel Performance Code

- 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

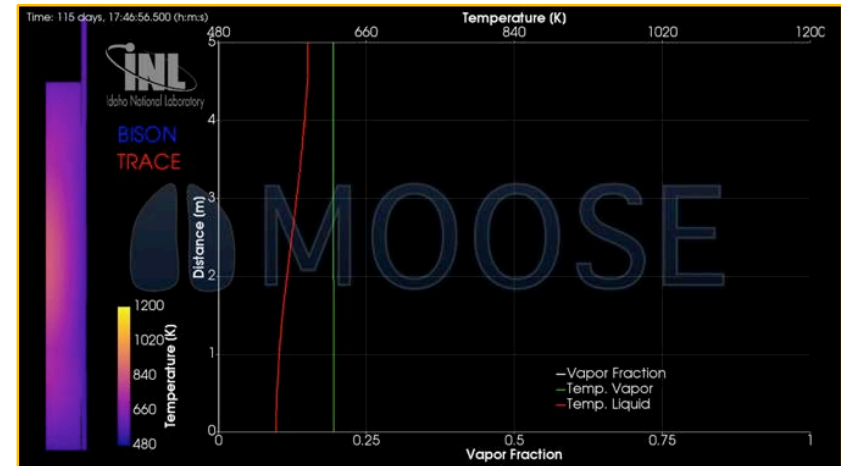




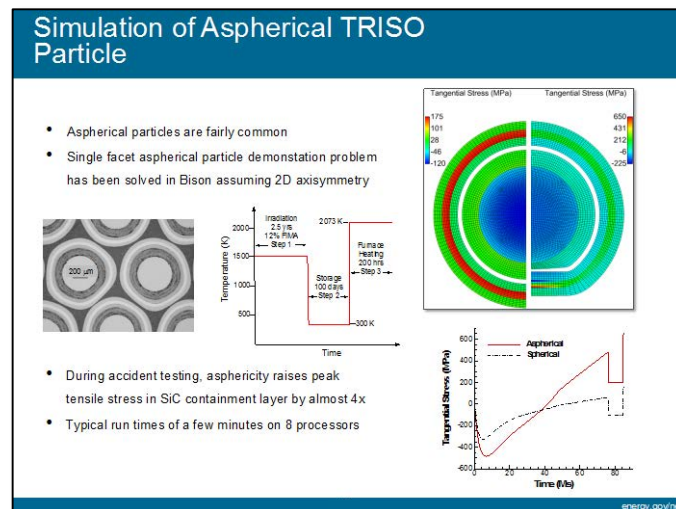
# What Makes Bison Different?



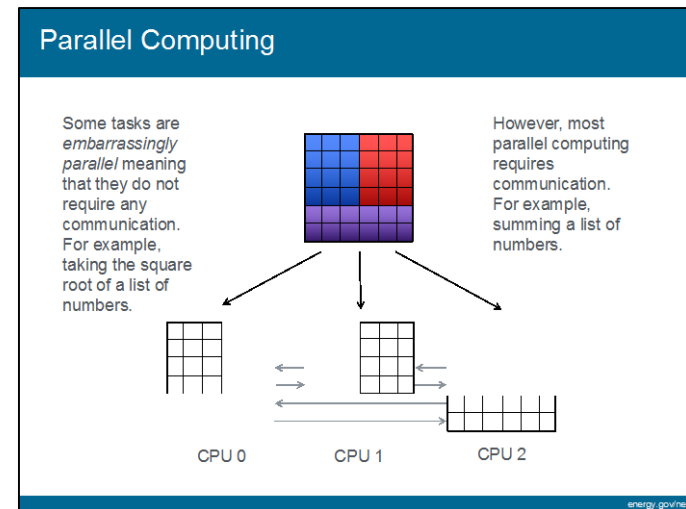
3D/Arbitrary Geometry



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/utilis	100.0 % 21 / 21	100.0 % 3 / 3
src/vectorpostprocessors	95.3 % 41 / 43	100.0 % 6 / 6

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**Verification of the BISON fuel performance code**

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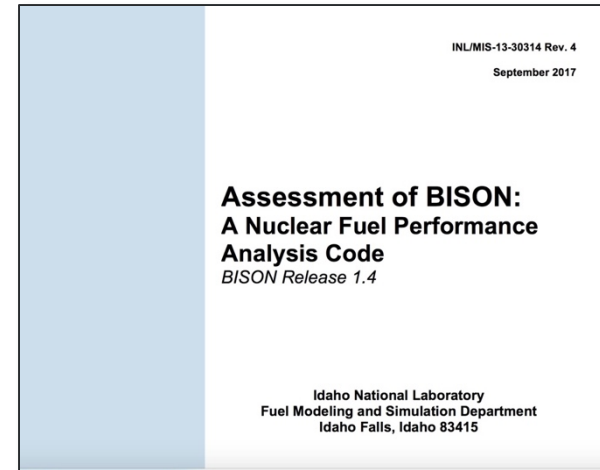
**ABSTRACT**

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

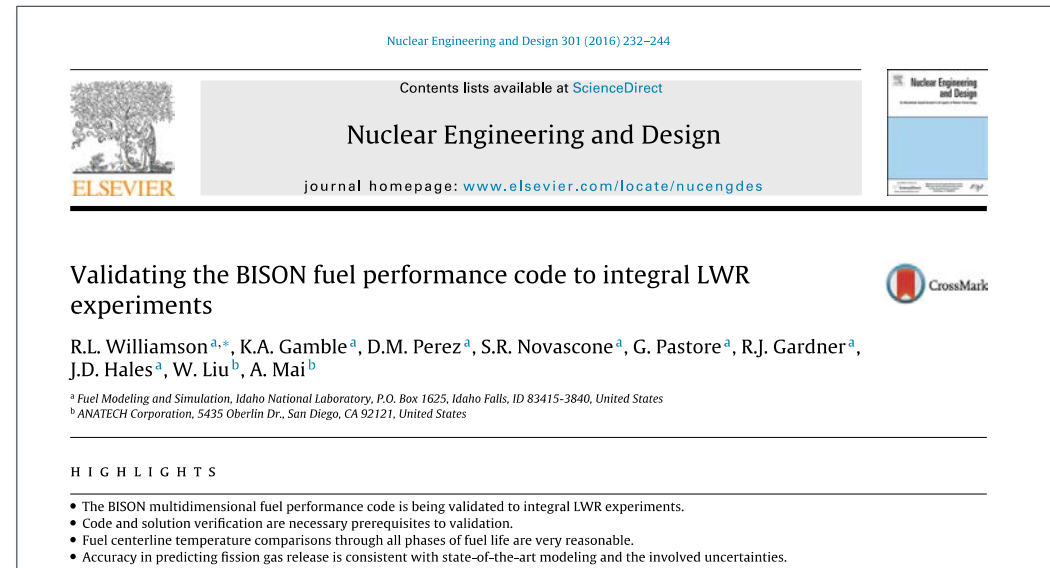


# Bison LWR Validation Status – 1/2

- 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



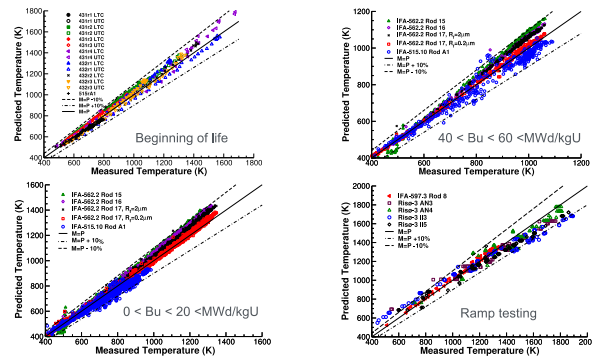
[https://bison.inl.gov/SiteAssets/BISON\\_assessment1.4.pdf](https://bison.inl.gov/SiteAssets/BISON_assessment1.4.pdf)





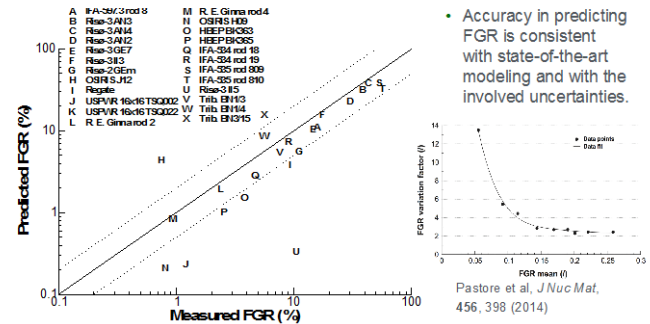
## Bison LWR Validation Status – 2/2

## LWR Validation Fuel Centerline Temperature



# Fuel Temperature

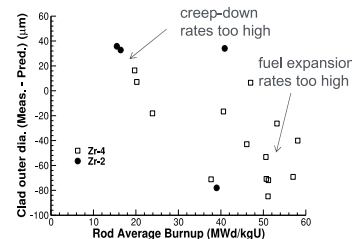
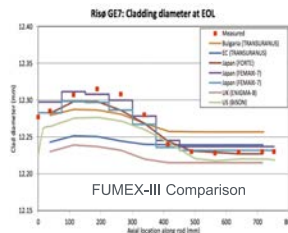
## LWR Validation Fission Gas Release



## Fission Gas Release

LWR Validation  
PCMI (rod diameter)

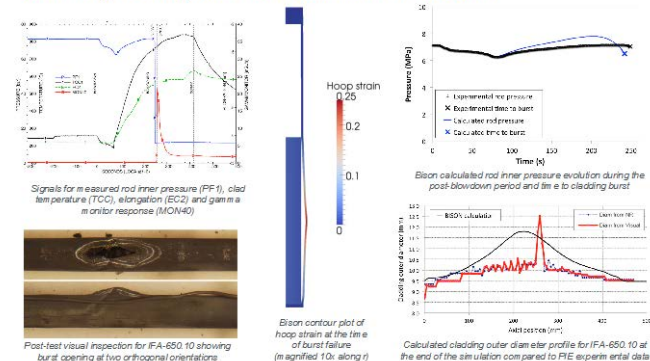
- Prediction of PCMI behavior remains difficult (for essentially all fuel performance codes)
  - FUMEX-II (2002-2007)
  - FUMEX-III (2008-2012)
  - Recent Bison efforts



## PCMI

## LWR Validation LOCA Integral Rod Experiment

## Bison analysis of integral fuel rod LOCA test Halden IFA-650.10



## LOCA



# Model Enhancements for ATF



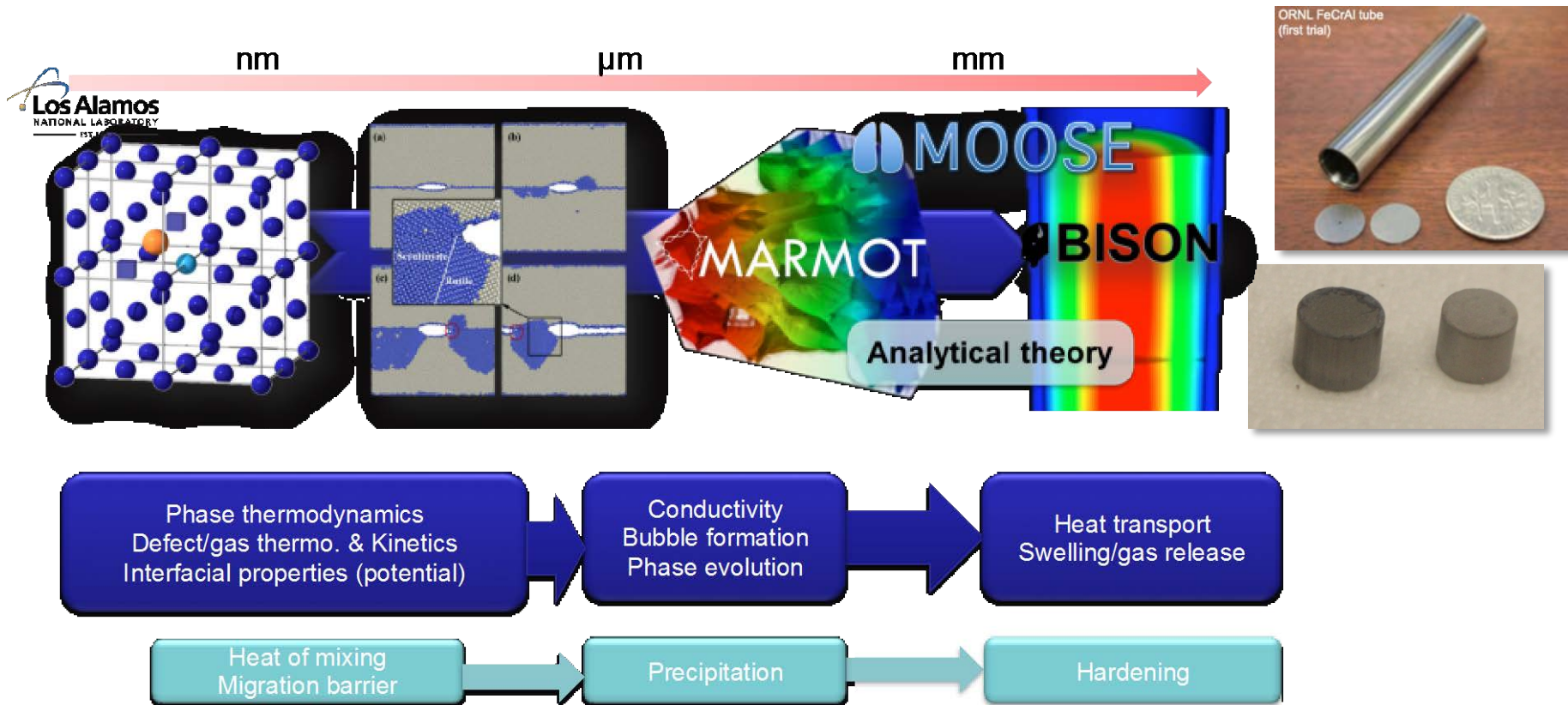
# Model Enhancements for ATF

- **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

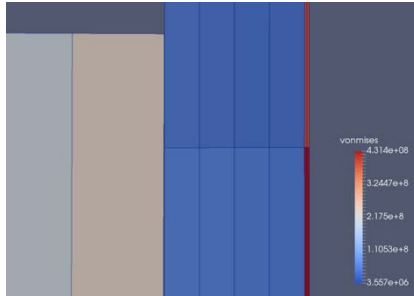




# ATF High Impact Problem (HIP) Highlights

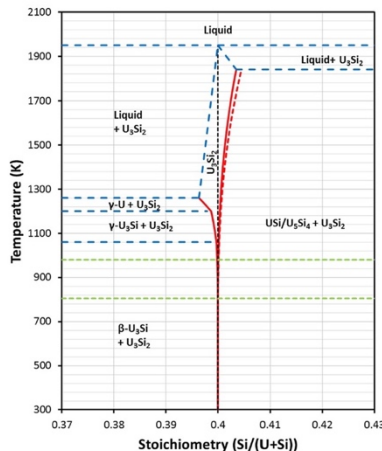
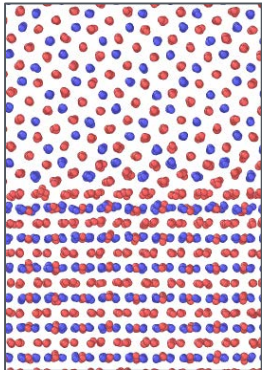
## Coated Claddings

Capability established in BISON to model coatings, and several case studies examined.



## $U_3Si_2$

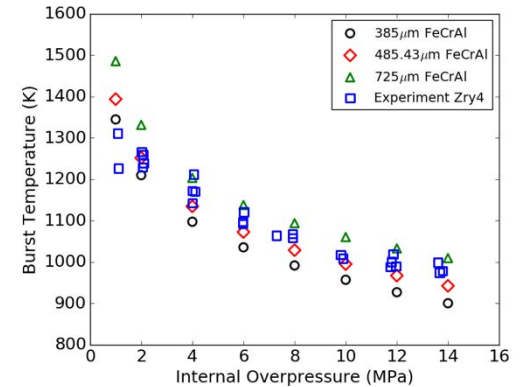
Non-stoichiometry, fission gas release, swelling, thermal conductivity



## FeCrAl

Advanced mechanical models being developed based upon cluster dynamics-informed crystal plasticity models.

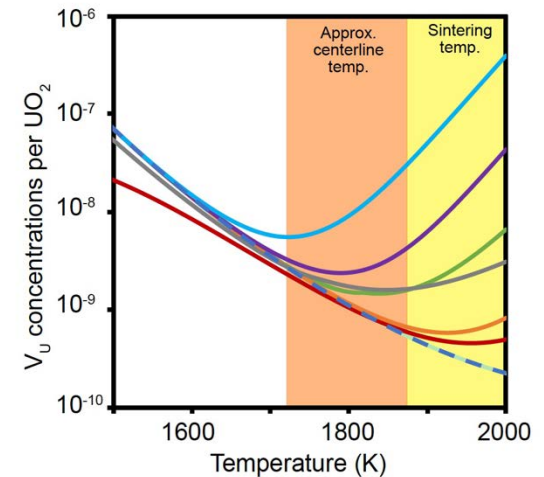
Burst model developed and implemented in BISON



## 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 <sub>2</sub> 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 <sub>3</sub> Si <sub>2</sub> Fuel	Yes	Yes	Yes	Support user needs
Metallic Fuel	Yes	Yes	No	Support user needs



# Cr<sub>2</sub>O<sub>3</sub> Doped UO<sub>2</sub> Fuel: Model Summary

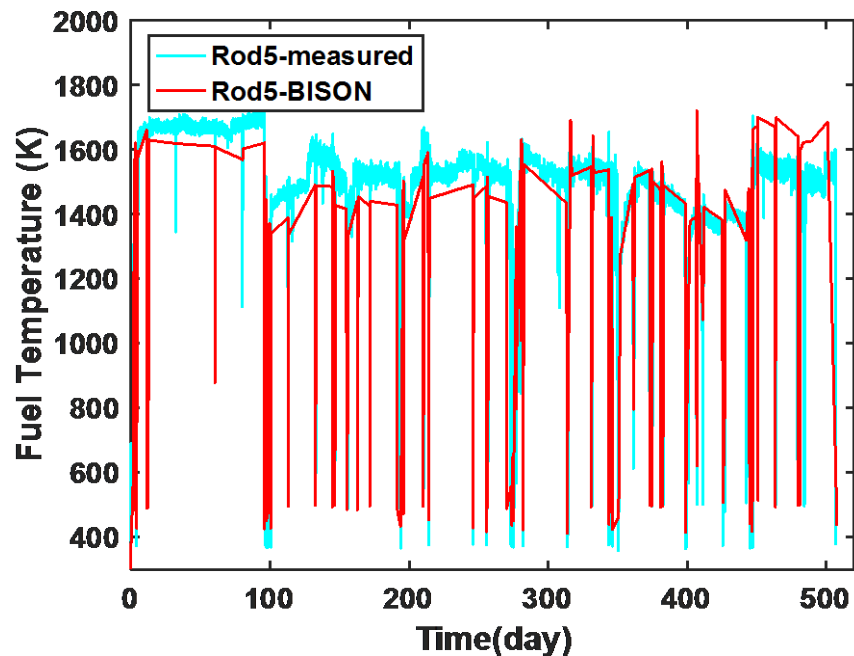
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes (UO <sub>2</sub> )	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes (UO <sub>2</sub> )	Yes	Yes	Yes	Yes
Basic mechanical properties	No (UO <sub>2</sub> )	Yes	No	Yes	Yes
Creep	No (UO <sub>2</sub> )	Yes	No	Yes	Yes
Swelling	No (UO <sub>2</sub> )	Yes	No	Yes	Yes
Fission gas release	Yes	Yes	Yes	Yes	Yes



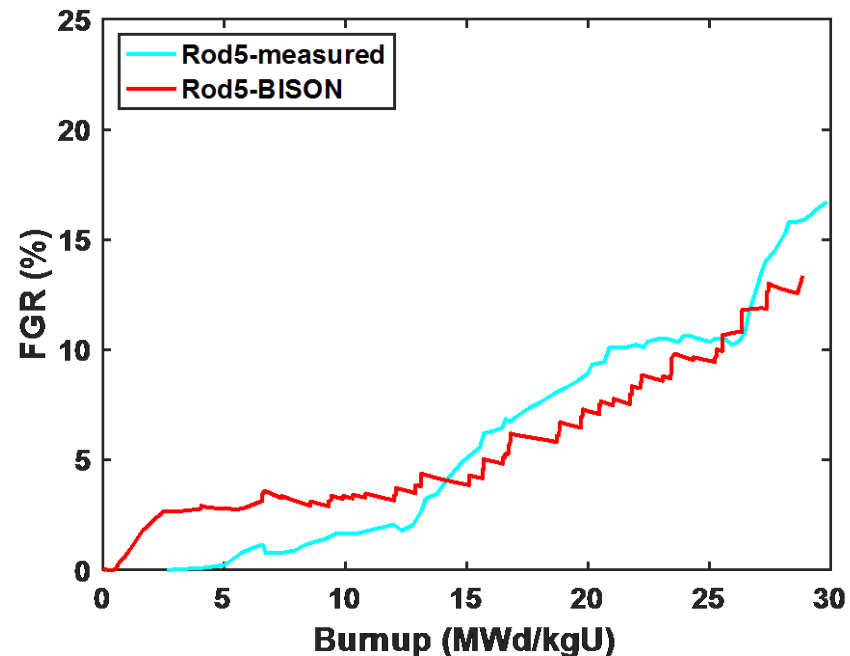
# Cr<sub>2</sub>O<sub>3</sub> Doped UO<sub>2</sub> Model Results

## Bison Simulation of Halden IFA-677 Rod 5

Fuel centerline temperature



Fission gas release



	Rod 3	Rod 5
Fuel	UO <sub>2</sub> +Add.	UO <sub>2</sub> +Add.
Cr <sub>2</sub> O <sub>3</sub> 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

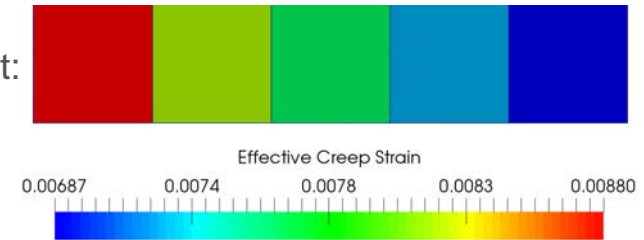
Note that no models incorporate irradiation effects. Cr-coated claddings under irradiation in ATF-2 (ATR).



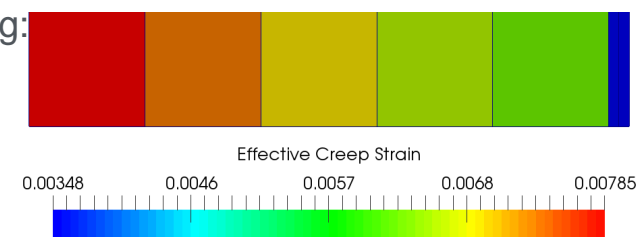
# Cladding Coating Mechanical Behavior

- 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 1/10<sup>th</sup> of the load in the hoop direction

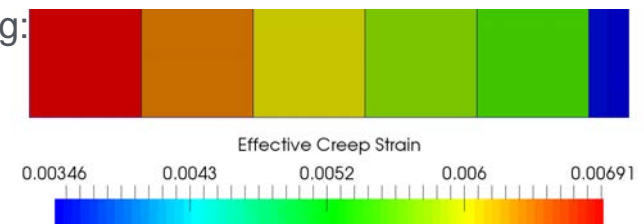
No coating:  
Displacement:  
3.74e-2 mm



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

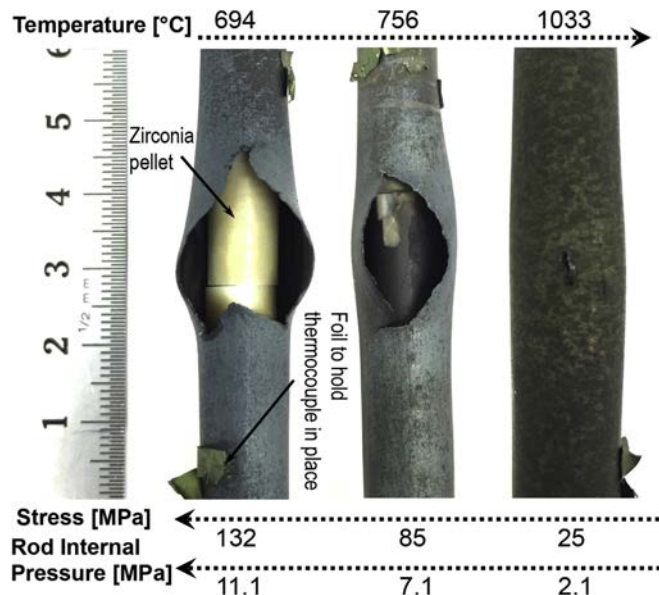
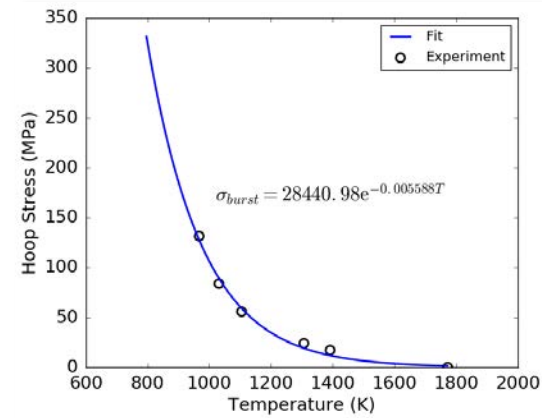
\*FeCrAl cladding under irradiation in Hatch and ATF-1 (ATR).



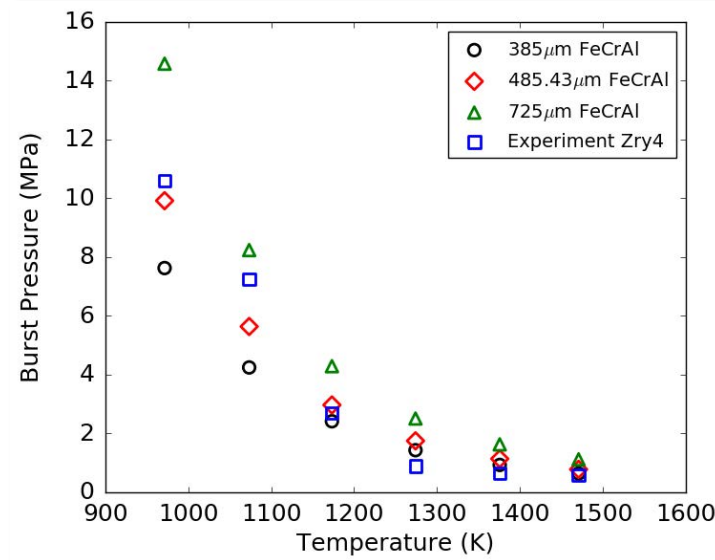
# FeCrAl Burst Model Results

- 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.

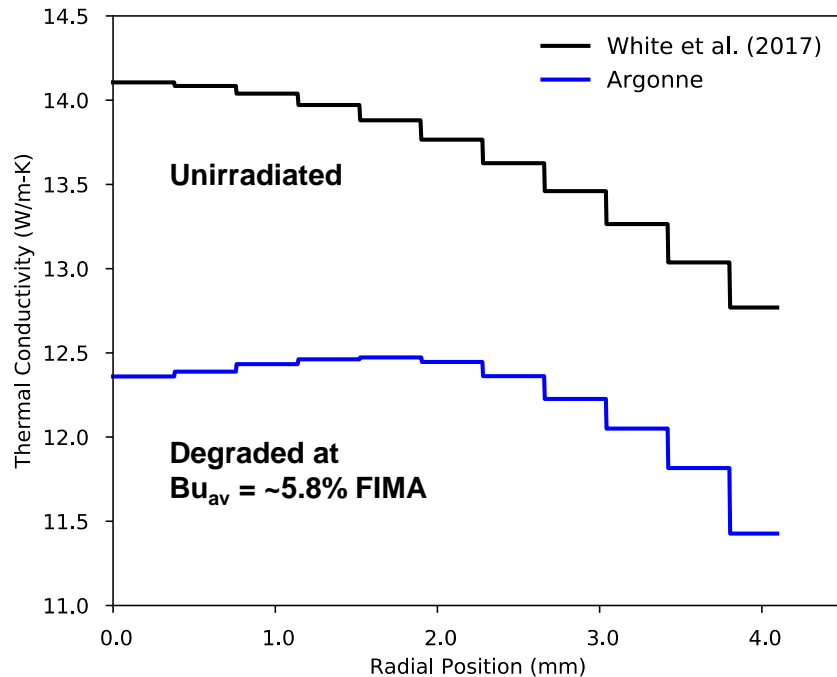


# U<sub>3</sub>Si<sub>2</sub> Fuel: Model Summary

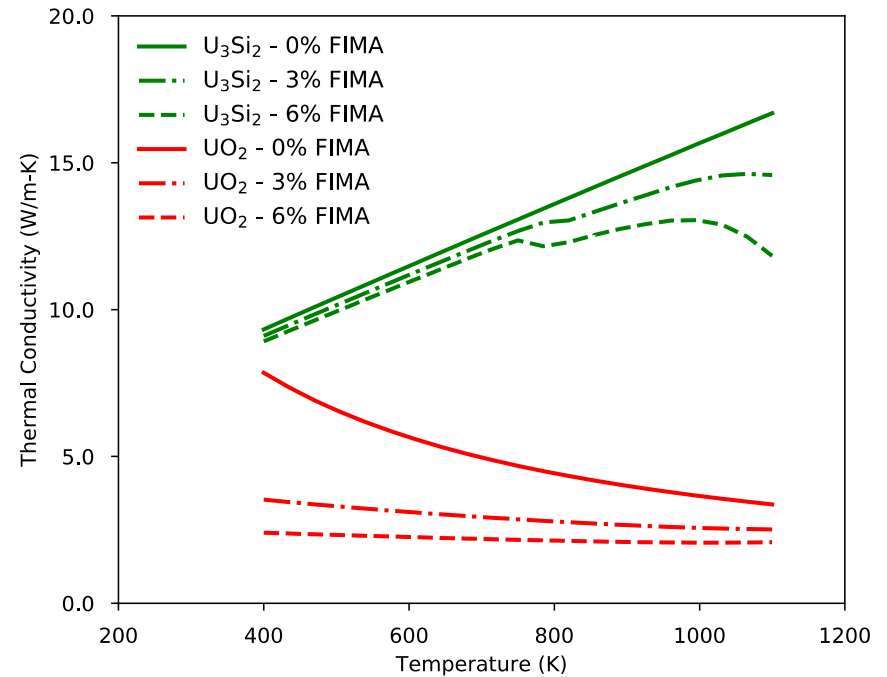
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes	No	Yes	Yes	Yes
Basic mechanical properties	Yes (constant values for elasticity)	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Swelling	Yes	Yes (very little)	Yes	Yes	Yes
Fission gas release	Yes	Yes (very little)	Yes	Yes	Yes



# $\text{U}_3\text{Si}_2$ Thermal Conductivity Model Results



Element averaged thermal conductivity at the midplane of a 10 pellet RZ-axisymmetric rodlet.



Degraded thermal conductivity comparisons between  $\text{U}_3\text{Si}_2$  and  $\text{UO}_2$  for a temperatures varying from 400 to 1100 K.



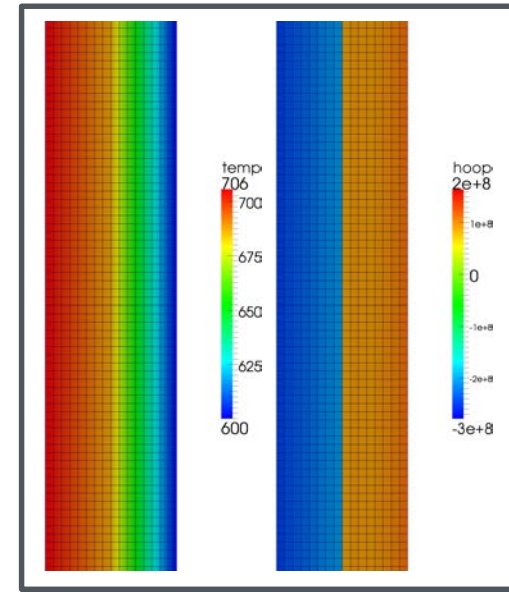
# SiC/SiC Cladding: Model Summary

	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

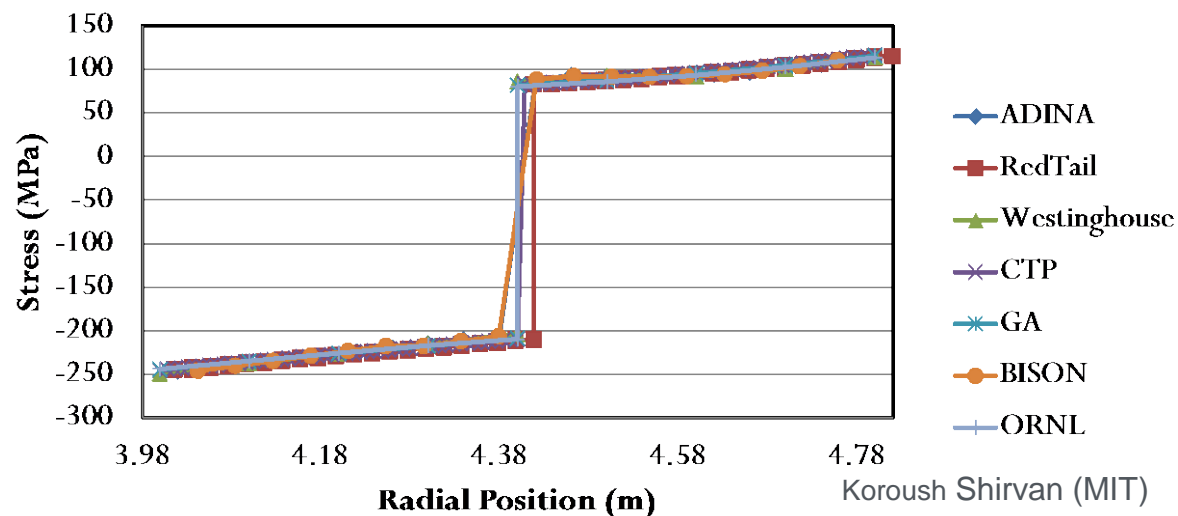


# SiC/SiC Cladding Model Results

- 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.



Hoop Direction





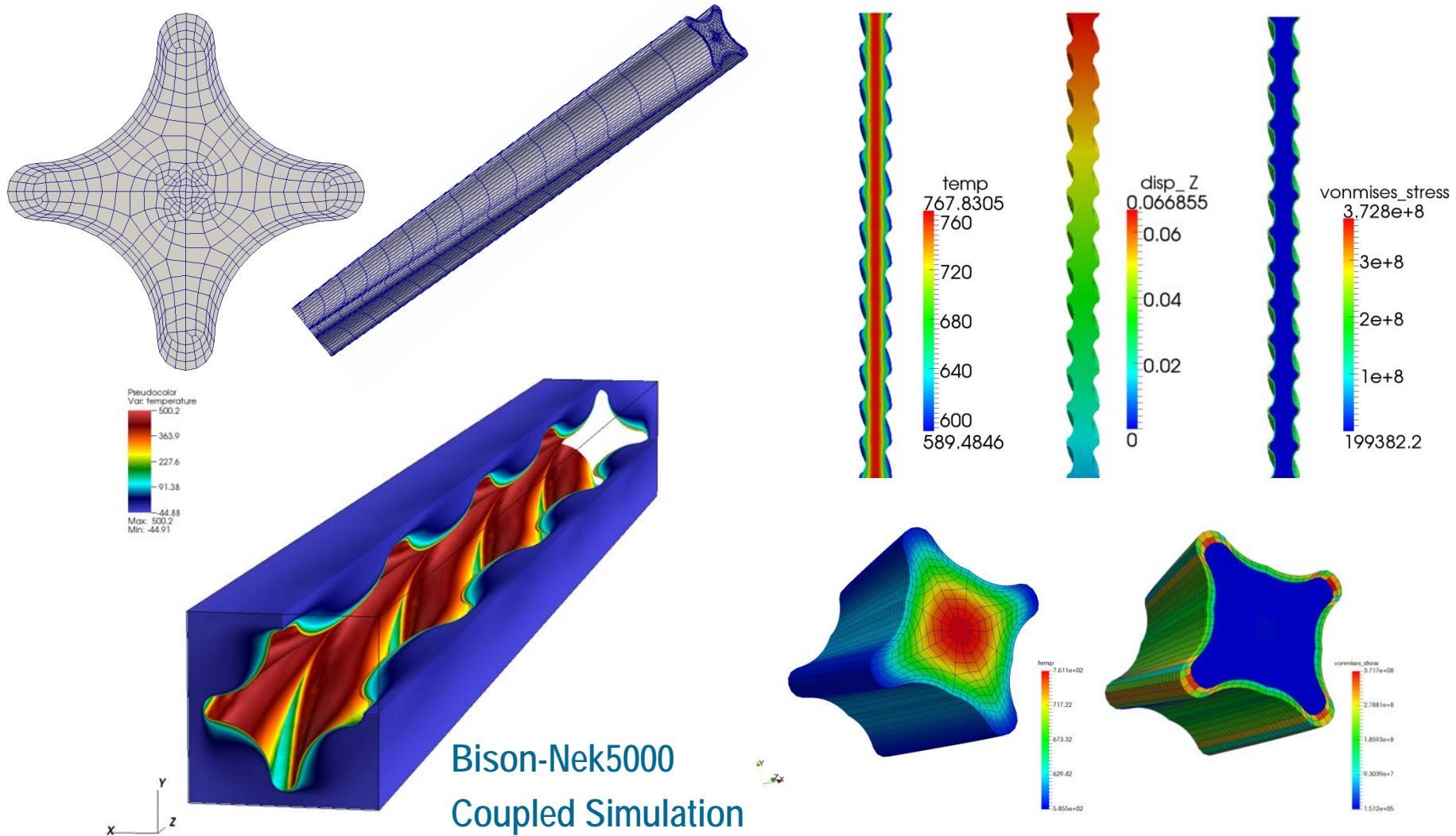
# Non-Cylindrical Metallic Fuel: Model Summary

	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, not Lightbridge Design



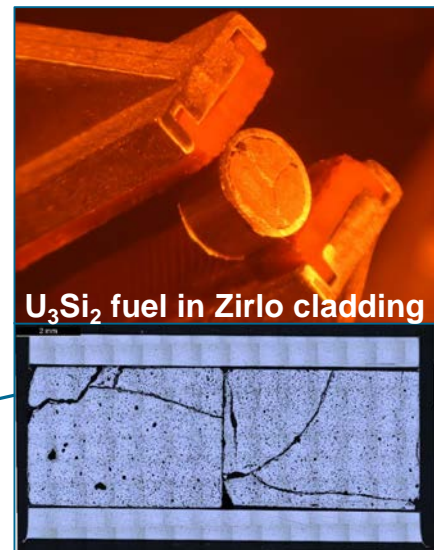


# Validation for ATF



# 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**





# 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 INEL for the microstructural characterization of irradiated fuels.



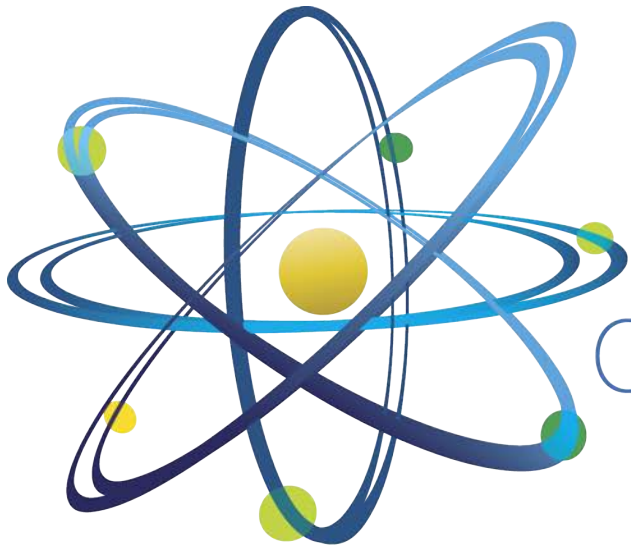
# Summary and Conclusions

- **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  $\text{UO}_2$
  - 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.**





# Neutronics and Thermal-Hydraulics Modeling for Accident Tolerant Fuels

August 21, 2018

DOE Briefing to ACRS:

*Advanced Modeling & Simulation Tools for Accident Tolerant Fuels*



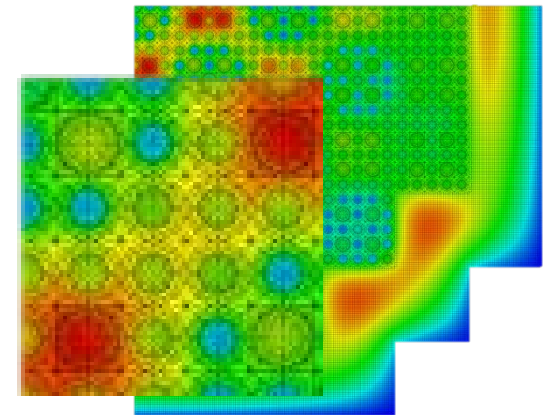
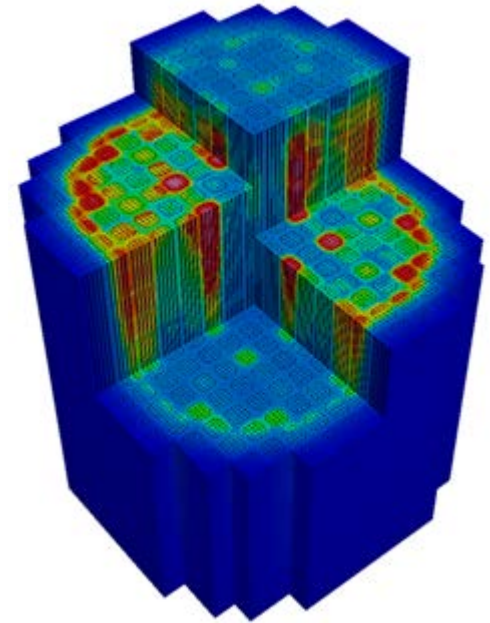
# Presentation Outline

- 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 UO<sub>2</sub> 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



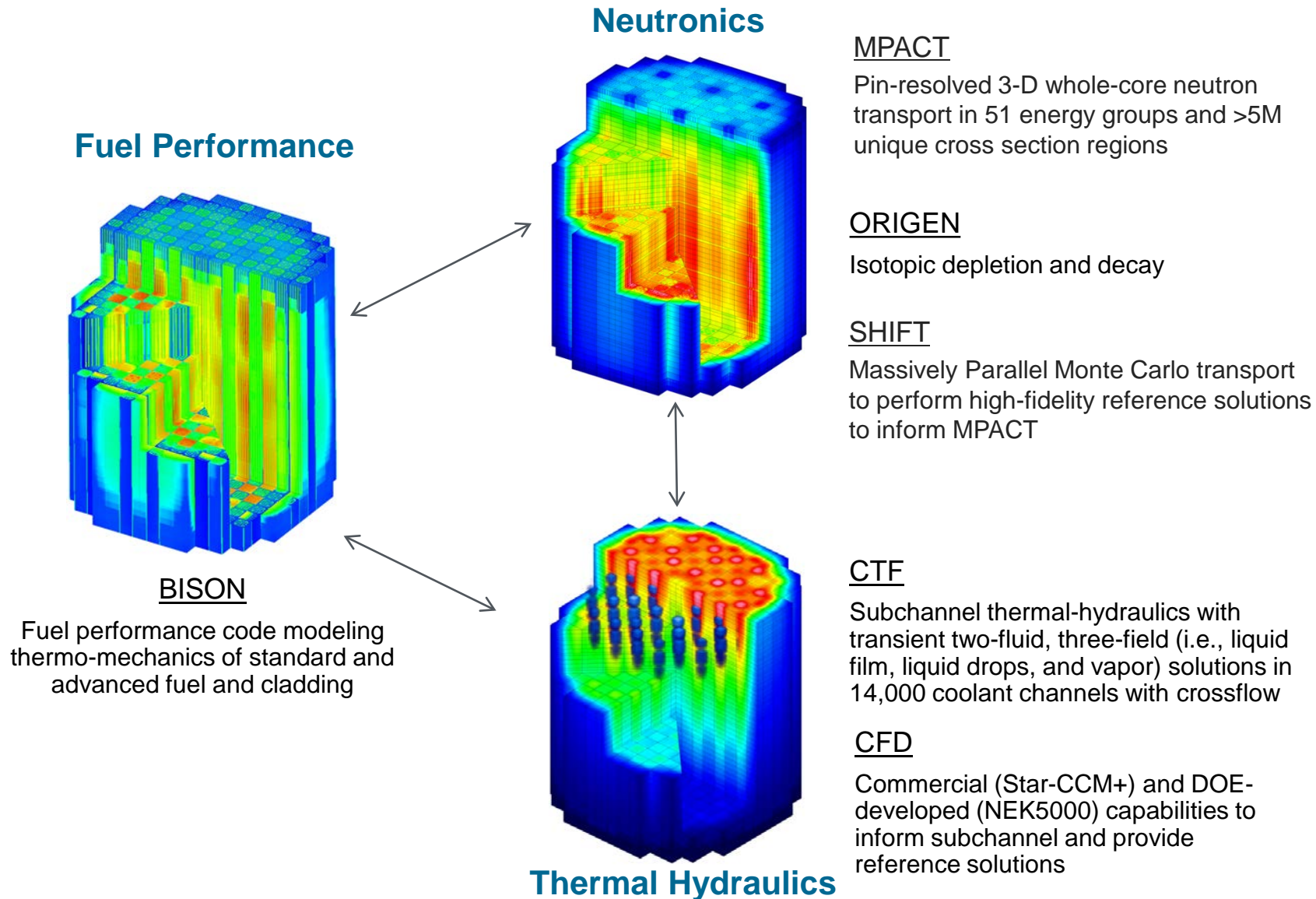


# Overall Applicability to Accident Tolerant Fuels

- 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<sub>2</sub>) and operations and can be extended for ATF concepts



# Codes and Coupling for LWR Simulations

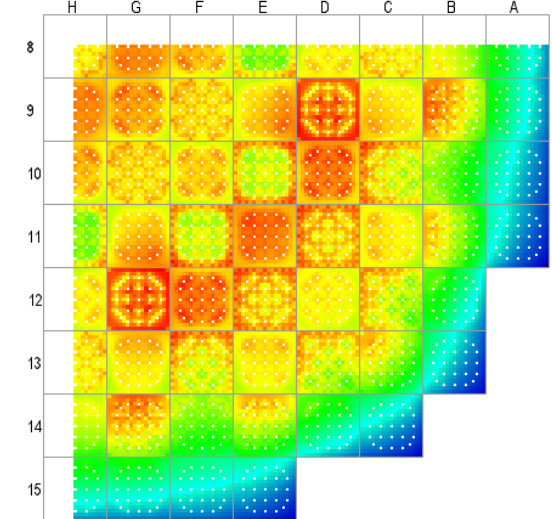




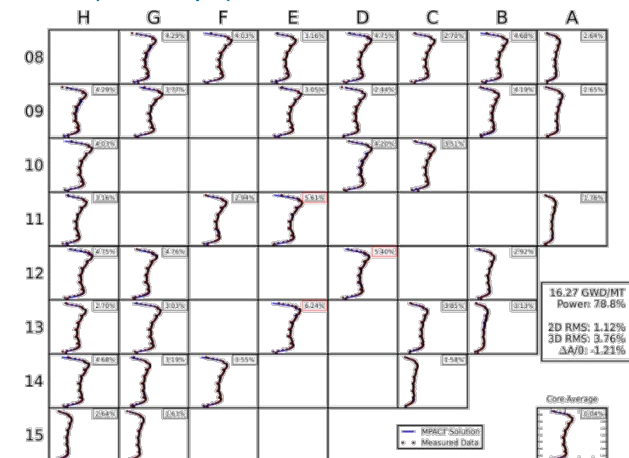
# MPACT 3D Core Pin-Resolved Neutronics

- 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*



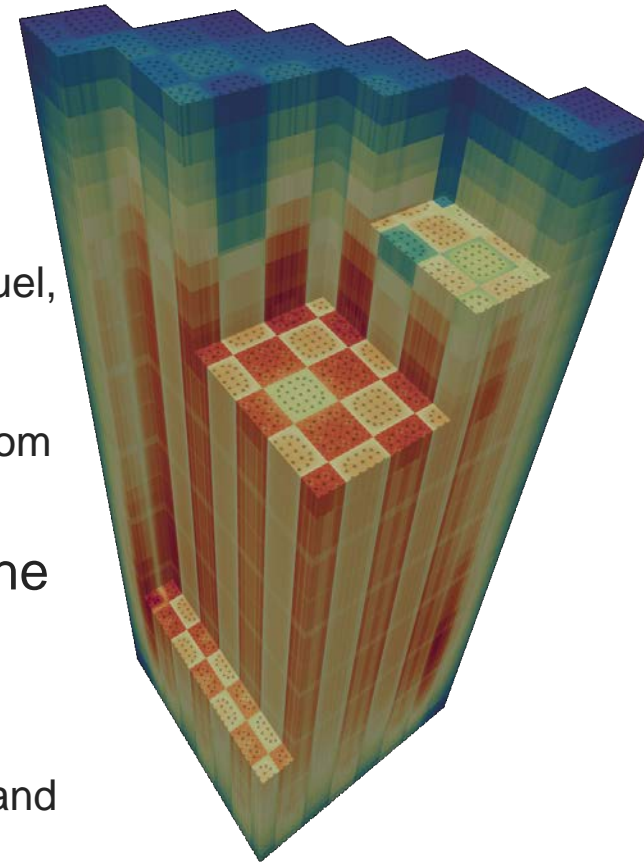
*Example of Comparisons with Reactor Operating Data (flux maps)*





# 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

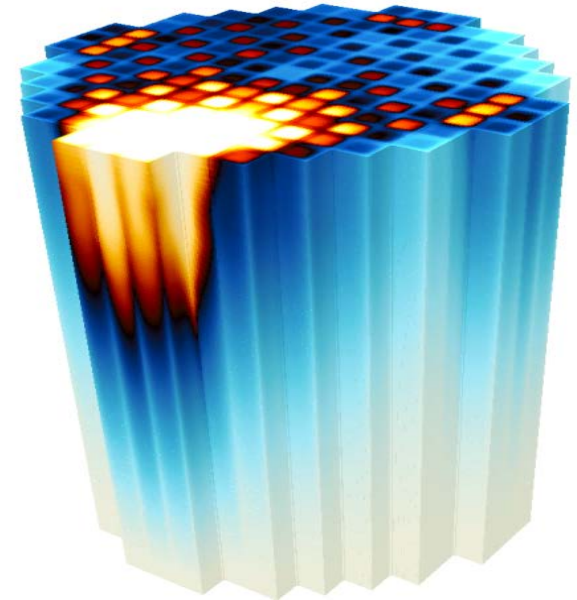
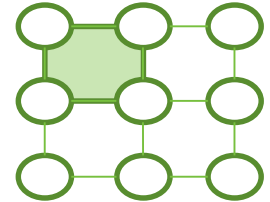
Physics Model	Industry Practice	DOE Codes (VERA)
Neutron Transport	Core: 3D diffusion, 2 energy groups, Lattice: 2D transport, 40-70 energy groups	3-D transport 51 energy groups
Power Distribution	nodal average with pin-power reconstruction	fuel pin resolved
Thermal-Hydraulics	1-D assembly-averaged	Fuel 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*



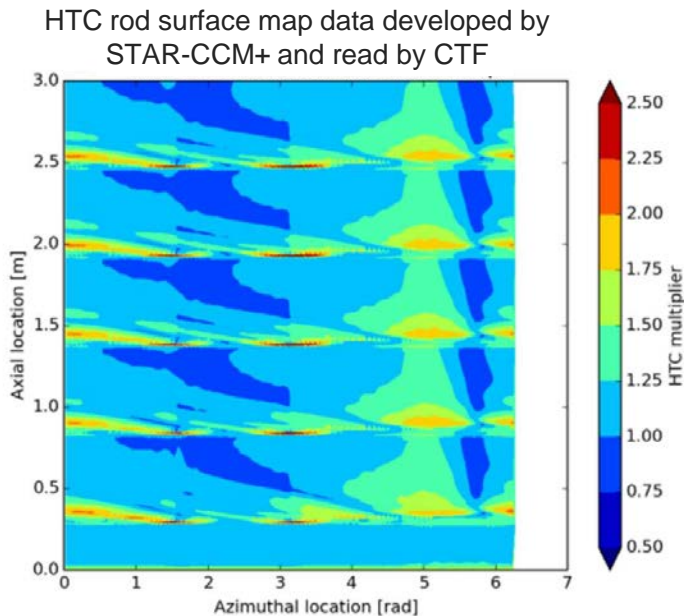
*Main Steam Line Break Application of CTF  
coupled with MPACT – core power distribution*



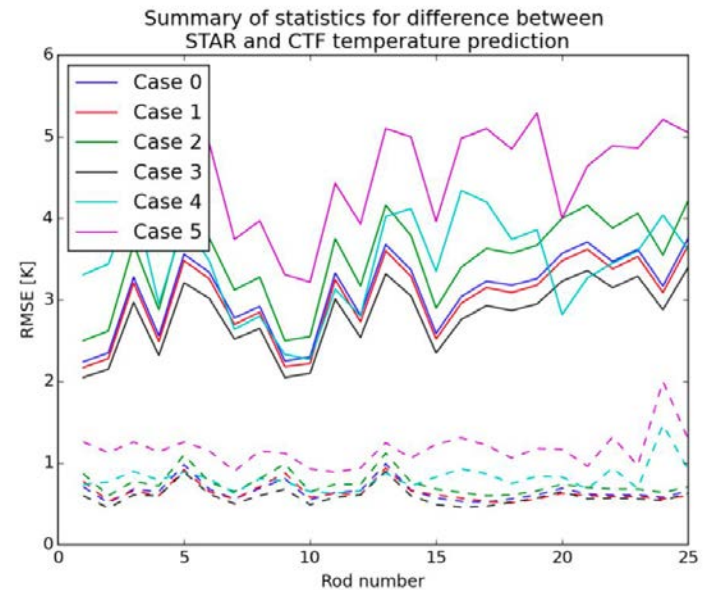
# CFD-Informed Subchannel Modeling Example

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 [ $\text{kg m}^{-1} \text{s}^{-2}$ ]	Heat rate [ $\text{kW m}^{-1}$ ]
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



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

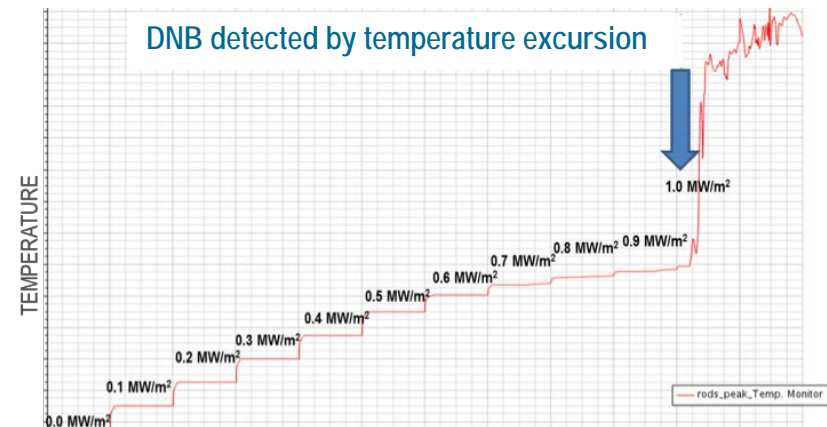


# CFD Evaluations of DNB

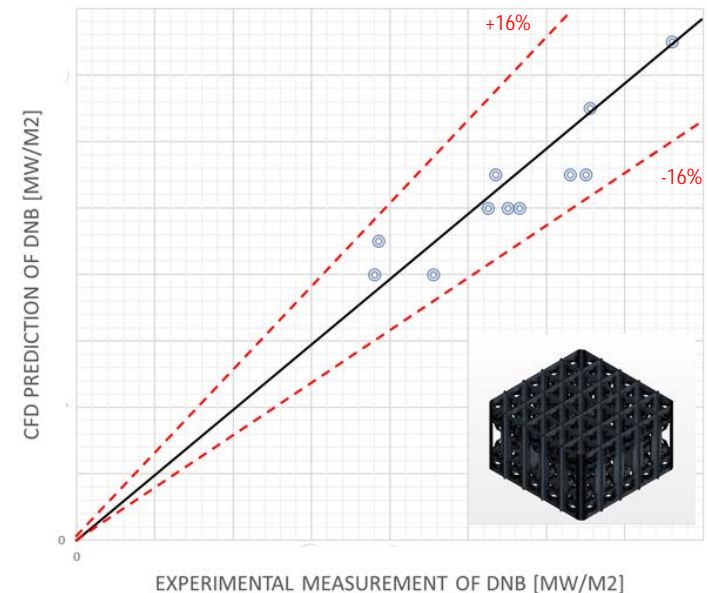
- Two-fluid Eulerian-Eulerian multiphase Navier-Stokes solution
- Carrier phase evaluated using standard single phase CFD models
- Sub-grid models define dynamic behaviors of bubble/droplet populations
  - Wall heat partitioning
    - Single phase convection
    - Bubble formation
    - Sliding bubble 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



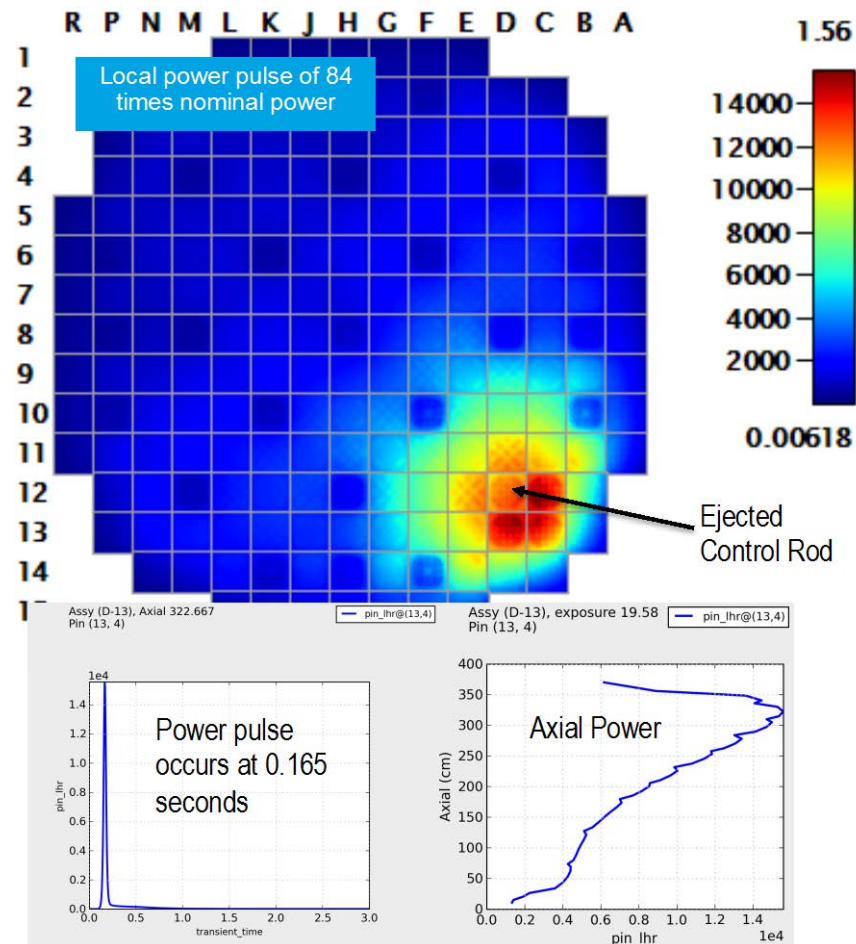
## Validation for full height 5x5 bundle with nonmixing vane grid





# 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

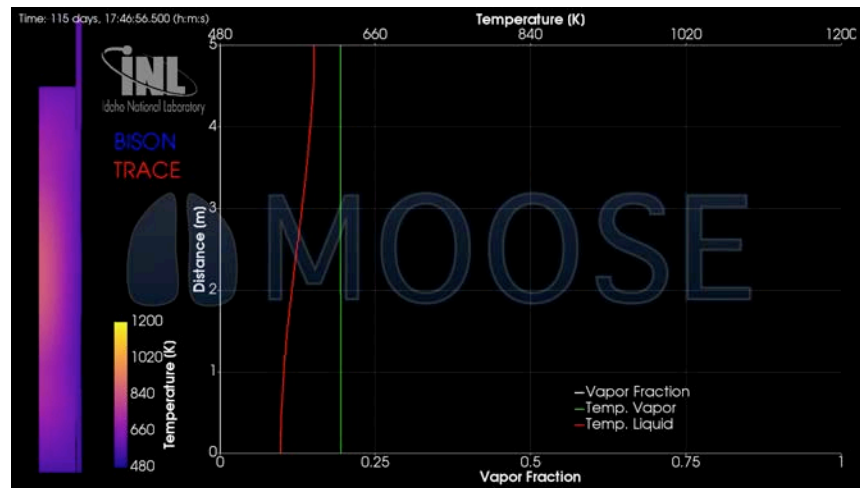


Full-Core PWR Control Rod Ejection Simulation  
Existing commercial Westinghouse 4-loop core  
design at End-of-Cycle



# 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)





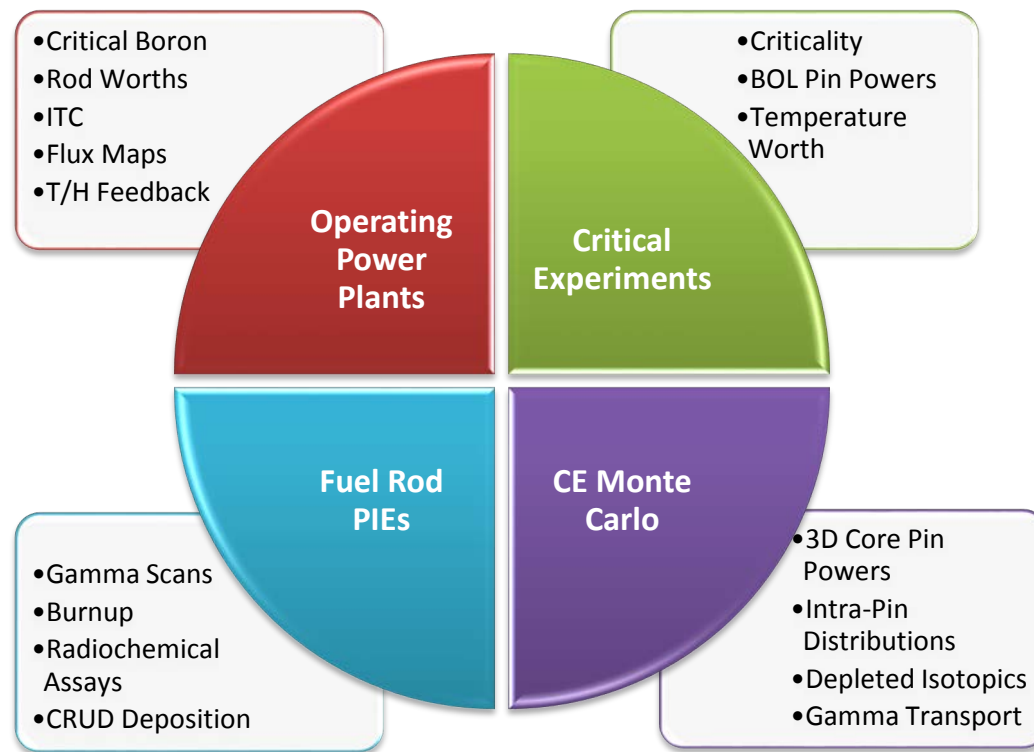
# DOE Code Applications for Source Terms for ATF

- 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

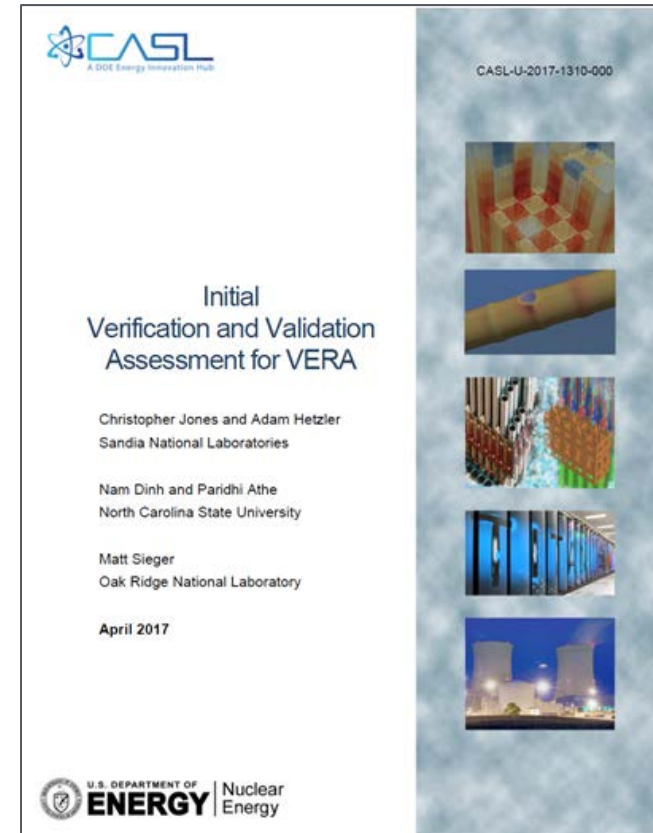
## Validation Experiments Examples

- 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

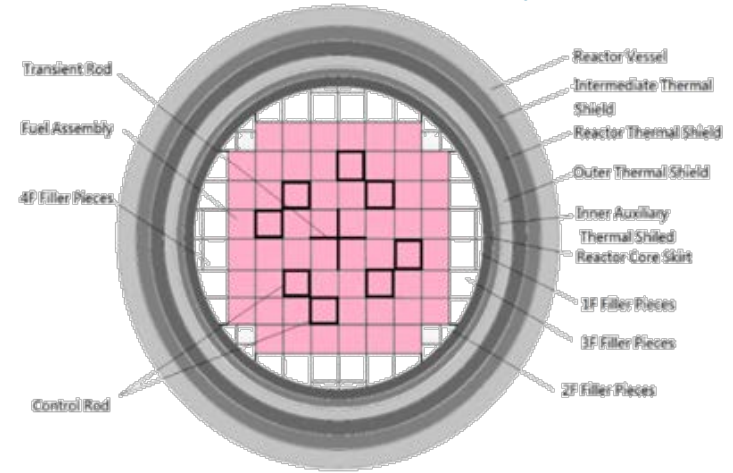




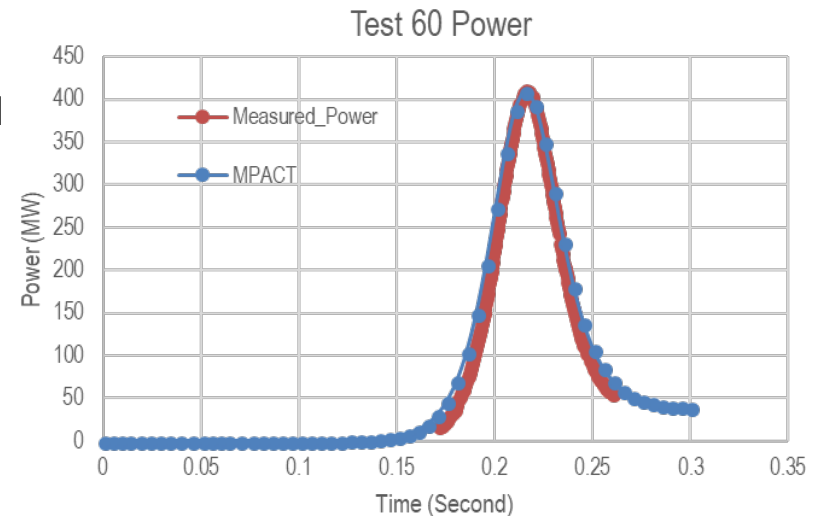
# VERA Transient Validation - SPERT-III

- 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	UO <sub>2</sub> Fuel	Coated Clad	Doped Fuel	FeCrAl Clad	U <sub>3</sub> Si <sub>2</sub> 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 <sub>2</sub> )	Yes (UO <sub>2</sub> )	No	No	No	No
Design Specific Validation data Availability	Yes	Yes (UO <sub>2</sub> )	Yes (UO <sub>2</sub> )	No	No	No	No

- Significant validation for UO<sub>2</sub> – 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.

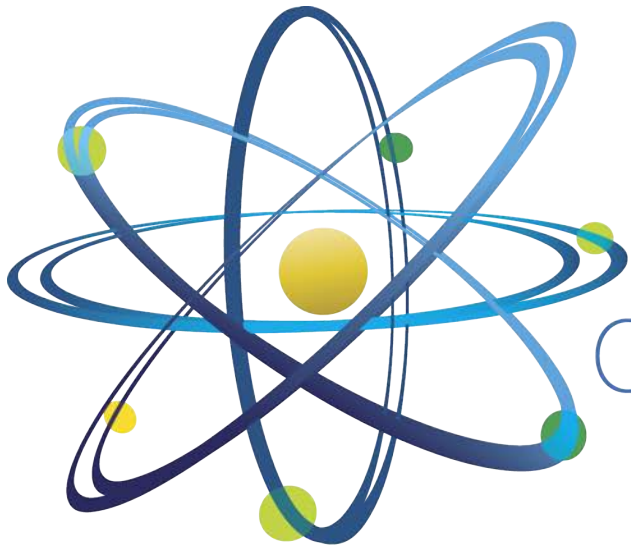


# Conclusions on Neutronics/Thermal Hydraulics Models

- 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  $\text{UO}_2$  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

		SFR	HTGR	FHR	MSR
1. Tanju Sofu	Neutronics	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake	MCC-3, PROTEUS, Rattlesnake
2. Rich Williamson	Fuels	MARMOT, BISON	MARMOT, BISON	MARMOT, BISON	In progress chemistry code
3. Elia Merzari	T-H	Nek-5000, SAM, SOCKEYE	Nek-5000, Pronghorn, SAM	Nek-5000, Pronghorn, SAM	Nek-5000, SAM
4. Tanju Sofu	Source term	SAM, PERSENT, BISON	Pronghorn, BISON	SAM, Nek-5000, Pronghorn, BISON	SAM, Nek-5000





# 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
  - MSR
  - HTGRs
  - Multiphysics analysis
- Conclusions

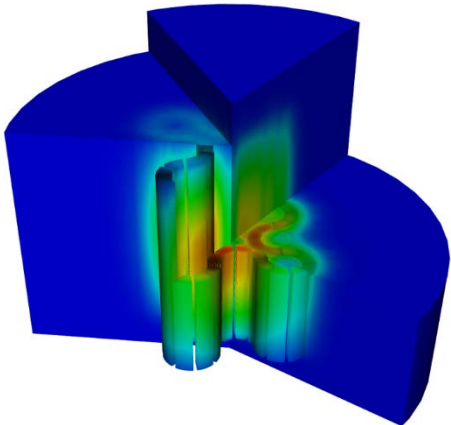
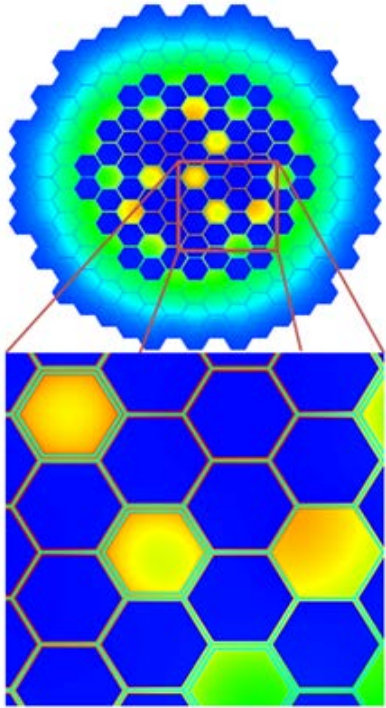


# Background

- 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<sup>2</sup>-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)

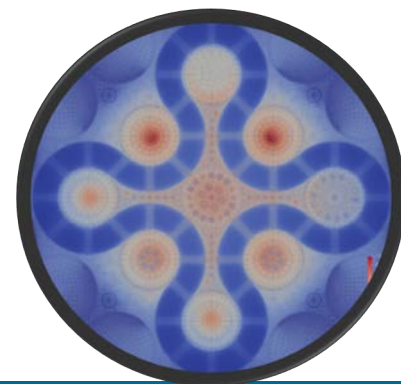
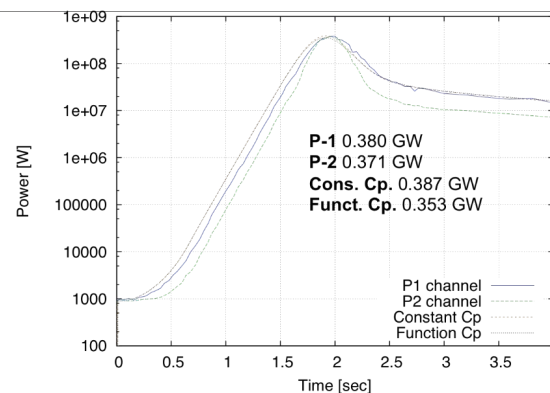
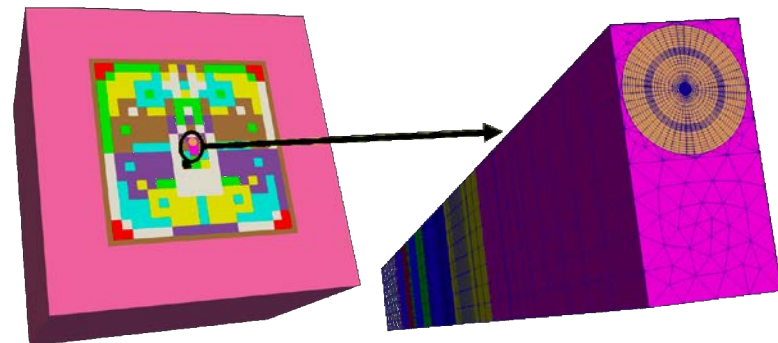


# RattleSnake

## 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>



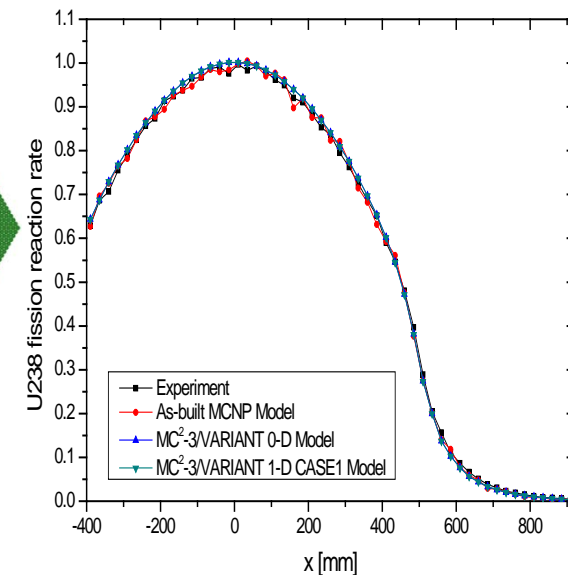
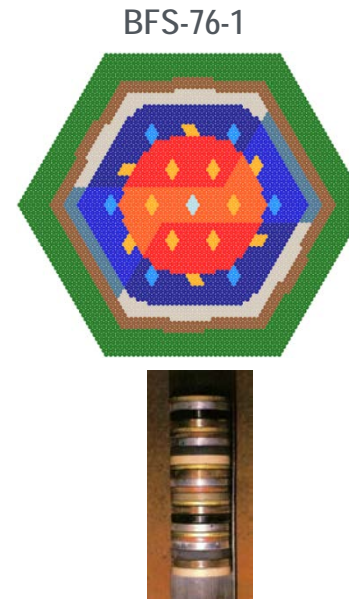
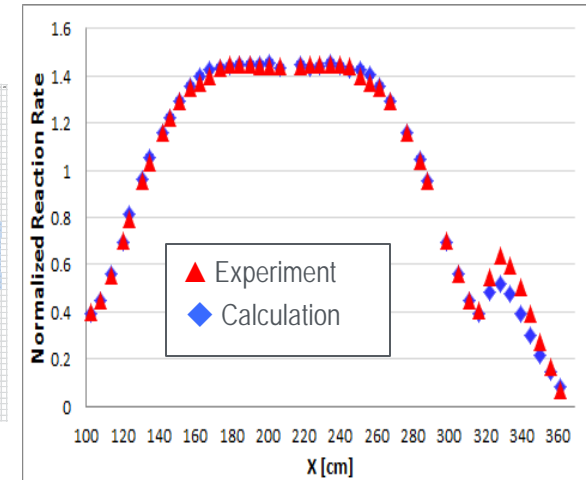
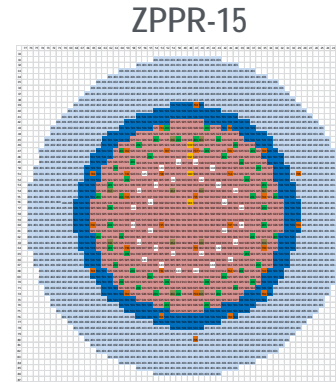


# Validation basis



# PROTEUS: Criticality Experiments

- LANL Experiments (Flatop, 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)

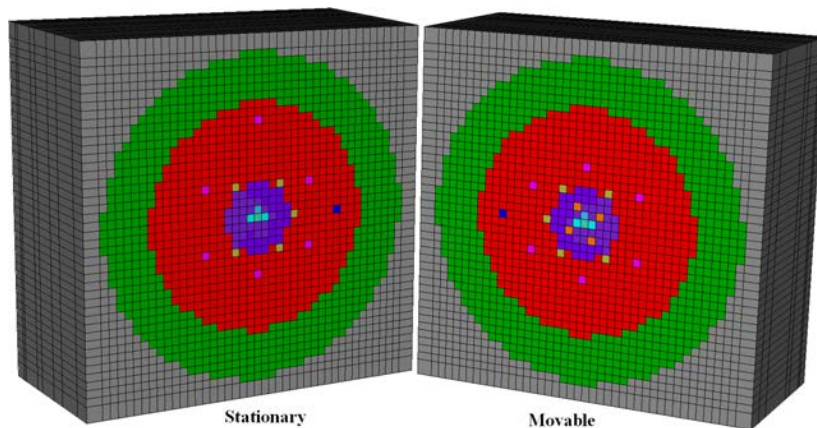




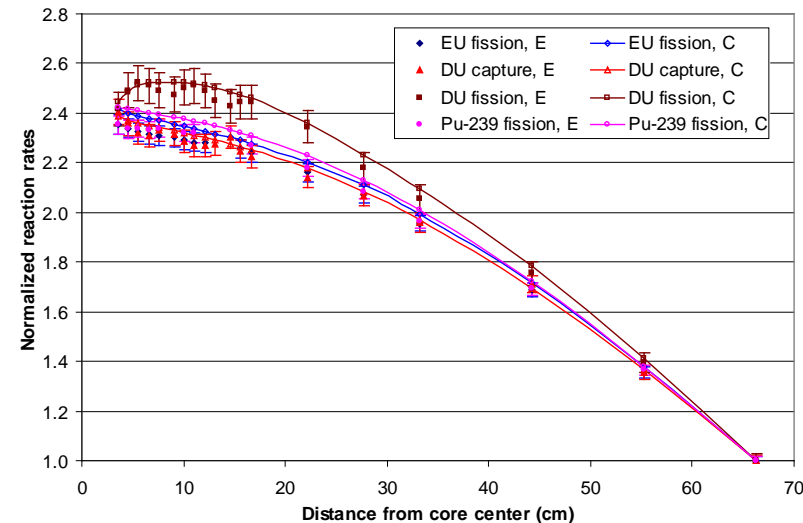
# PROTEUS: Criticality Experiments (cont.)

## Detailed ZPR-6/7 Comparisons as an example

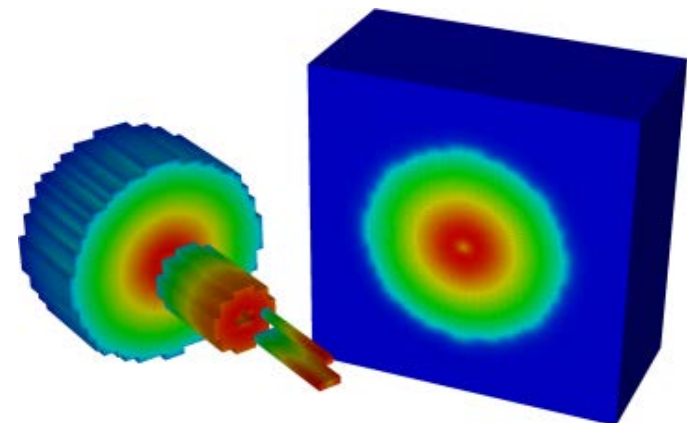
- Good agreement of core eigenvalues with the measurements within  $\sim 80$  pcm
- Foil reaction rates predicted within 1 sigma of experimental uncertainties



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*

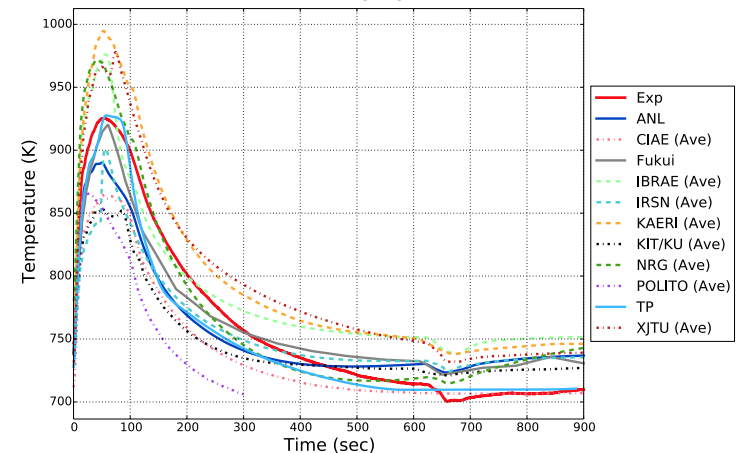
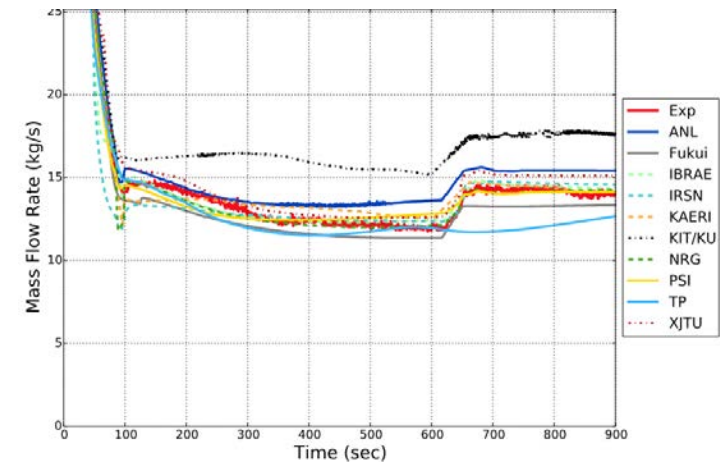
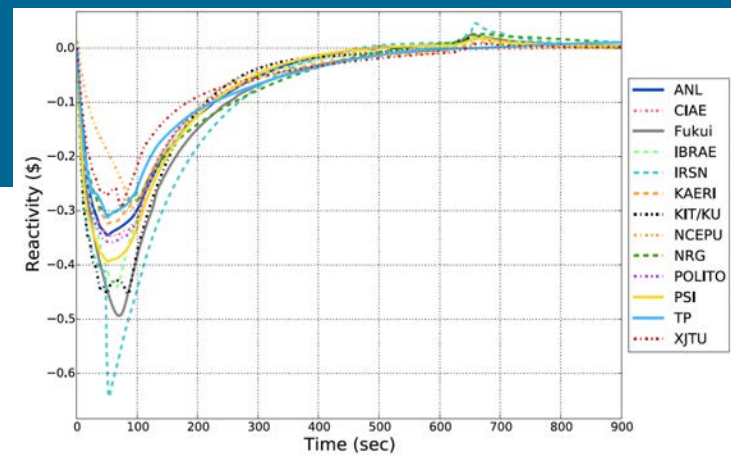


*Flux in group 1 of 70 (10 MeV to 14 MeV)  
Loading 106*



# PROTEUS: EBR-II Inherent Safety Demonstration Test

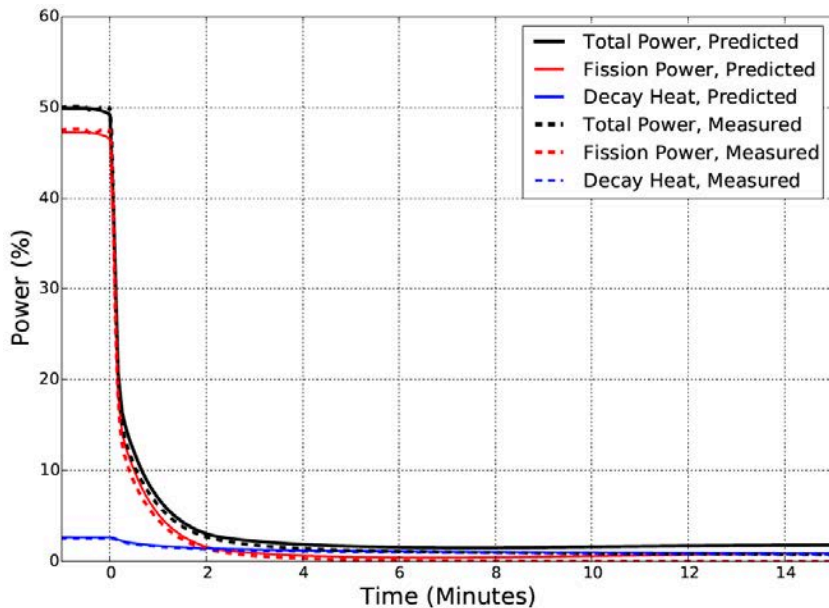
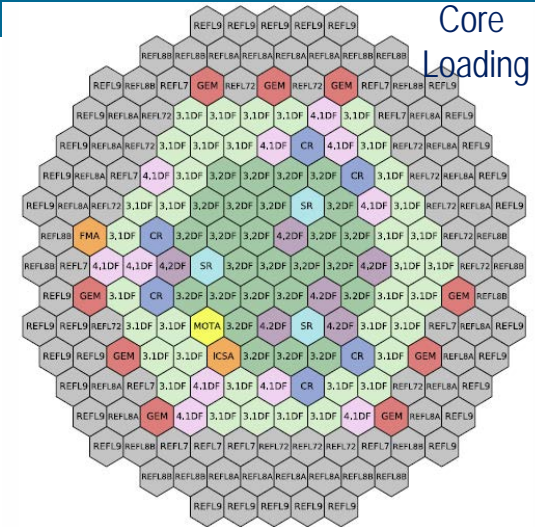
- SHRT-45R: Unprotected (no-scram) station blackout from full power to demonstrate inherent safety
  - Instrumented fuel assemblies for in-assembly temperature and flow measurements
- Neutronic benchmark for reactivity feedback coefficients
  - Following detailed depletion analyses for several run cycles 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



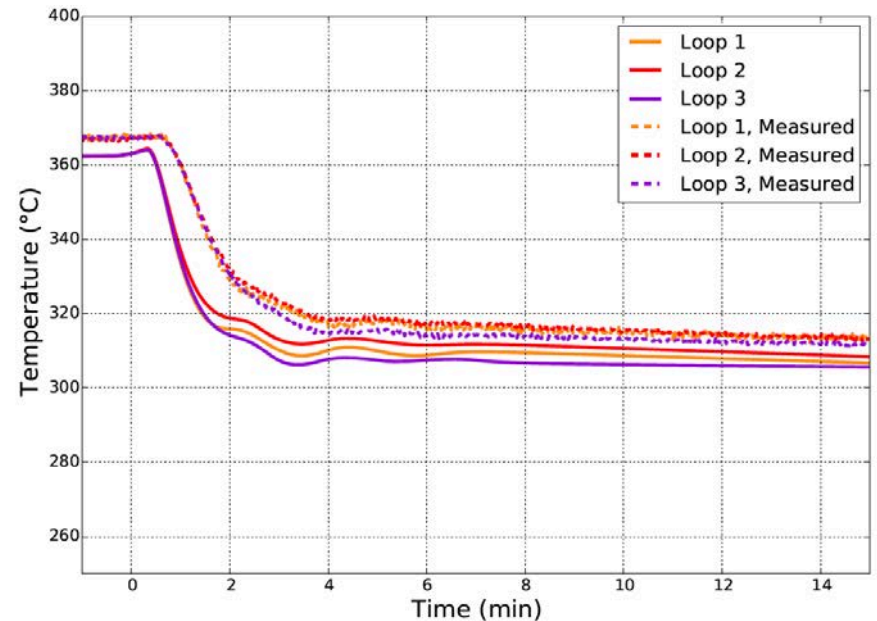


# PROTEUS: FFTF Passive Safety Demonstration Test

- 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)



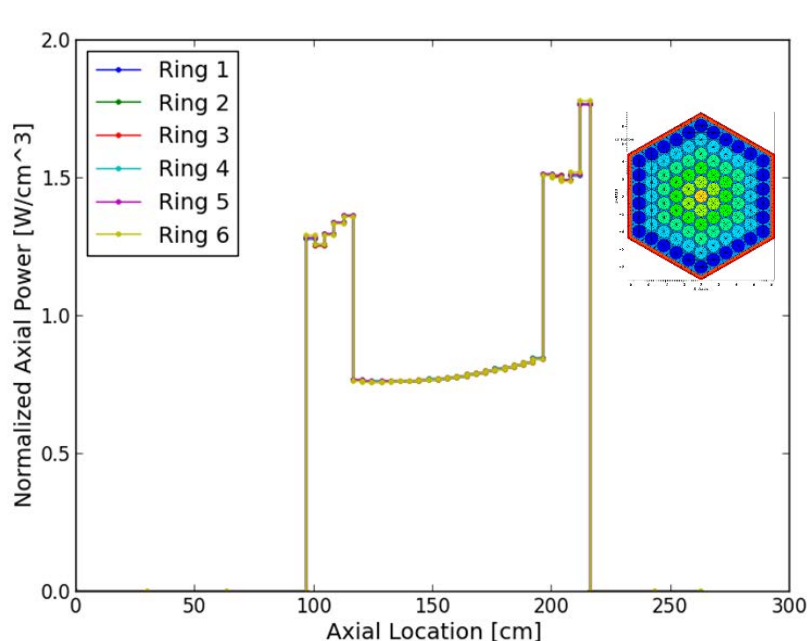
# Application of neutronics codes to advanced reactors



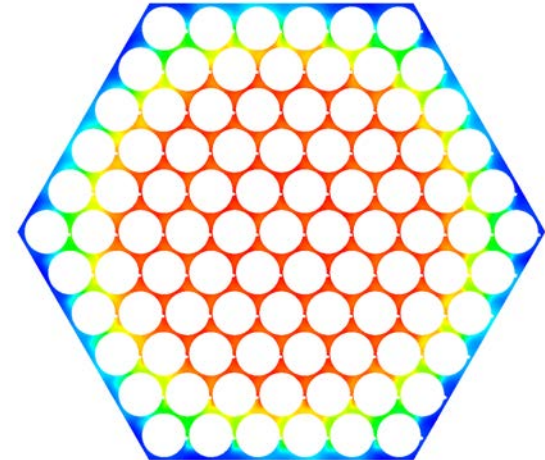
# SFR Hot Channel Factor Evaluation

## 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



Pseudocolor  
Var: temperature  
865.1  
833.7  
802.3  
770.8  
739.4  
Max: 867.1  
Min: 729.6



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

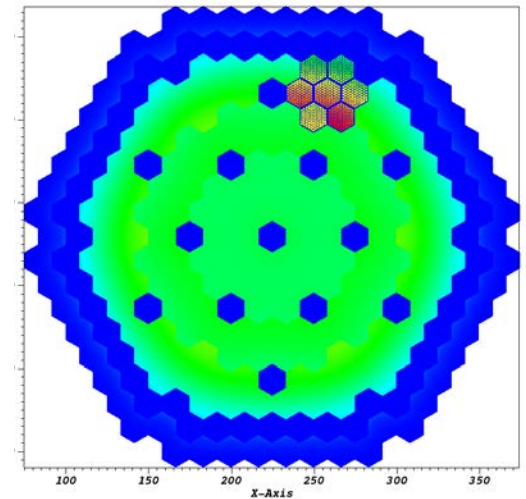
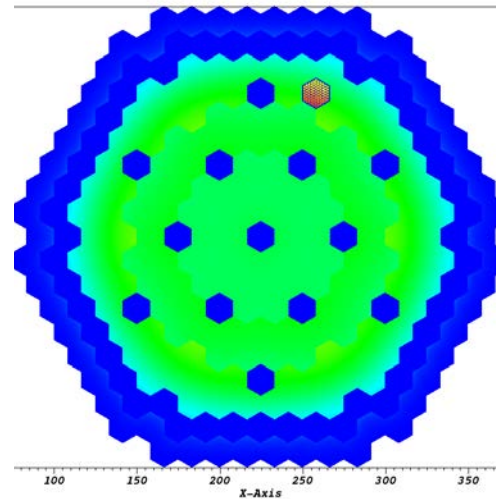
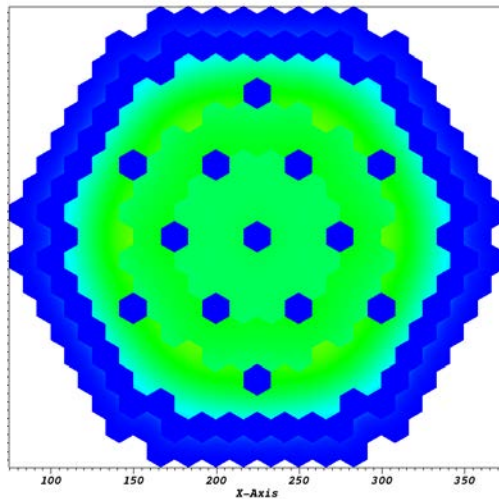
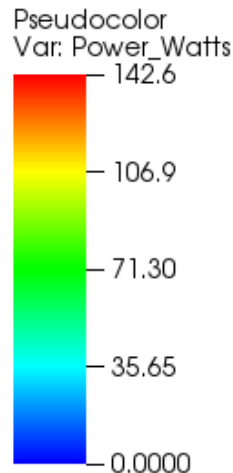
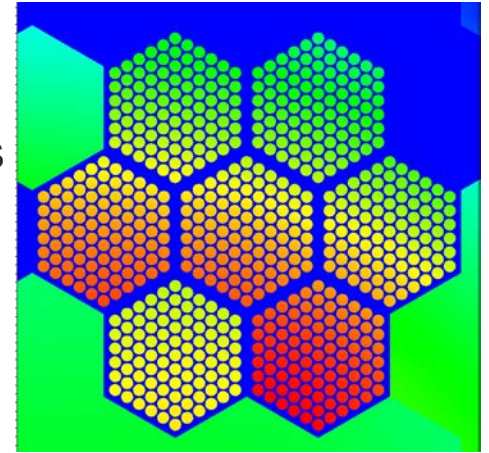
		Cladding thickness	Cladding thermal conductivity	Fuel thermal conductivity	Coolant density	Cladding circumferential temp.	Wire orientation
<b>Uncertainties (3s), %</b>		±3	±7	±25	±0.5	-	-
<b>Cladding Outer Wall</b>	Nominal	868.2	868.2	868.2	868.2	868.2	853.6
	Perturbed	-	-	-	869.1	866.4	856.2
	HCF-Legacy	-	-	-	1.016	2.19	1.01
	HCF-SHARP	-	-	-	1.001	1.002*	1.003*
<b>Cladding Inner Wall</b>	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	-
<b>Fuel Centerline</b>	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

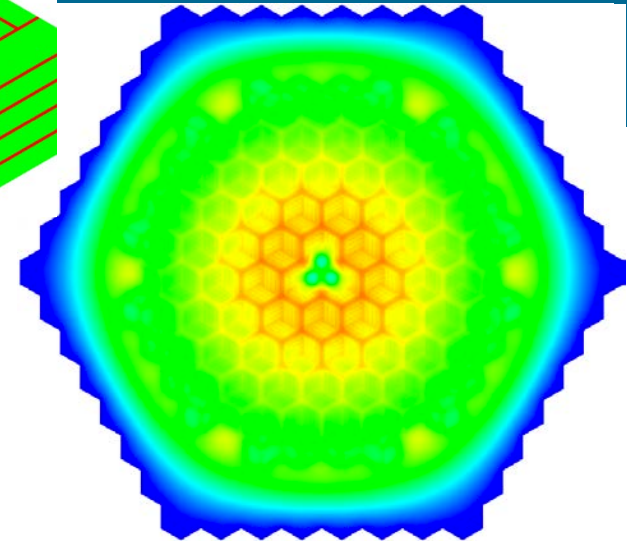
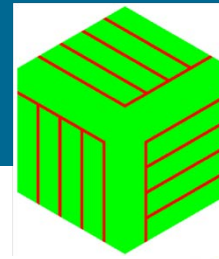
- Cross section processing with MC<sup>2</sup>-3 preserves heterogeneity effects in homogenized core model
- Can be applied for more accurate HCF calculation (includes global spectrum effects) at reduced computational expense
- Consistent k-eff and average power profiles across 3 cases using PROTEUS-SN solver
- Consistent pin-by-pin power distributions in focal assembly



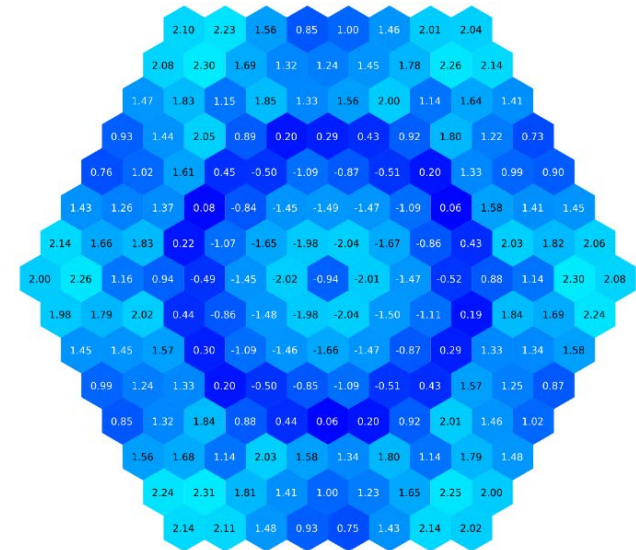


# MSR Core Evaluations

- 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 ( $\Delta k$ , pcm)	-124 (MOC)	207 (NODAL)

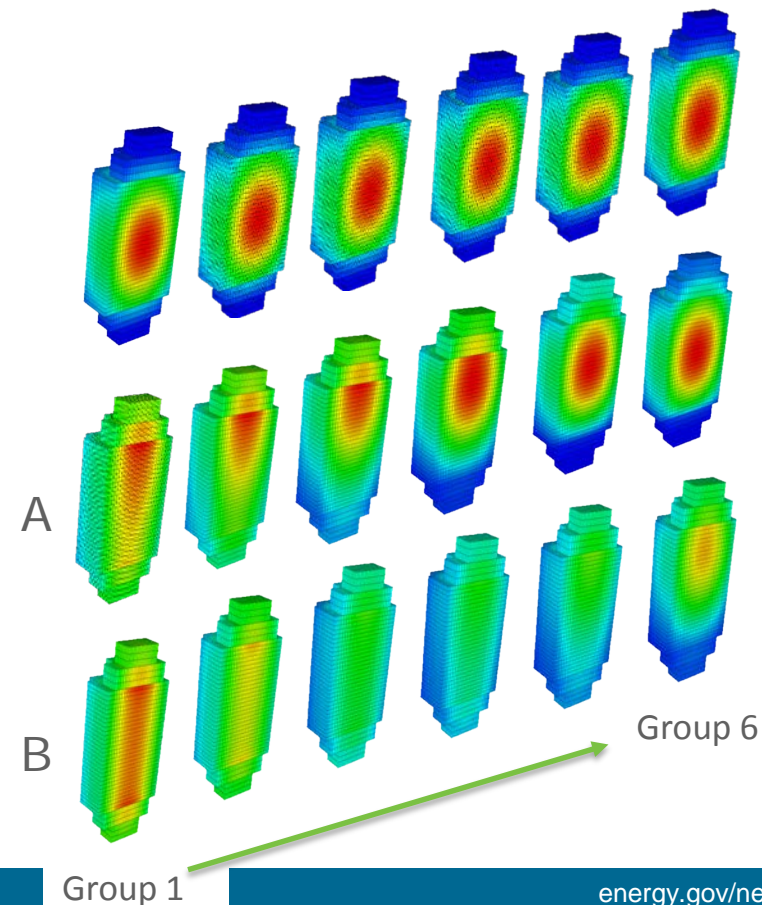


# Flowing Fuel Treatment for MSRs

## 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<sub>3</sub> (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

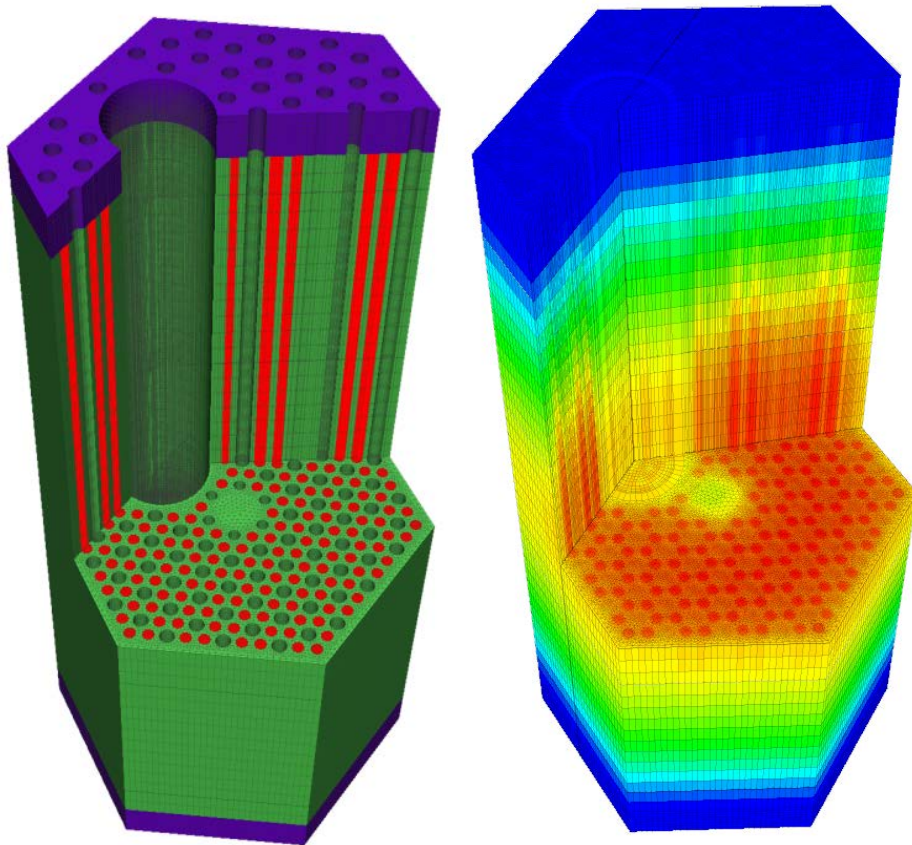




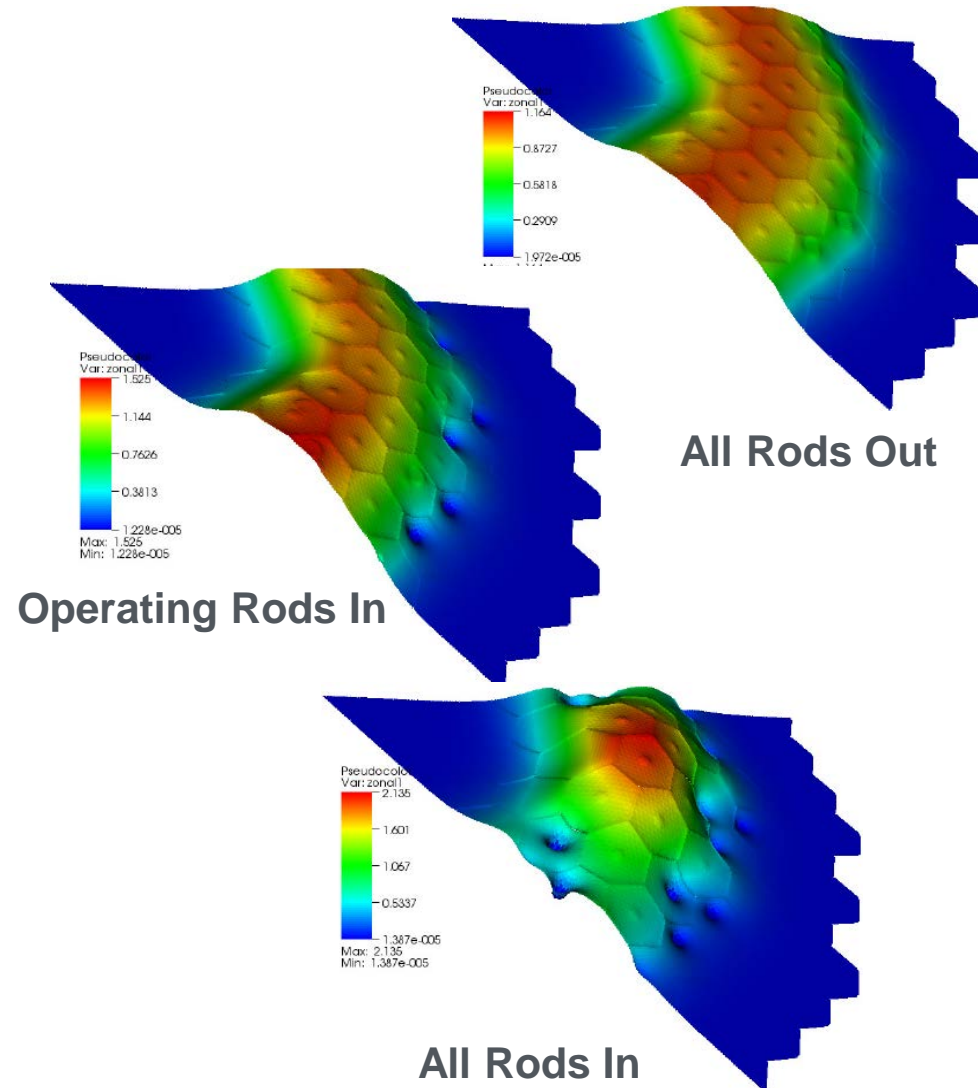
# High Temperature Gas-cooled Reactor Applications

## Model for 3D prismatic fuel assemblies

- Challenges for modeling the control channel leading to large neutron streaming



## VHTR whole-core calculations





# 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

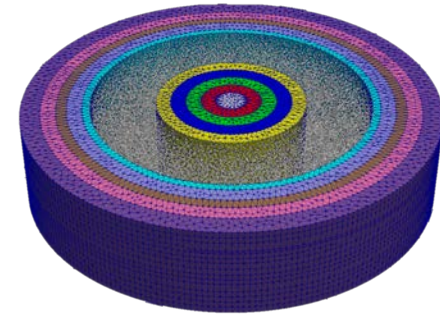
## Capabilities

- DEM (discrete element method) to provides time-dependent positions of all pebbles for establishing an equilibrium core

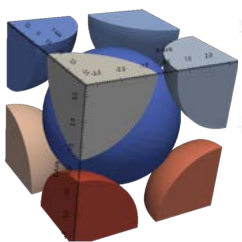
Goal: Ability to track burnup of individual pebbles as they move down the core

## Preliminary Results:

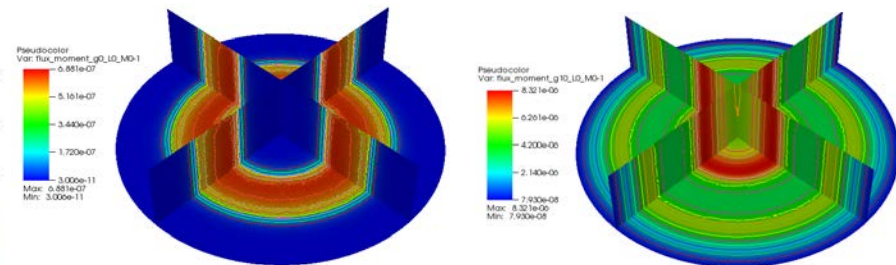
- PTT can converge  $k_{\text{eff}}$  and reaction rates less than 0.1% for all cases with respect to reference case with Serpent (simple 9-sphere model, fresh fuel)



HTR-10 Pebble Bed Mesh: Total 437,735 tetrahedra. 76,869 node points. Pebble packing region has 291,107 tetrahedra, reflection top and bottom.



Error in $k_{\text{eff}}$ (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



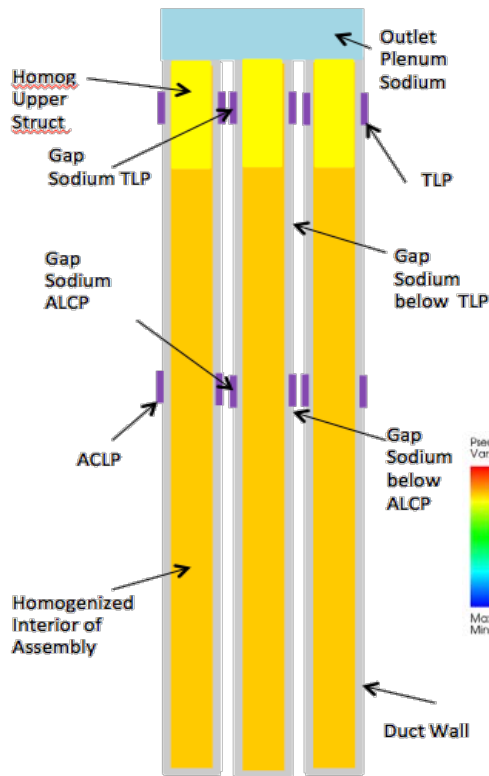
Fast (left) and thermal (right) fluxes in HTR-10 simulation



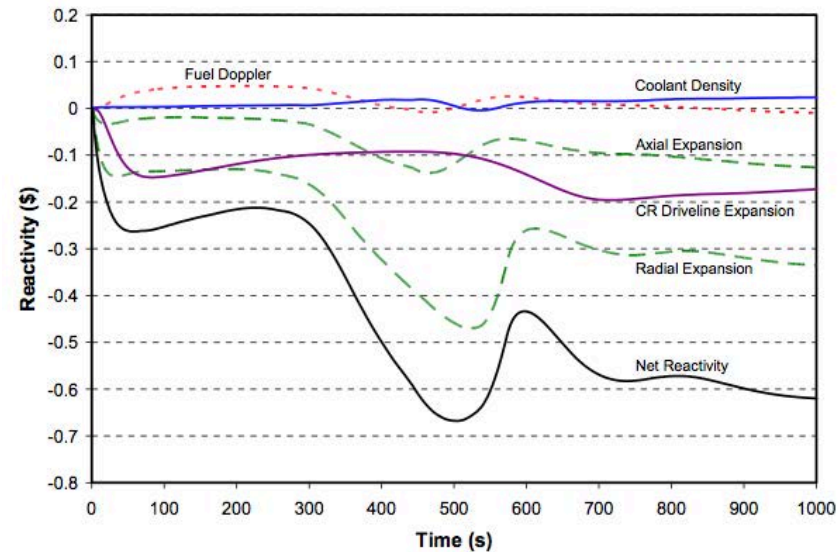
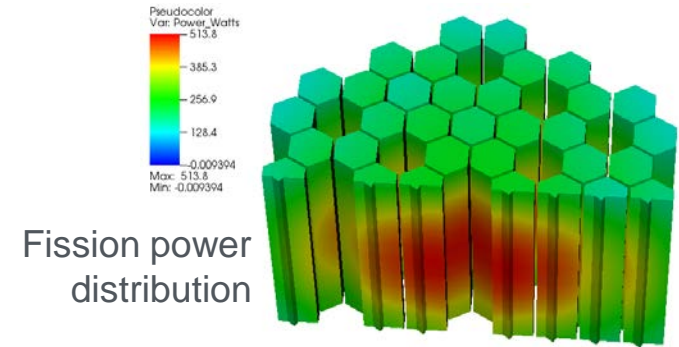
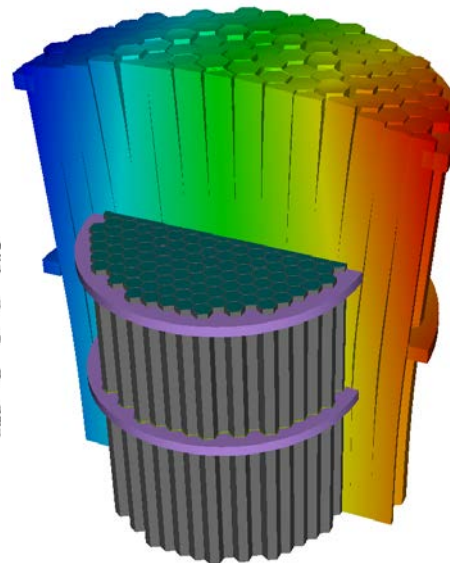
# Multi-physics Analysis for SFR Core Deformation

## 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



ABTR core deformation (magnified 100x) computed with SHARP



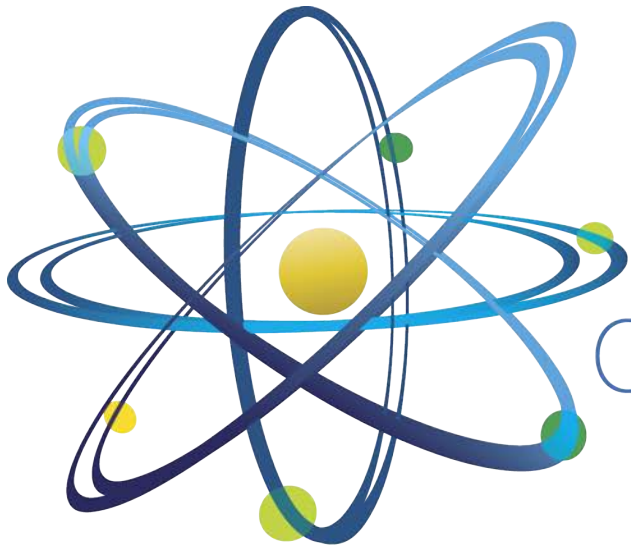


# Conclusions

- 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<sup>2</sup>-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?



Clean. **Reliable. Nuclear.**





# 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  $\text{UO}_2$  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

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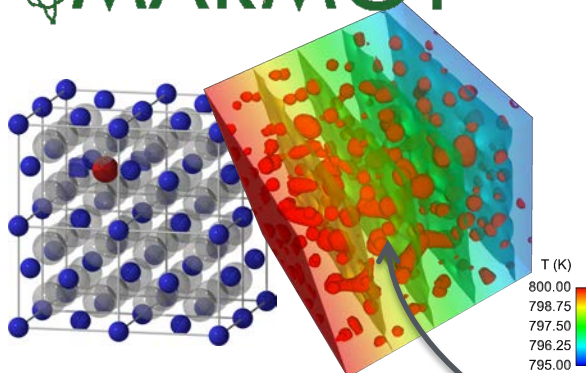
- 1) Overview
- 2) Verification and Validation
- 3) Documentation



# MOOSE-Bison-Marmot (MBM)

- The MOOSE-Bison-Marmot (MBM) codes provide an advanced multidimensional, multiphysics, multiscale fuel performance capability

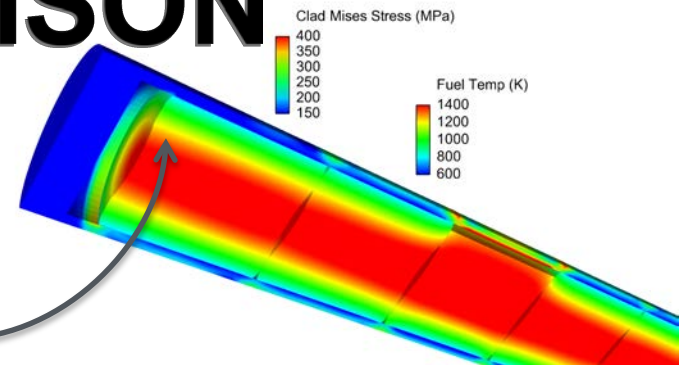
 **MARMOT**



## Atomistic/Mesoscale Material Model Development

- Predicts microstructure evolution in fuel and cladding
- Used with atomistic methods to develop multiscale materials models

 **BISON**



## 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

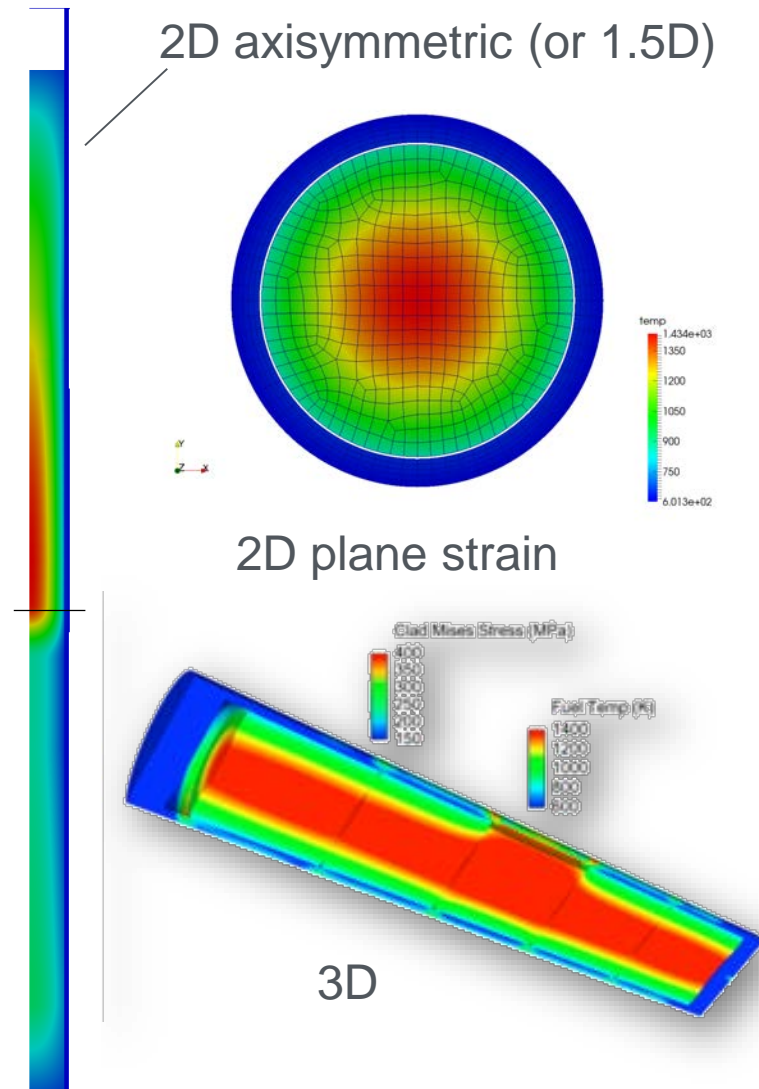
 **MOOSE**  
Multiphysics Object-Oriented Simulation Environment

- Simulation framework allowing rapid development of FEM-based applications



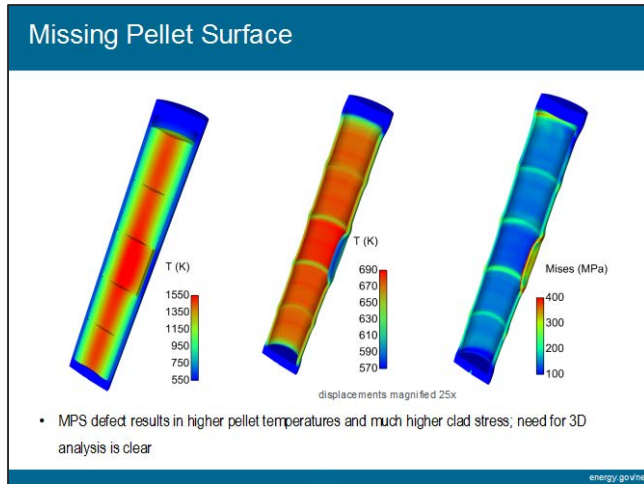
# Bison Fuel Performance Code

- 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

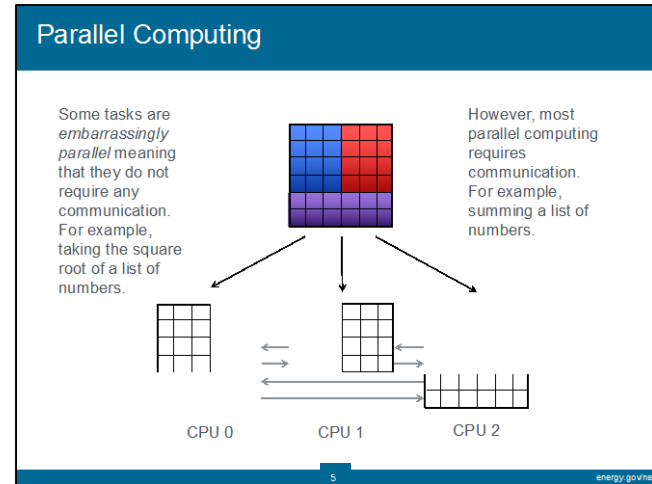




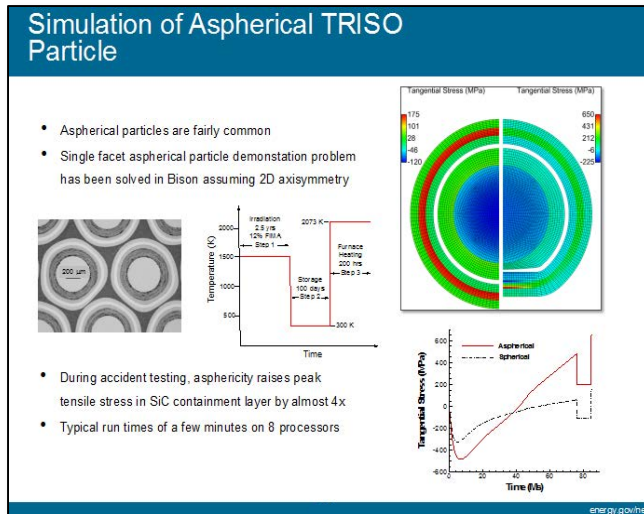
# What Makes Bison Different?



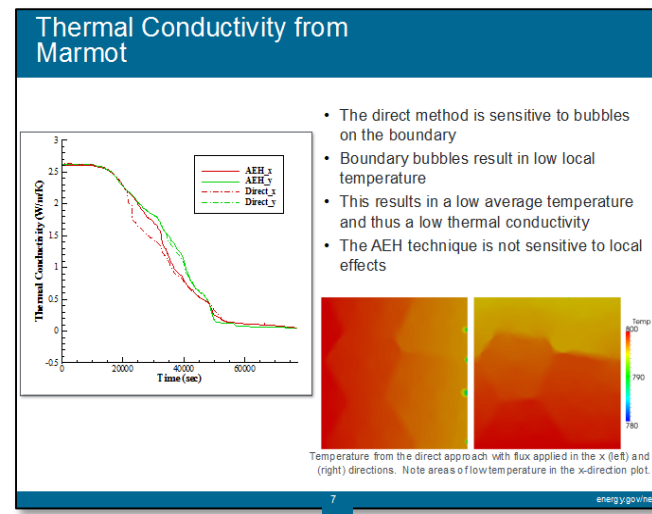
3D FEM: Applicable to any geometry



Parallel Computing: Large problems



Multiple fuel/reactor applicability

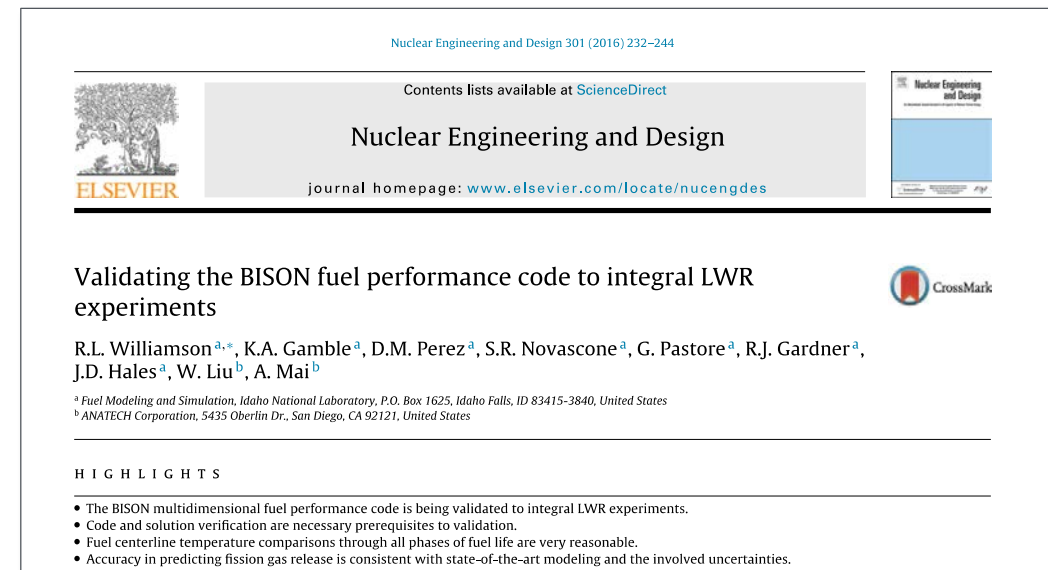
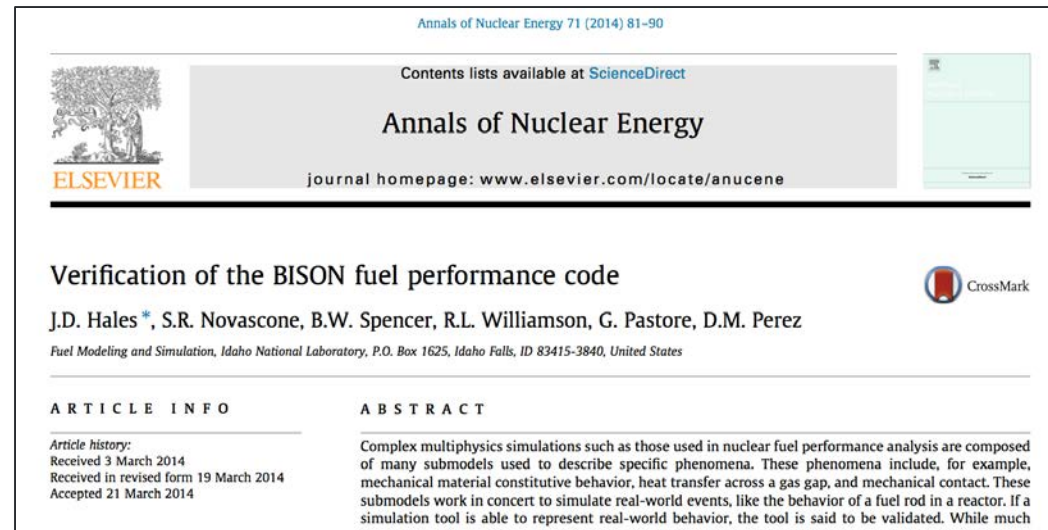


Readily couples to LLS or other codes



# Bison V&V and Statistical Analysis

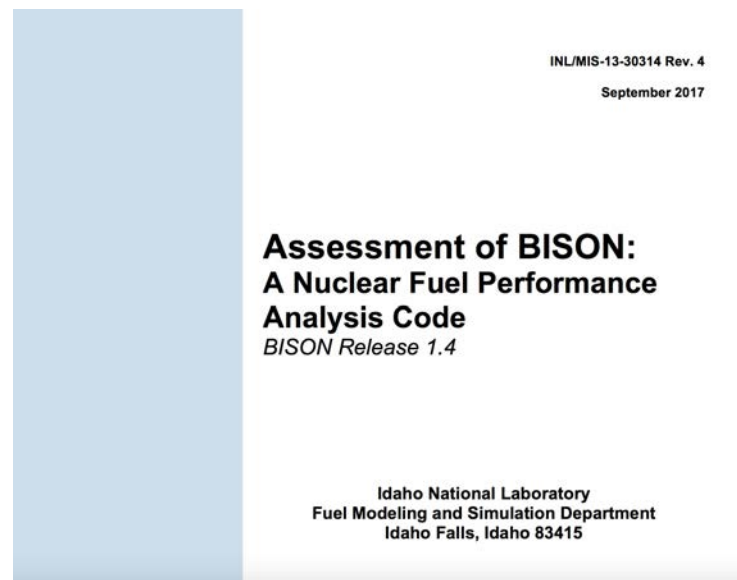
- Code Verification
  - MOOSE/**Bison** is supported by >2000 unit and regression tests
  - All new code must be accompanied with verification testing; all tests are required to pass prior to any code change
- LWR Validation
  - ~**75** integral, normal operation and ramp fuel rod experiments
  - **47** 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





# 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





# TRISO Particle Fuel



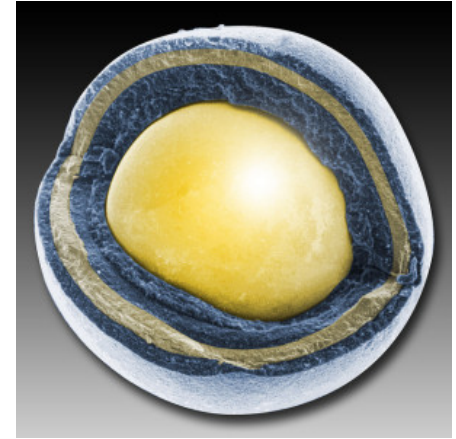
# Bison - Particle Fuel Capabilities

## 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

## 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



## Fuel Kernel ( $\text{UO}_2$ )

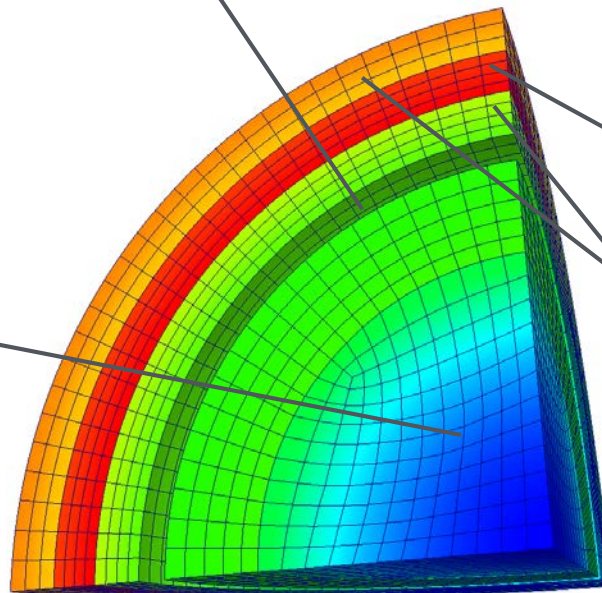
- Temperature/burnup/porosity dependent thermal conductivity
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fission gas release (two stage)
- CO production
- Radioactive decay

## Silicon Carbide

- irradiation creep

## Pyrolytic Carbon

- Anisotropic irradiation-induced strain
- Irradiation creep



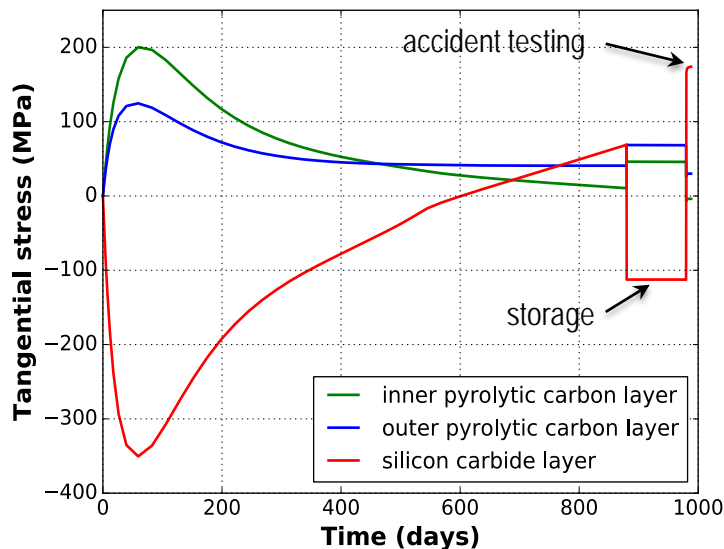
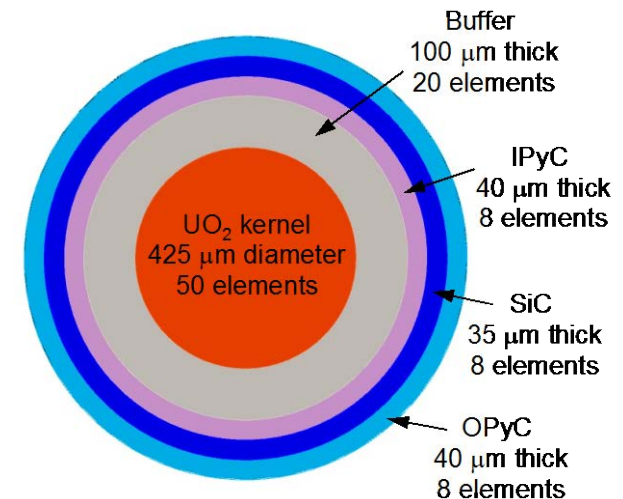
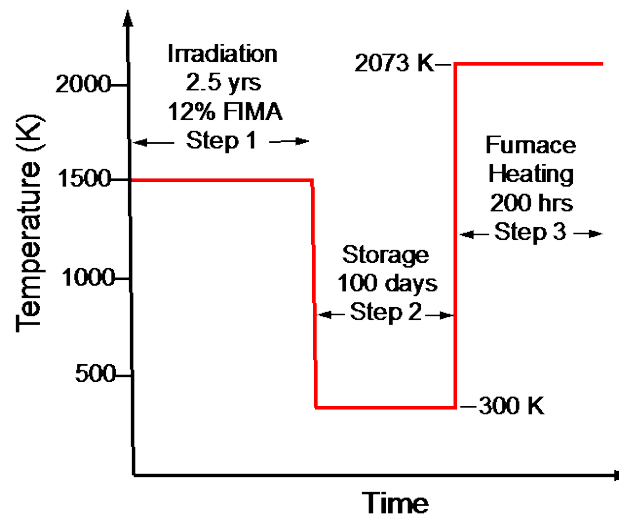
**Tangential Stress**

**Empirical models for SiC and PyC from:**  
D. Petti, P. Martin, M. Phelp, R. Ballinger,  
Development of improved models and  
designs for coated-particle gas reactor  
fuels. Technical Report INL/EXT-05-  
02615, December 2004.

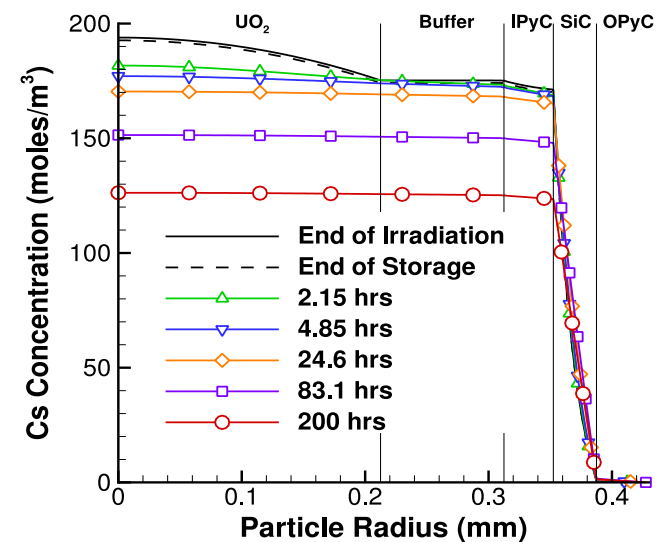


# Example: 1D Spherical Particle

- 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

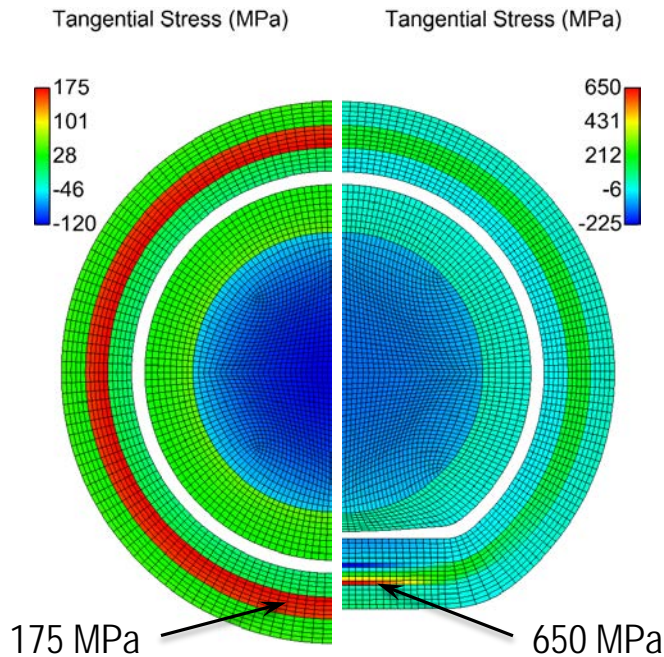
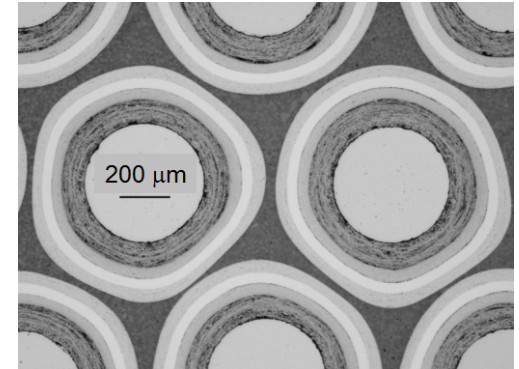


Cesium radial profiles

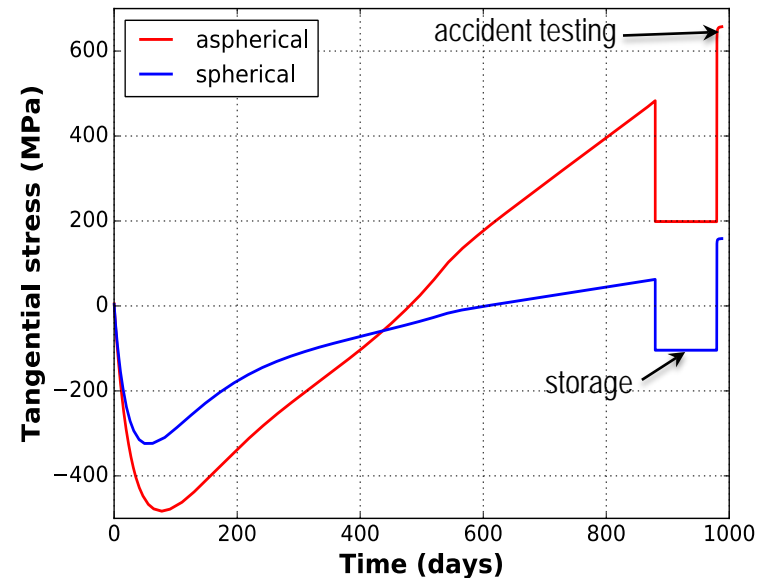


# Example: 2D RZ - Aspherical Particle

- 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

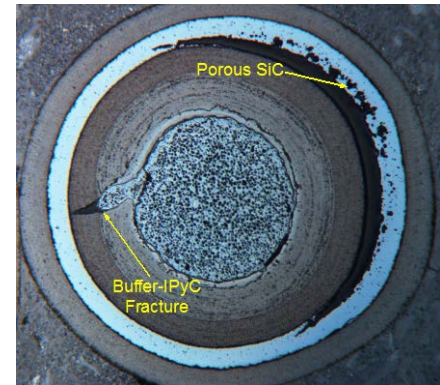
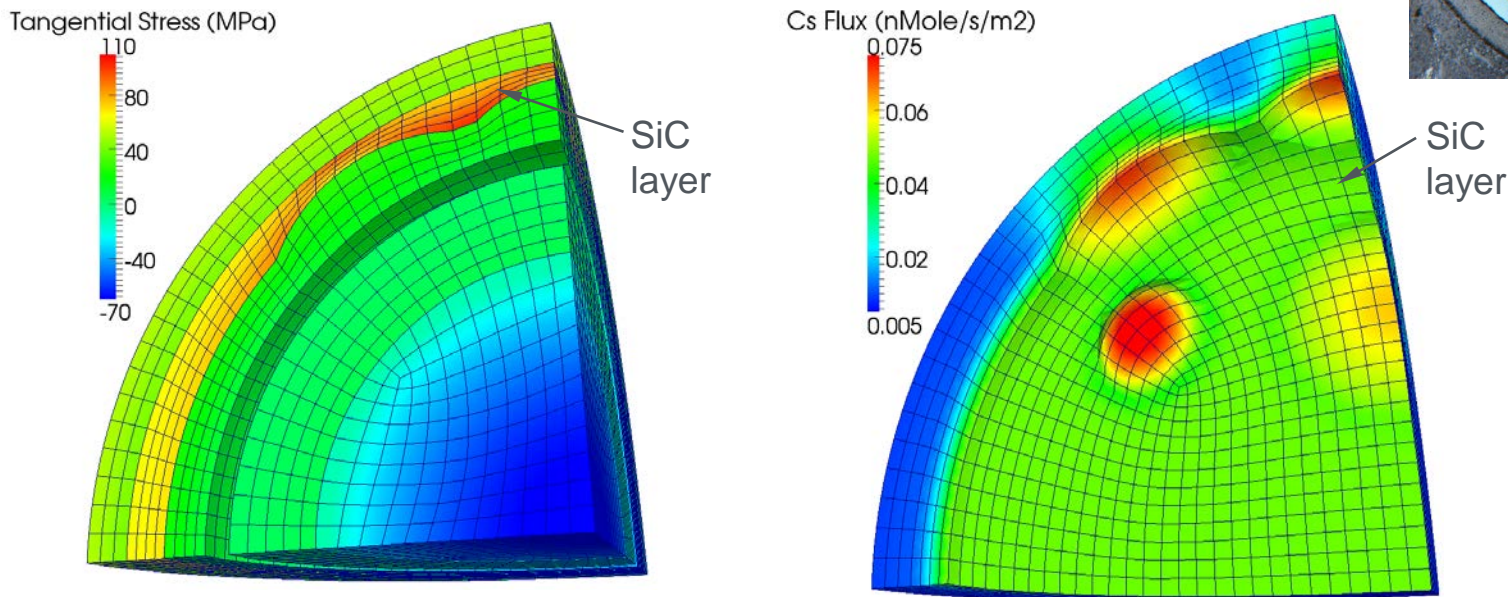


Stress history at the outer SiC surface



# 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 $\mu\text{m}$ kernel, real conditions
6	TRISO	500 $\mu\text{m}$ 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, $5.3 \times 10^{-25} \text{n/m}^2$ fluence
11	HFR-P4	14% FIMA, $7.2 \times 10^{-25} \text{n/m}^2$ fluence

## Comparisons of tangential stress at end of simulation

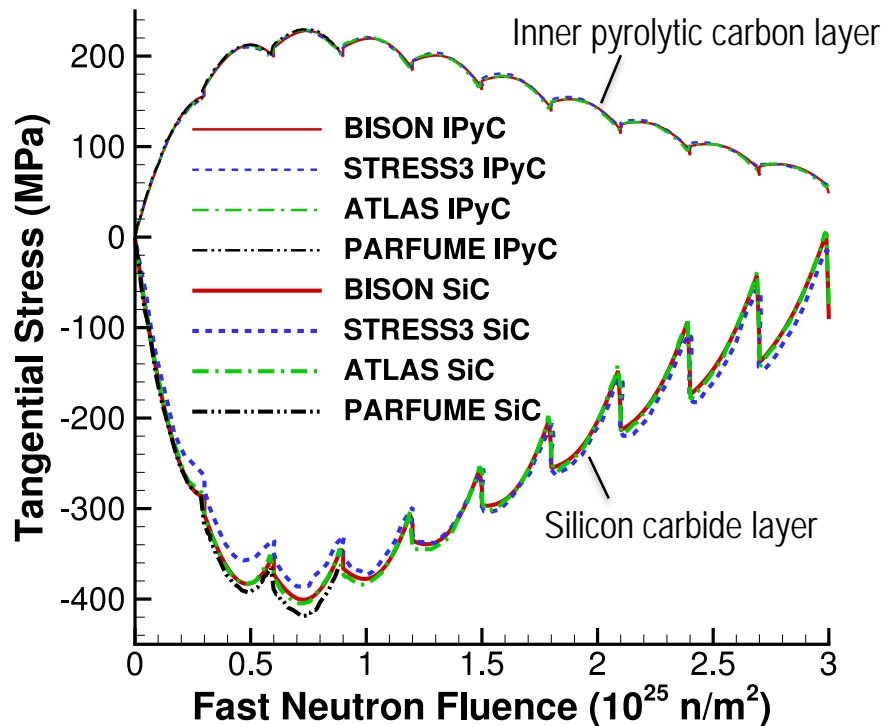
Case	Layer	Analytical	BISON	Error (%)
1	SiC	125.19	125.23	0.032
2	IPyC	50.200	50.287	0.173
3	IPyC/SiC	8.8/104.4	8.7/104.5	1.14/0.10

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

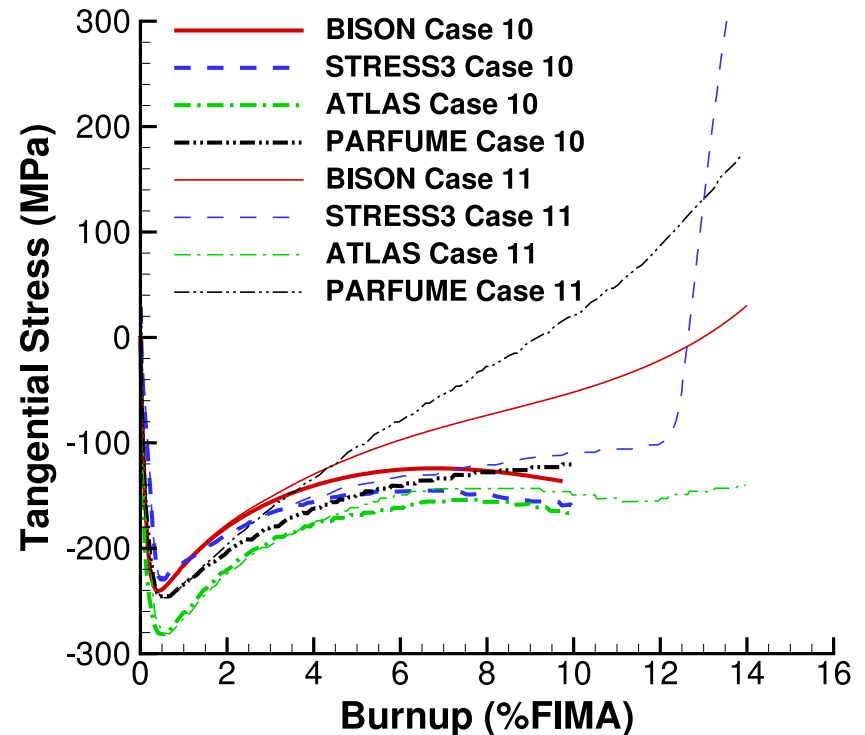


# Comparison to IAEA Benchmarks (2/2)

- 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

[Journal of Nuclear Materials 443 \(2013\) 531–543](#)



Contents lists available at [ScienceDirect](#)

Journal of Nuclear Materials

journal homepage: [www.elsevier.com/locate/jnucmat](http://www.elsevier.com/locate/jnucmat)



## Multidimensional multiphysics simulation of TRISO particle fuel



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#### Article history:

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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.

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# 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

## 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

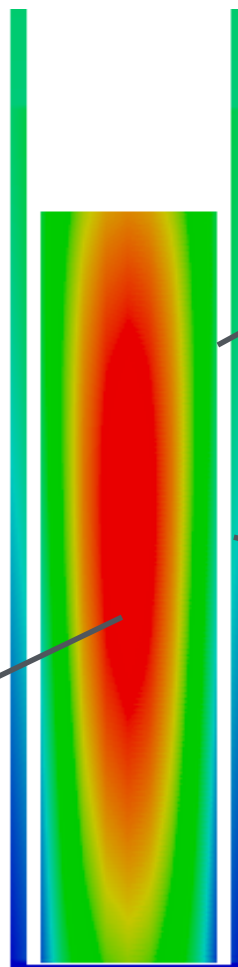
## Cladding Behavior

### 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

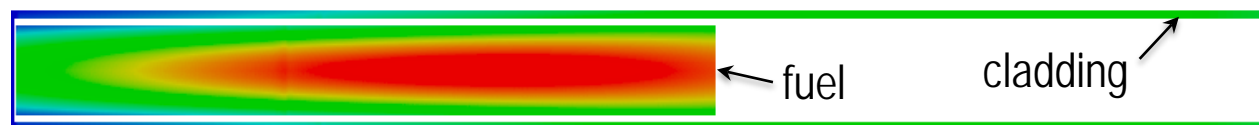


Temperature

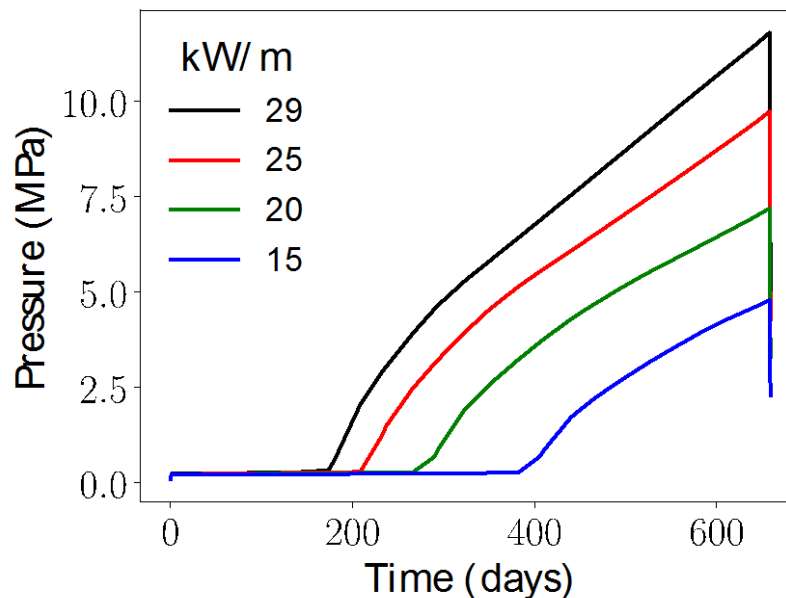
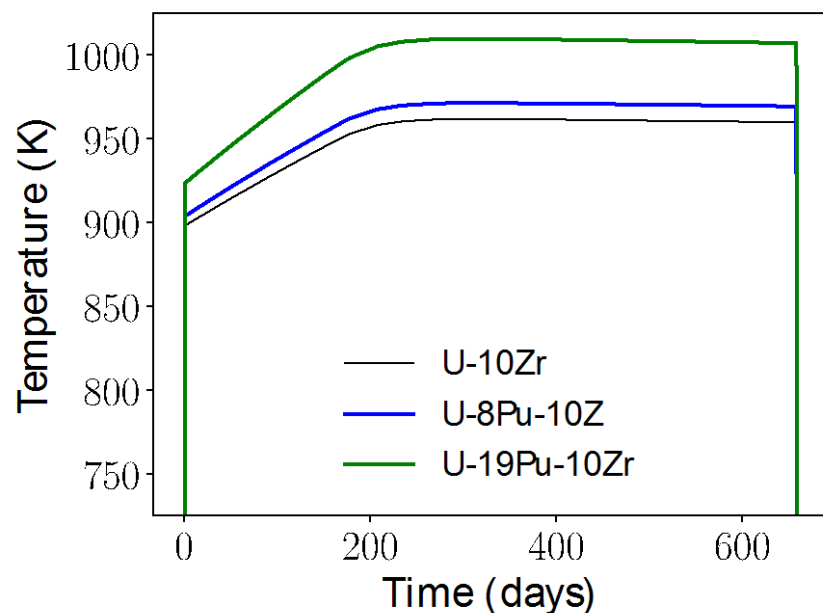


# Example: EBR-II Fuel Pin

- 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



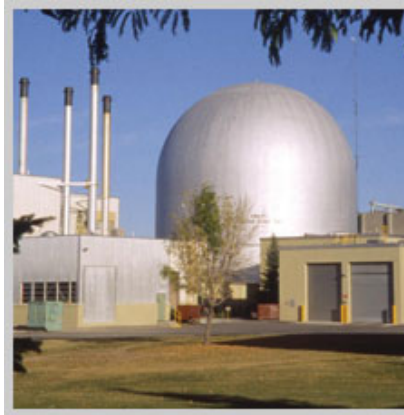
Typical temperature field  
(geometry scaled 10x radially)





# 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

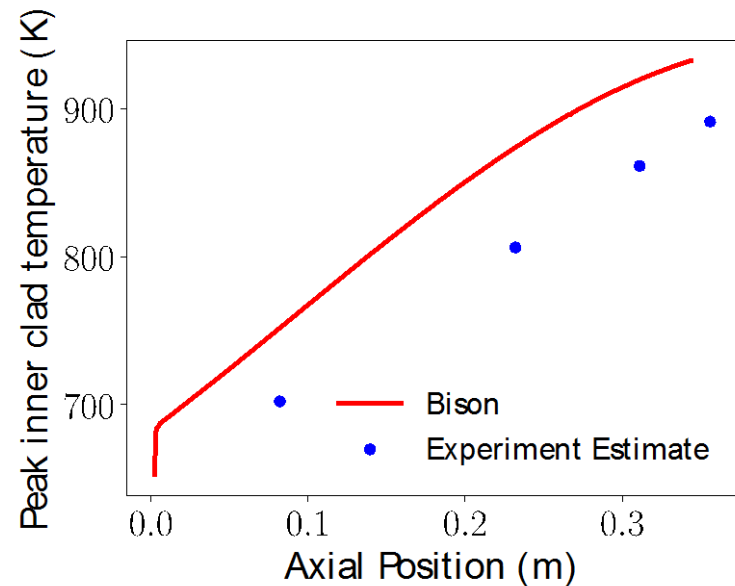
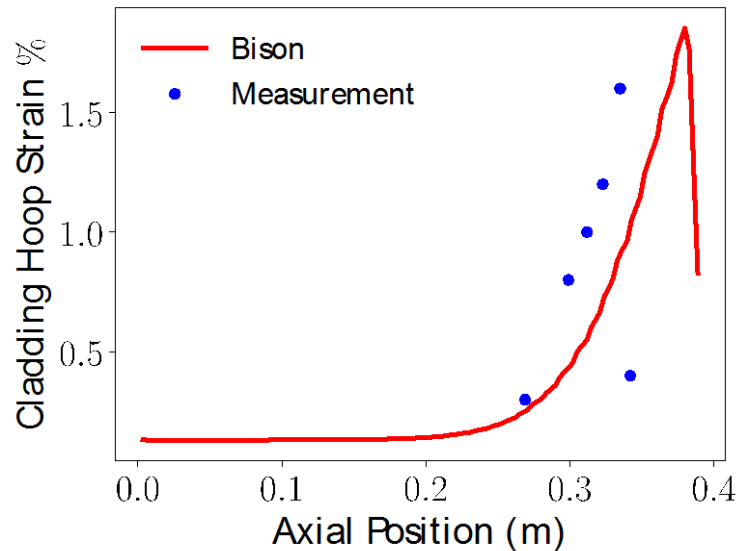
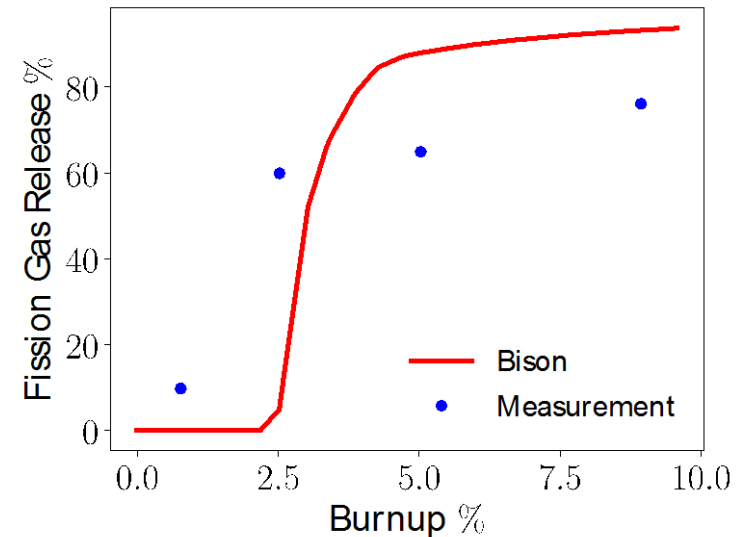
Experiment	Fuel type	Cladding	Measurements
X447 (EBR-II)	U10Zr	HT9/D9	Pin profilometry, fission gas release
X441 (EBR-II)	U10Zr U19PuxZr	HT9	Pin profilometry, cladding strain, plenum pressure, fission gas release
X423 (EBR-II)	U10Zr UxPu10Zr	316 SS	Fuel slug dimensions
M7-IFR (TREAT)	U10Zr U19Pu10Zr	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**

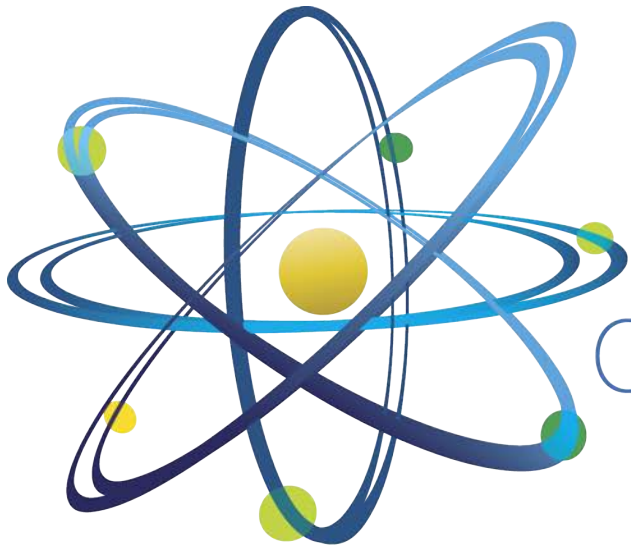
- Applicable to a wide variety of fuel types, geometries, spatial scales and operating conditions
- Basic capabilities in place and demonstrated for high-priority advanced reactor fuel concepts including:
  - TRISO particle fuel (MHTGR and FHR)
  - Metallic fuel (SFR)
- Multiscale modeling approach (Bison/Marmot) 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?



Clean. **Reliable. Nuclear.**





# Thermal-Hydraulic Capabilities for Advanced Reactors

August 21<sup>st</sup>, 2018

DOE Briefing to ACRS:

*Advanced Modeling & Simulation Tools for  
Advanced Reactors*



# Outline of Presentation

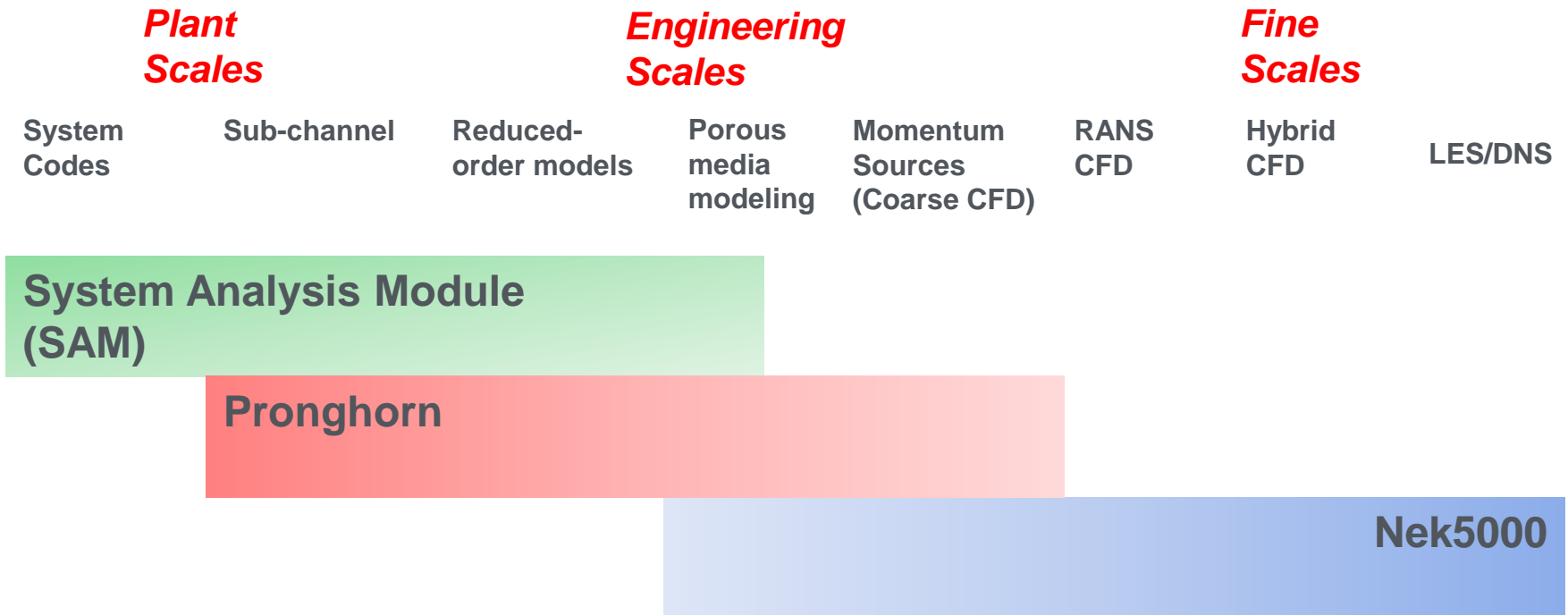
- Background and Objective
- SAM
  - Capabilities/Examples
  - Validation
- Pronghorn
  - Capabilities/Examples
  - Validation
- Nek5000
  - Capabilities/Examples
  - Validation
- Summary and Conclusions



# 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

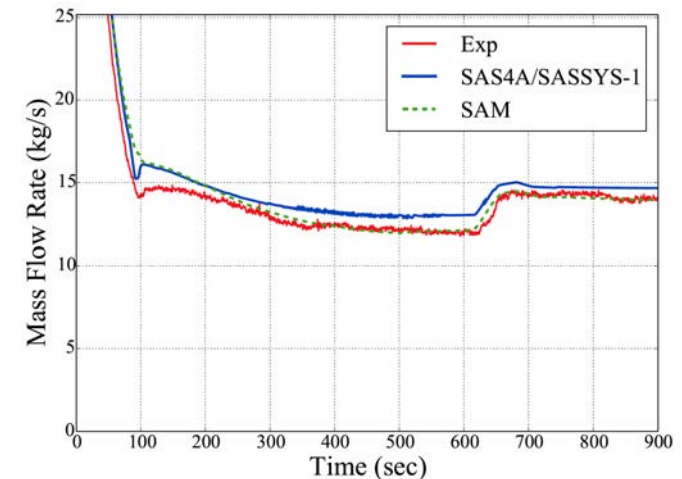
- Provide current status of DOE T/H codes for application to specific advanced reactor concepts including:
  - Code capabilities
  - Validation status
  - Future plans
- When 1D approximations are sufficient SAM is the applicable DOE code for safety analysis (LBEs).
  - It can be combined as desired 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

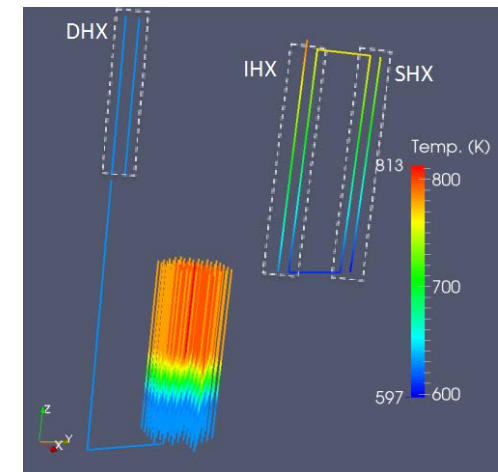


# SAM: Overview

- 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:**

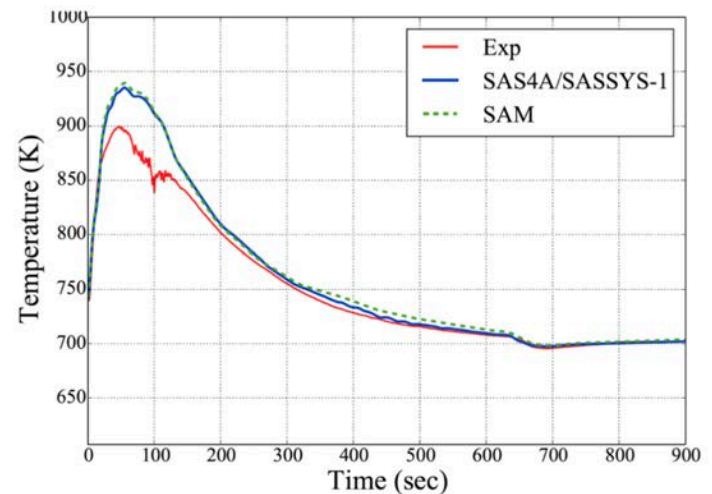
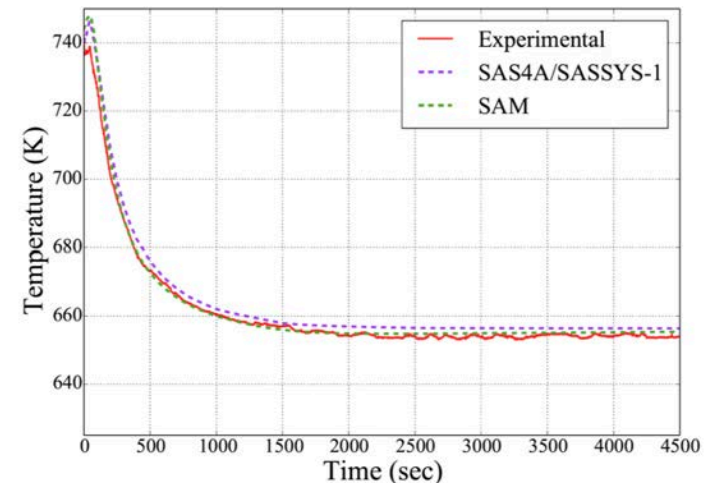
- SAM can reproduce behavior of several EBR-II and FFTF benchmarks

- **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.

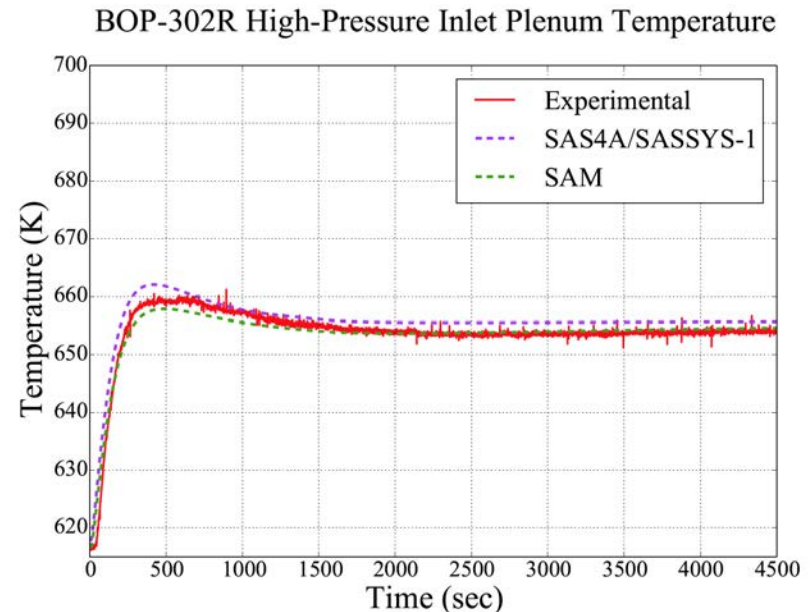


EBR-II - Subassembly 6C4 outlet temperature during unprotected loss of heat rejection tests (BOP-302R - top) and unprotected loss of flow (SHRT-45R - bottom)

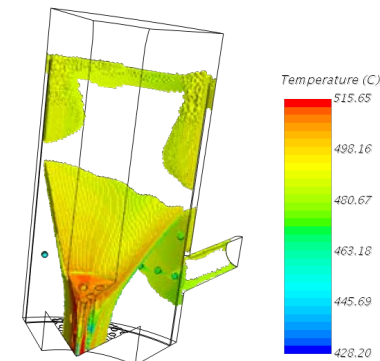


# SAM for Fast Reactors: Options for stratification models

- 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

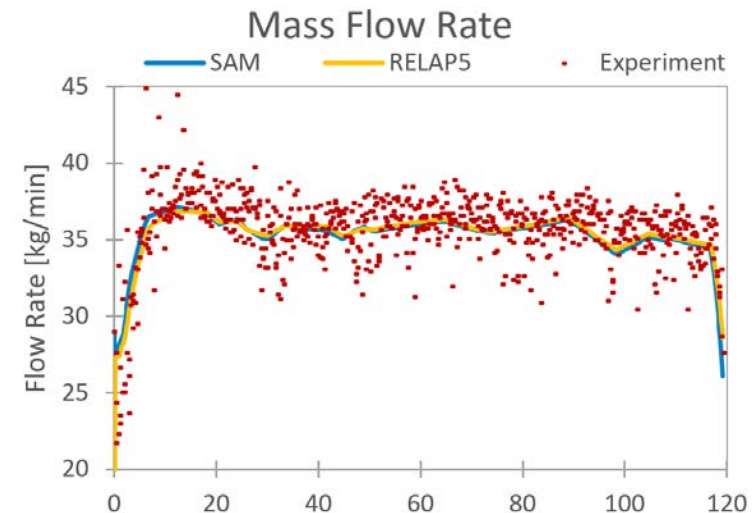
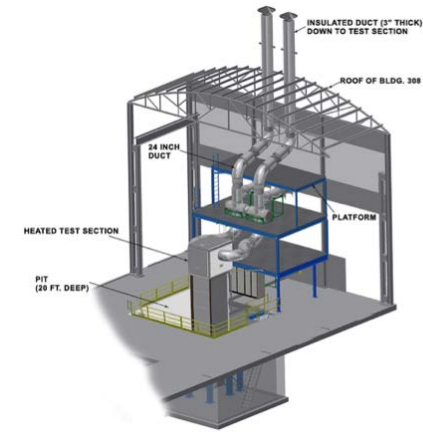


Coupled CFD calculation in the upper plenum of Monju (1995 turbine trip test) – Temperature predictions



# 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.

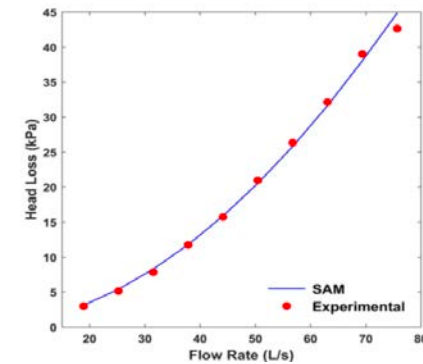


# SAM for MSR Reactors: Challenges and Status

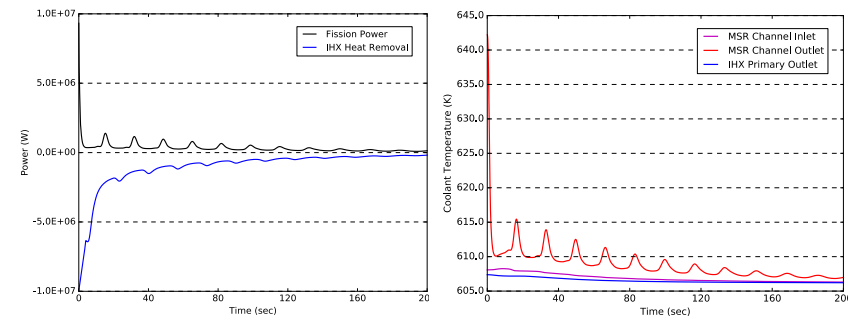
- **Unique T/H challenges:**
  - Heat is produced directly in the “coolant”
  - Unique design with “fuel circuit”
  - Unique core configurations with potential recirculation and stagnation zones
  - Reactivity management challenges
  - Delayed neutron precursor drift
  - Quick reconfiguration of the 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 <sub>t</sub>	10 MW <sub>t</sub>
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 Fluoride 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.

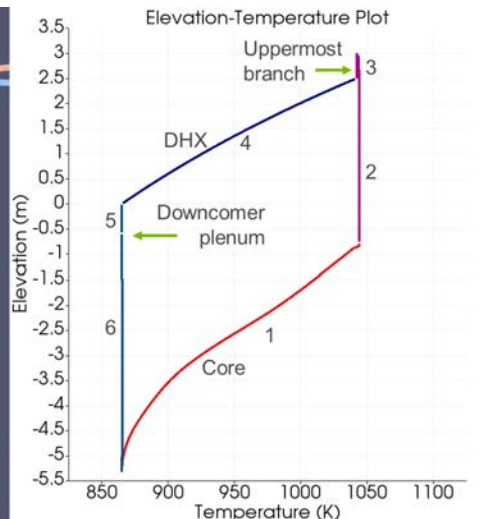
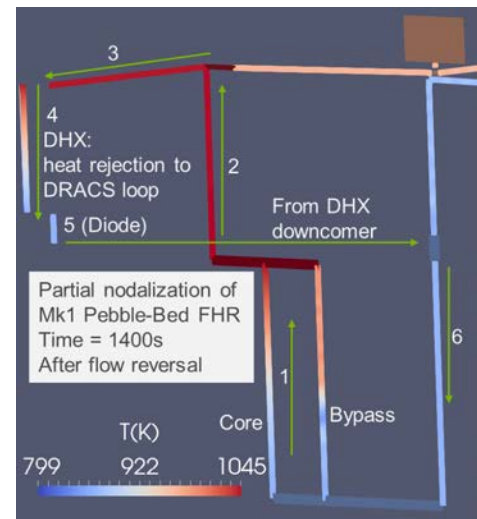
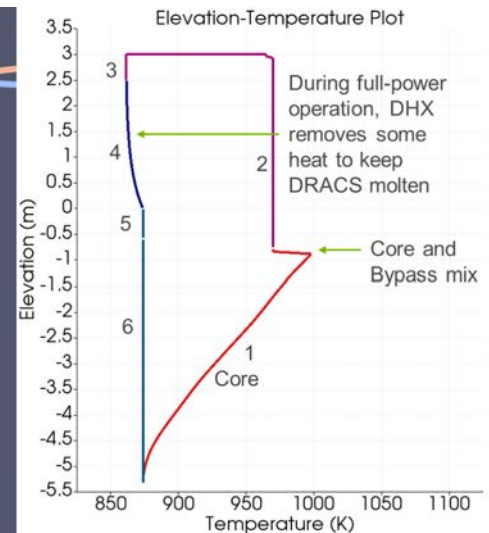
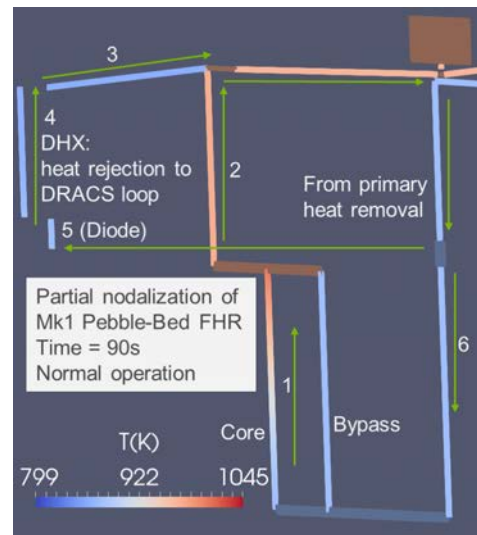
- Collaboration with vendors and universities.

- **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
<b>BASIC PHENOMENOLOGICAL MODELS</b>												
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
Buyoancy 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
<b>TYPES OF CALCULATIONS</b>												
Single-phase flow transients			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

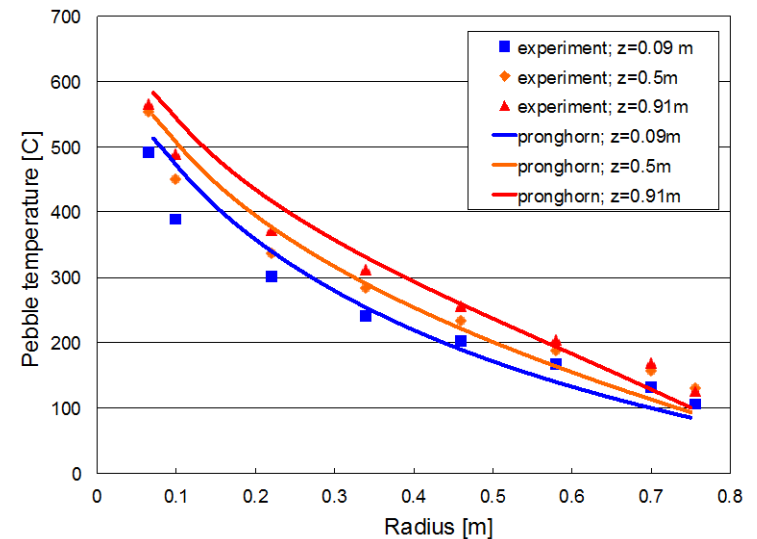
- Ongoing validation and plans identified. C- Complete, O- Ongoing, P- Planned.

TEST MATRIX FOR SAM VALIDATION - MSR/FHR Applications								
	UCB-PBHE	UW-Flibe NC Loop	OSU-LTDF	UM-HTDF	UCB-CIET	ORNL LSTL	MSRE Water Mockup	MSRE
<b>BASIC PHENOMENOLOGICAL MODELS</b>								
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
<b>TYPES OF CALCULATIONS</b>								
Single-phase flow transient		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

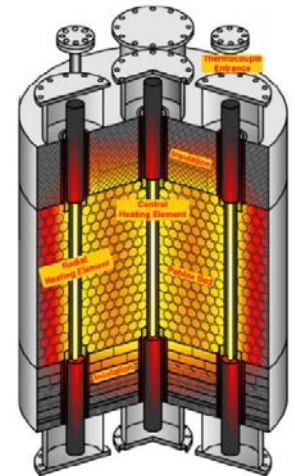


# Pronghorn: Overview

- 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 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 Jülich, 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

$$\frac{\partial \alpha \rho_g}{\partial t} + \vec{\nabla} \cdot \alpha \rho_g \vec{u}_g = 0$$

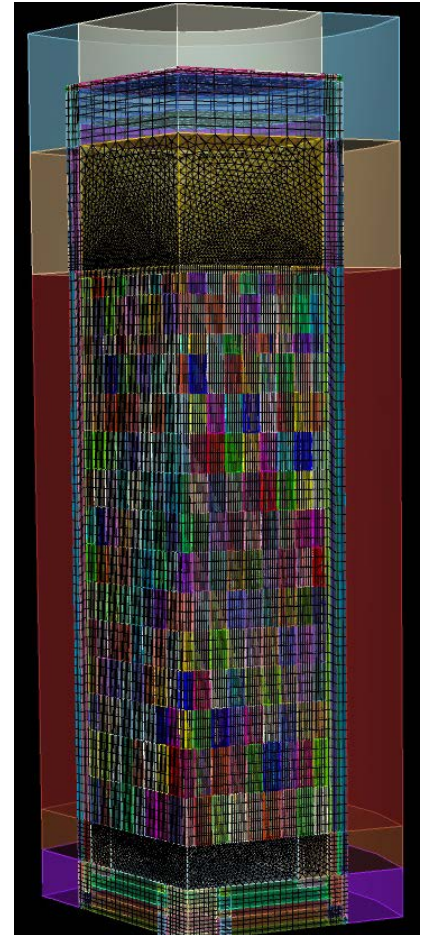
$$\frac{\partial \alpha \rho_g \vec{u}_g}{\partial t} + \vec{\nabla} \cdot (\alpha \rho_g \vec{u}_g \otimes \vec{u}_g) = -\alpha \vec{\nabla} p_g - \xi \rho_g \left\| \vec{u}_g \right\|^2 \vec{\nabla} \alpha - \lambda \vec{u}_g$$

$$\frac{\partial \alpha \rho_g E_g}{\partial t} + \vec{\nabla} \cdot (\alpha \rho_g \vec{u}_g H_g) + \vec{\nabla} \cdot \alpha \vec{q}_g - \alpha \rho_g \varepsilon_g = \vartheta (T_s - T_g)$$

$$\frac{\partial (1-\alpha) \rho_s e_s}{\partial t} + \vec{\nabla} \cdot (1-\alpha) \vec{q}_s - (1-\alpha) \rho_s \varepsilon_s = -\vartheta (T_s - T_g)$$

### 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

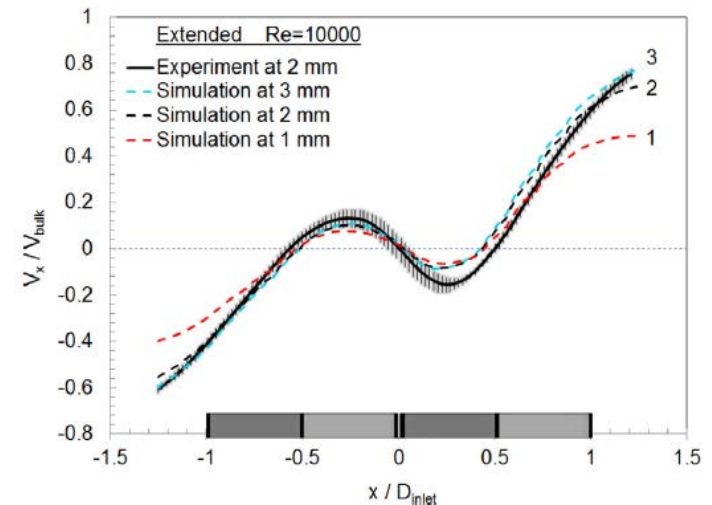
- Validation on SANA dataset for Pronghorn, other simulations are planned. C- Complete, O- Ongoing, P- Planned.

	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)
<b>BASIC PHENOMENOLOGICAL MODELS</b>										
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	
<b>TYPES OF SIMULATIONS</b>										
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	

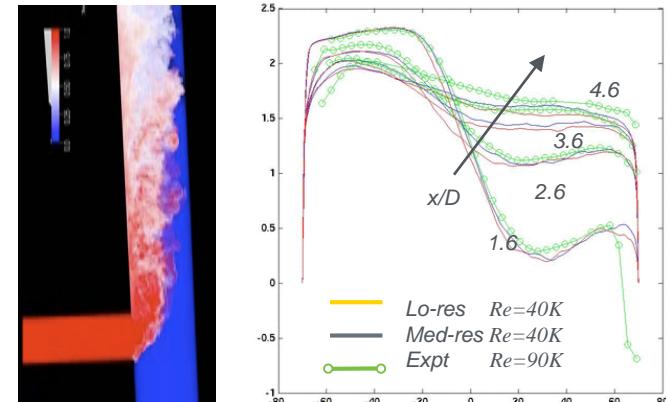


# Nek5000: Overview

- 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-stripping 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:**

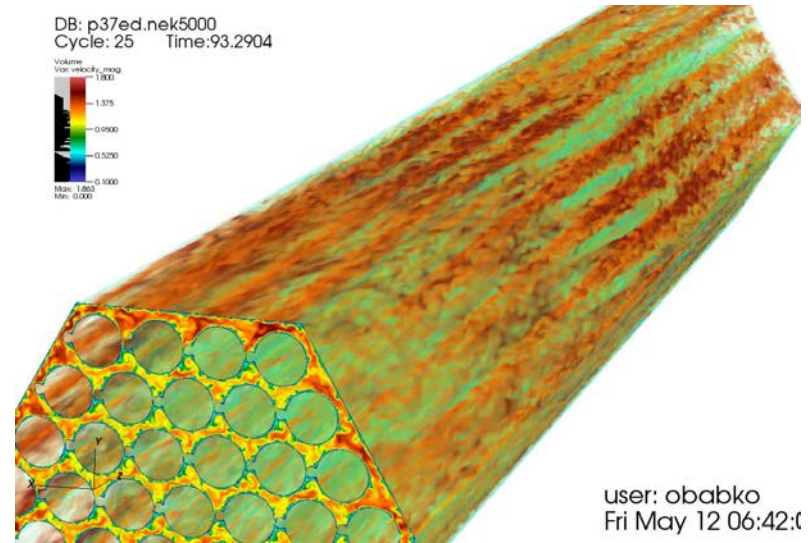
- Nek5000 has extensive validation for thermal striping
- Evaluation of Nek5000 against legacy wire-wrapped fuel assembly experiments and new experimental campaigns.

- **Nek5000 improvements:**

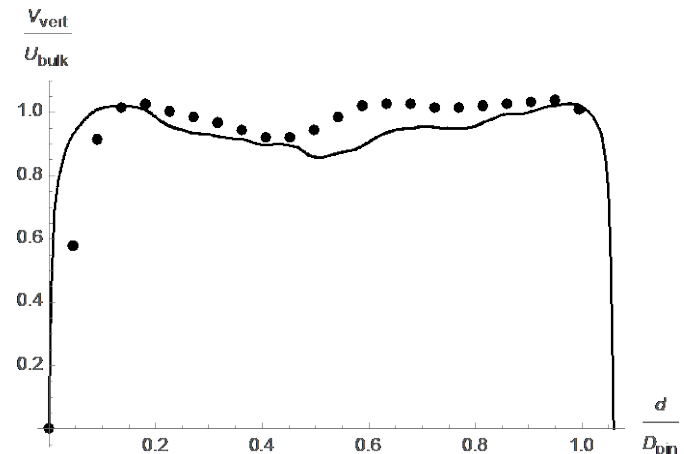
- Coupling to SAM for modeling of upper plenum
- Coupling to Diablo (structural mechanics) for evaluation of thermal-striping in structures.
- Accurate predictions through Large Eddy Simulation modeling

- **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:**

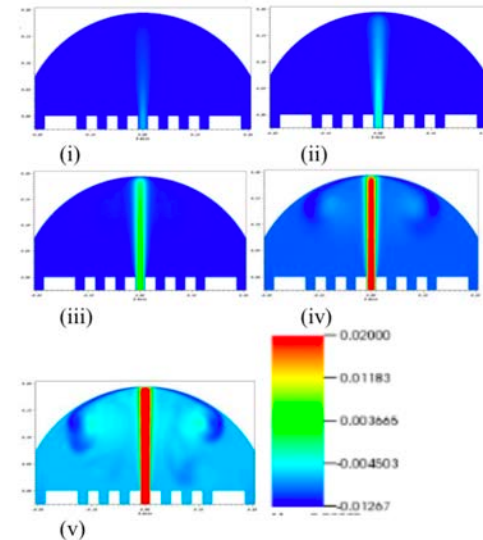
- Modeling of Decay heat removal through Reactor Cavity Cooling systems to drive system code model development.
- Simulation of onset of unique accident scenarios (Air ingress, water ingress).
- Mixing in large enclosures.
- Pebble bed flow and heat transfer models

- **Nek5000 validation basis:**

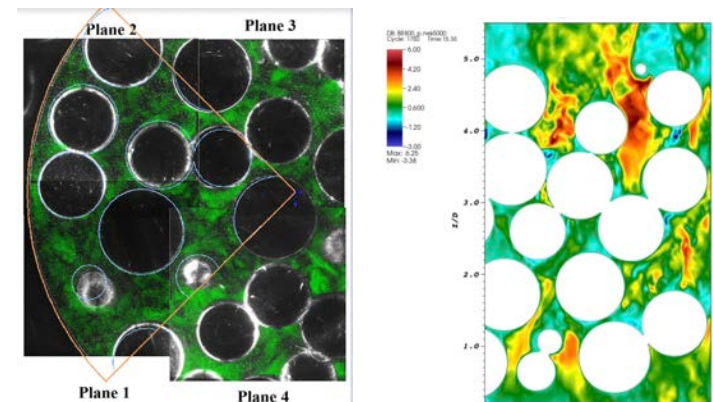
- Ongoing validation effort against TAMU experiments for upper plenum.
- Ongoing validation against random pebble bed data at TAMU (useful also for FHRs). Verification against available DNS data.
- Collaboration with vendors.

- **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:**

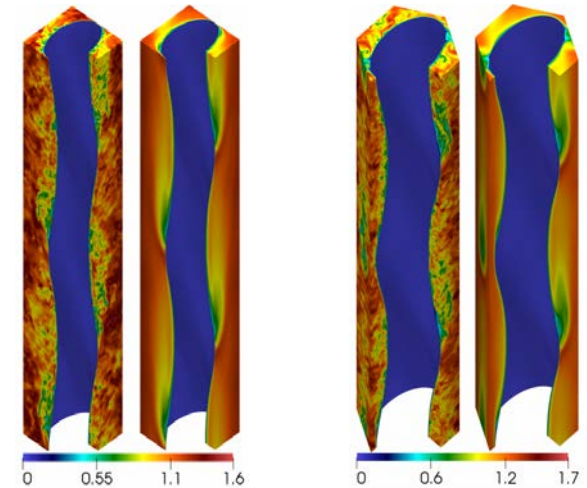
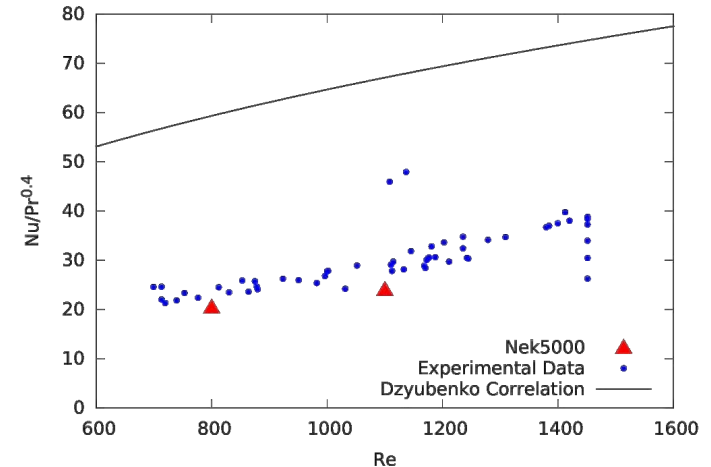
- Validation on available experiments for twisted tubes HX (e.g., DRACS) and pebble “beds”
- Collaboration with vendors.

- **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 plenum 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:

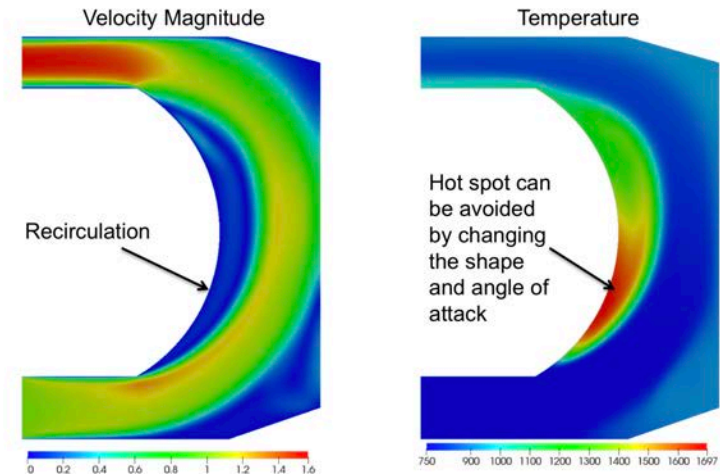
- Limited MSR-specific validation basis. Ongoing collaborations for validation on MSRE data.

## Nek5000 improvements:

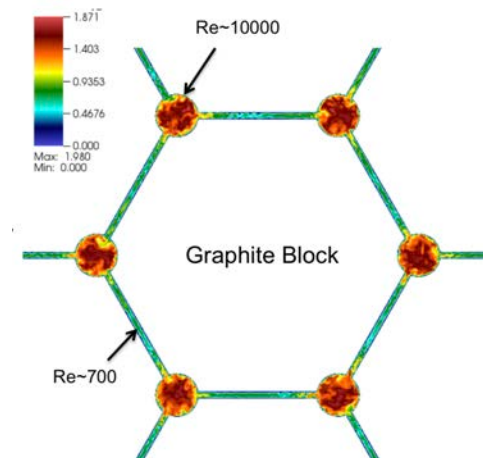
- Coupling to SAM for modeling of full system when 3D effects are important (fast MSR core)
- Modeling of mass transport for DNP and fission products.
- Efficient Large Eddy Simulation approach provides accurate results at low Reynolds number conditions.

## 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	ENE- NACIE	ENE- CIRCE	CEA- SUPERCARNA	KTH- TALL/TALL3D	JAEA- PLAJEST	ANL-MAX	JAEA- PLANTDL
<b>BASIC PHENOMENOLOGICAL MODELS</b>										
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
Buyoancy driven flow				O	O	O	O			P
Thermal stratification						O	O			
Pool dynamics				O	O	O	O		C	P
<b>TYPES OF CALCULATIONS</b>										
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
<b>BASIC PHENOMENOLOGICAL MODELS</b>										
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 exchangers			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
<b>TYPES OF CALCULATIONS</b>										
Single-phase flow transient				P	P	P	P	P	P	O
Transition to natural circulation				P	P	P	P	P	P	O
Thermal stratification									P	O

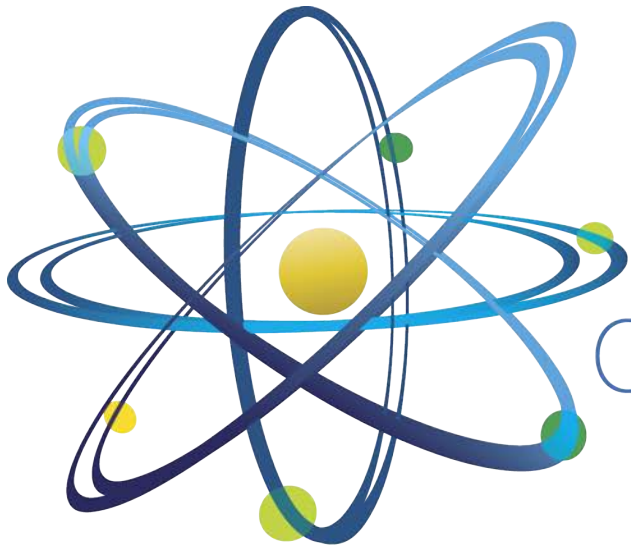


# Conclusions

- 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?



Clean. **Reliable. Nuclear.**



# 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

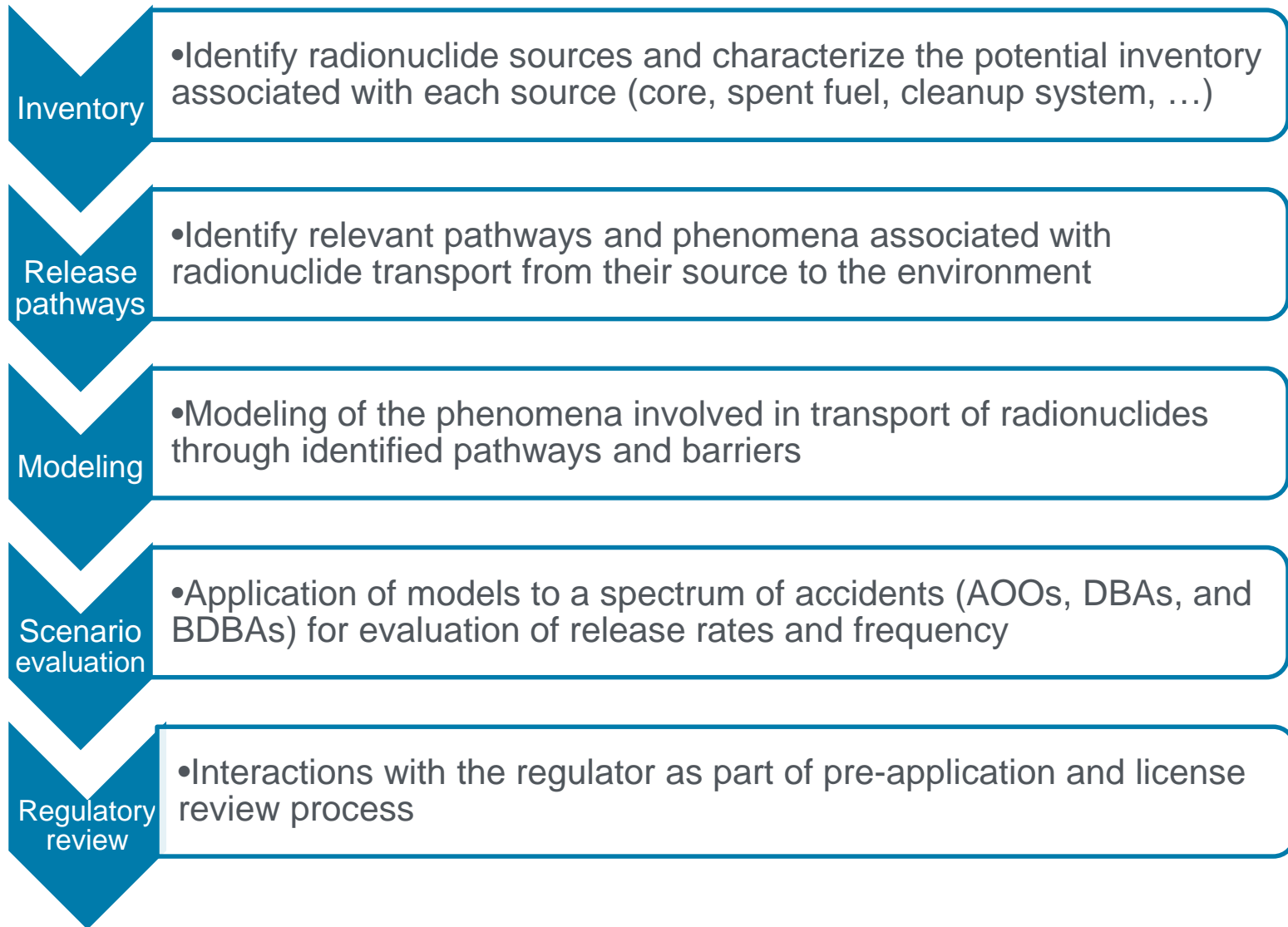


# Rationale for MST for Advanced Reactors

- 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.*



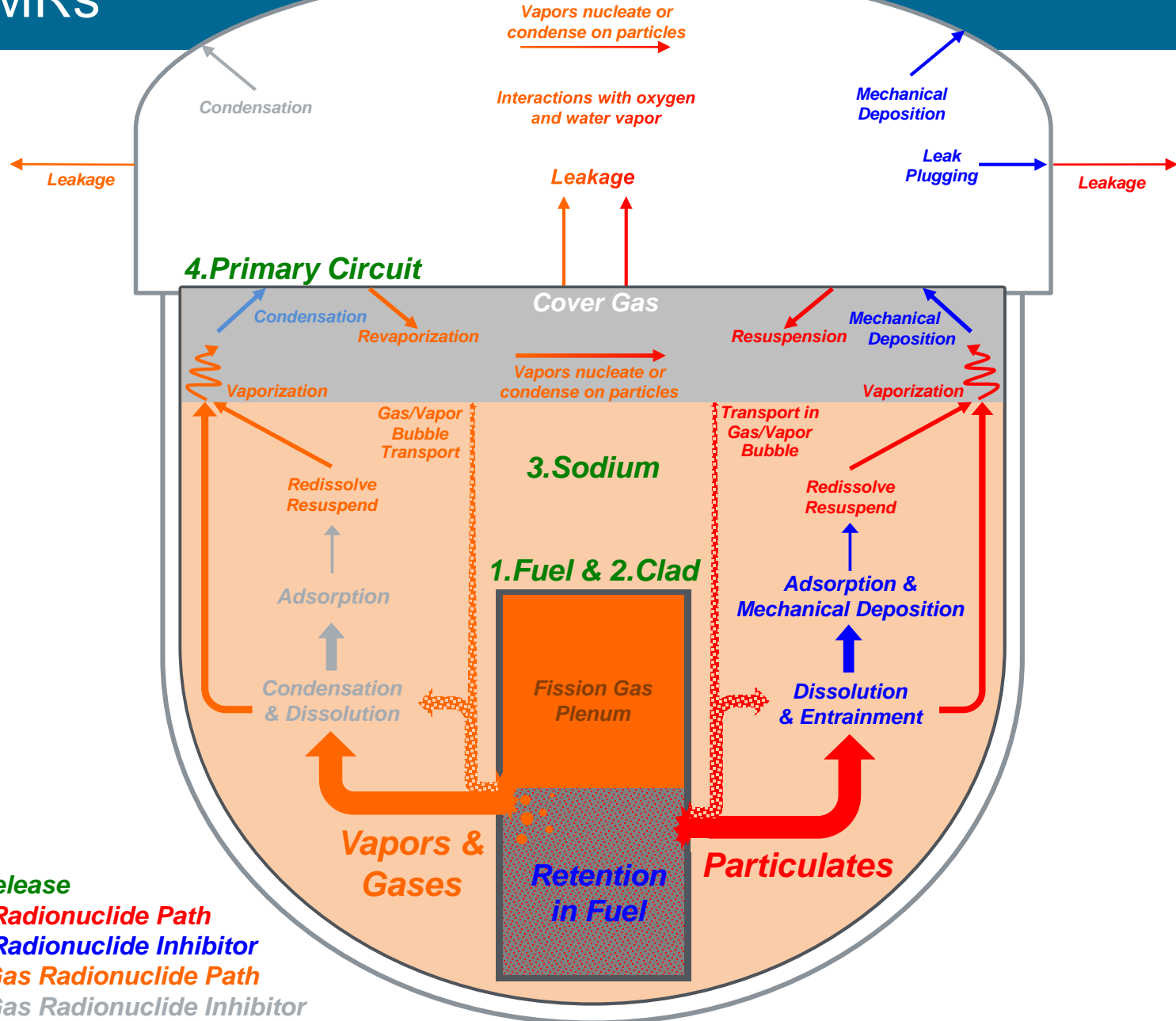
# General MST Approach





# Release pathways for LMRs

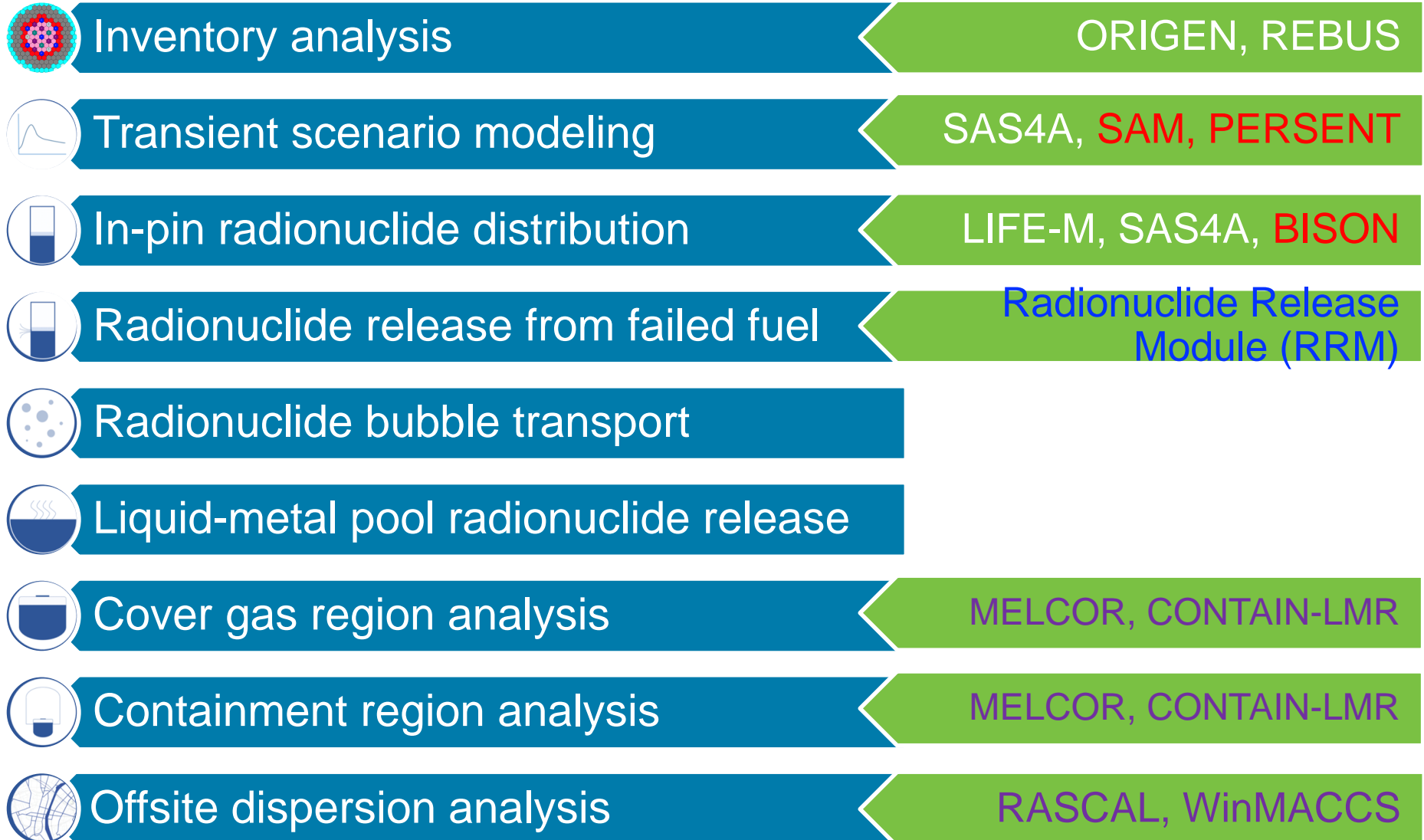
## 5. Containment





# MST Approach for LMRs

Existing codes  
NEAMS Program Tools  
Developmental Capabilities  
NRC-supported codes





# 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:

<b><i>Phenomena</i></b>	<b><i>Importance</i></b>
<i>Pool Bypass (Bubble Transport)</i>	<i>Very High</i>
<i>Fuel Release Fractions (Actinide/Lanthanide)</i>	<i>High</i>
<i>Aerosol Deposition/Removal</i>	<i>Medium</i>
<i>Reactor Head/Containment Leak Rate</i>	<i>Medium</i>
<i>Pool Vaporization</i>	<i>Low</i>
<i>Noble Gas Decay Chains</i>	<i>Low</i>

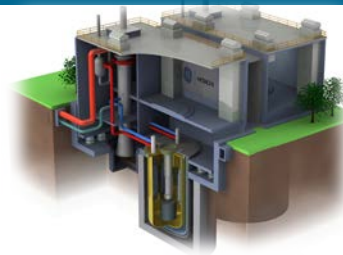
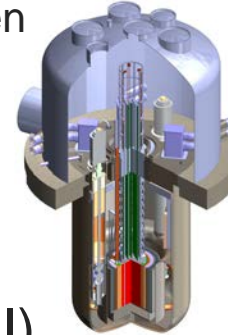


# Other LMR MST Applications

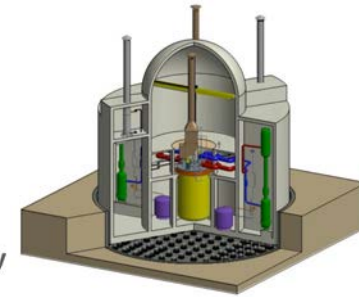
- **GE-Hitachi**
  - MST findings as a major part of PRISM PRA update/modernization effort (2-year collaboration between GEH and Argonne)
- **TerraPower**
  - Company-funded work at Argonne to repeat trial MST calculation for TWR design
- **Korean Atomic Energy Research Institute (KAERI)**
  - KAERI-funded 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



**HITACHI**



**TerraPower**



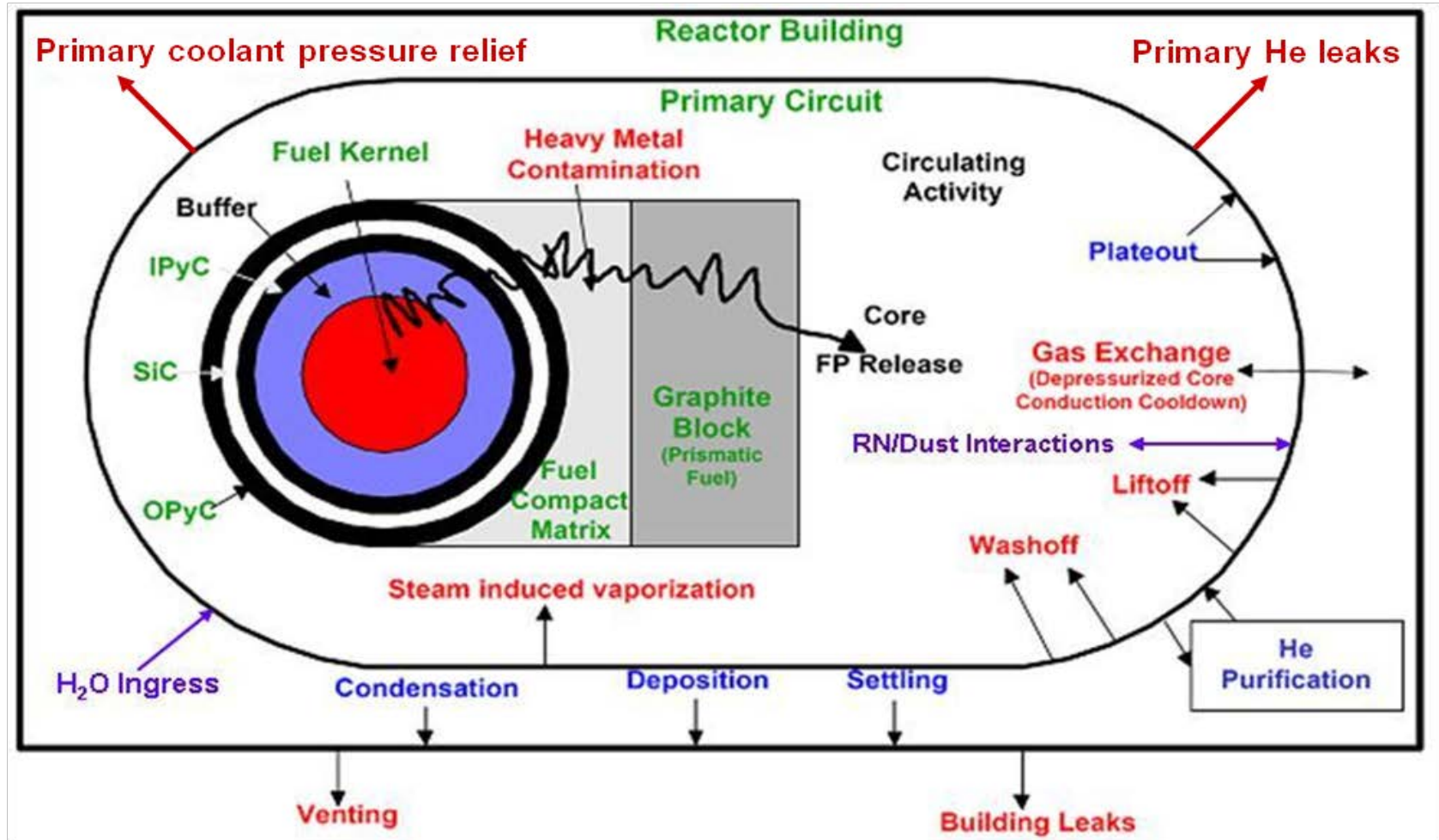
Korea Atomic Energy  
Research Institute

**FAUSKE**  
& ASSOCIATES, LLC



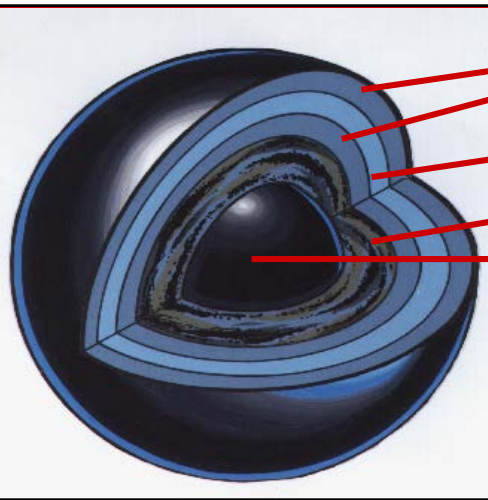


# Release Pathways for HGTRs



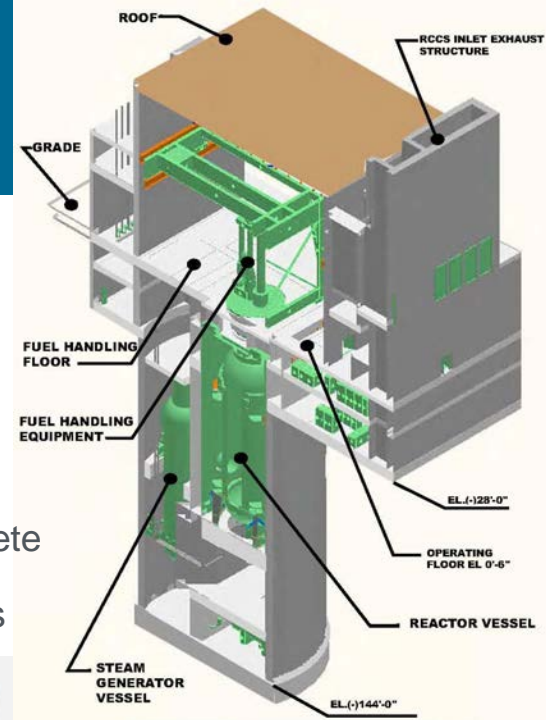


# Multiple Barriers for HGTRs



- Pyrolytic Carbon (Inner and Outer)
- Silicon Carbide
- Porous Carbon Buffer
- Fuel Kernel

Multicell reinforced concrete reactor building based on IBC, ACI, AISC standards

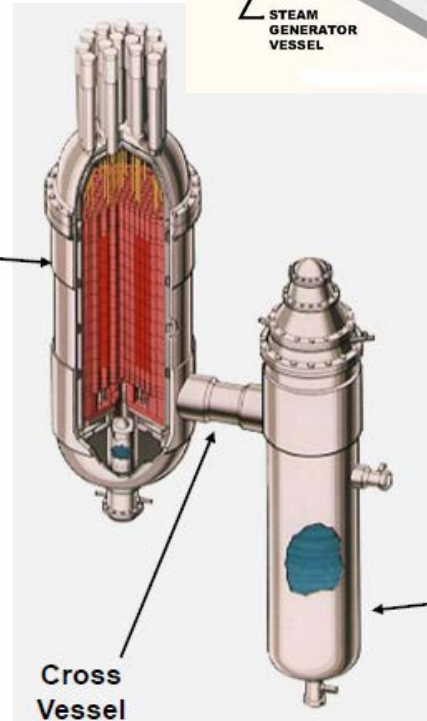


COMPACTS



FUEL ELEMENTS

Reactor Vessel



Cross Vessel

Steam Generator Vessel

Helium Pressure Boundary fabricated based on ASME B&PV Code Section III



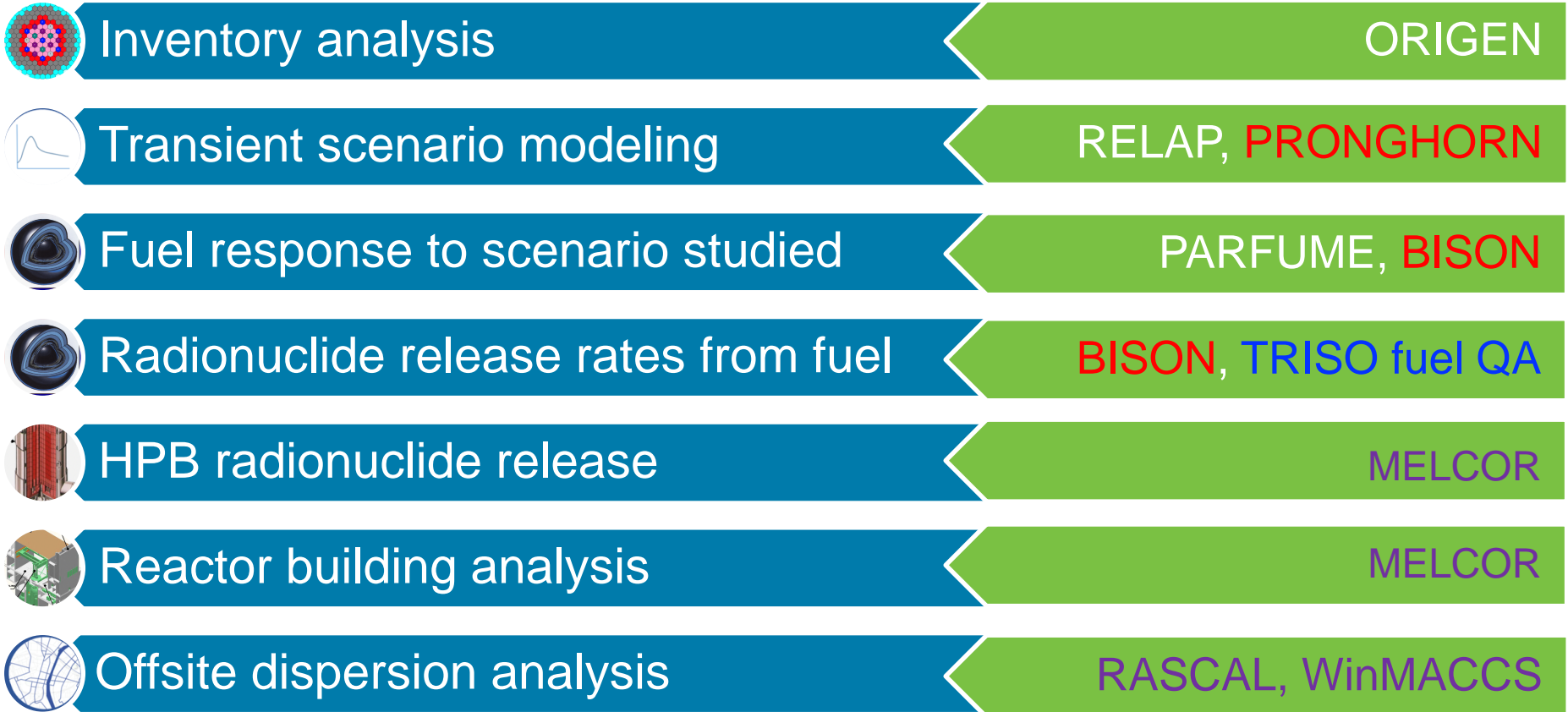
# MST Approach for HTGRs

- 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

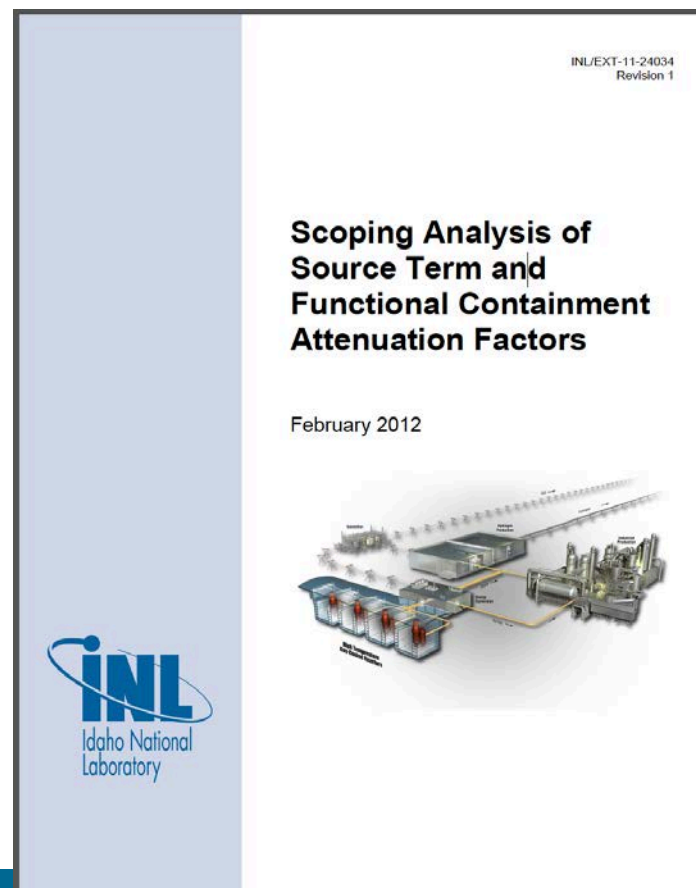
Existing codes  
NEAMS Program Tools  
Developmental Capabilities  
NRC-supported codes





# 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>





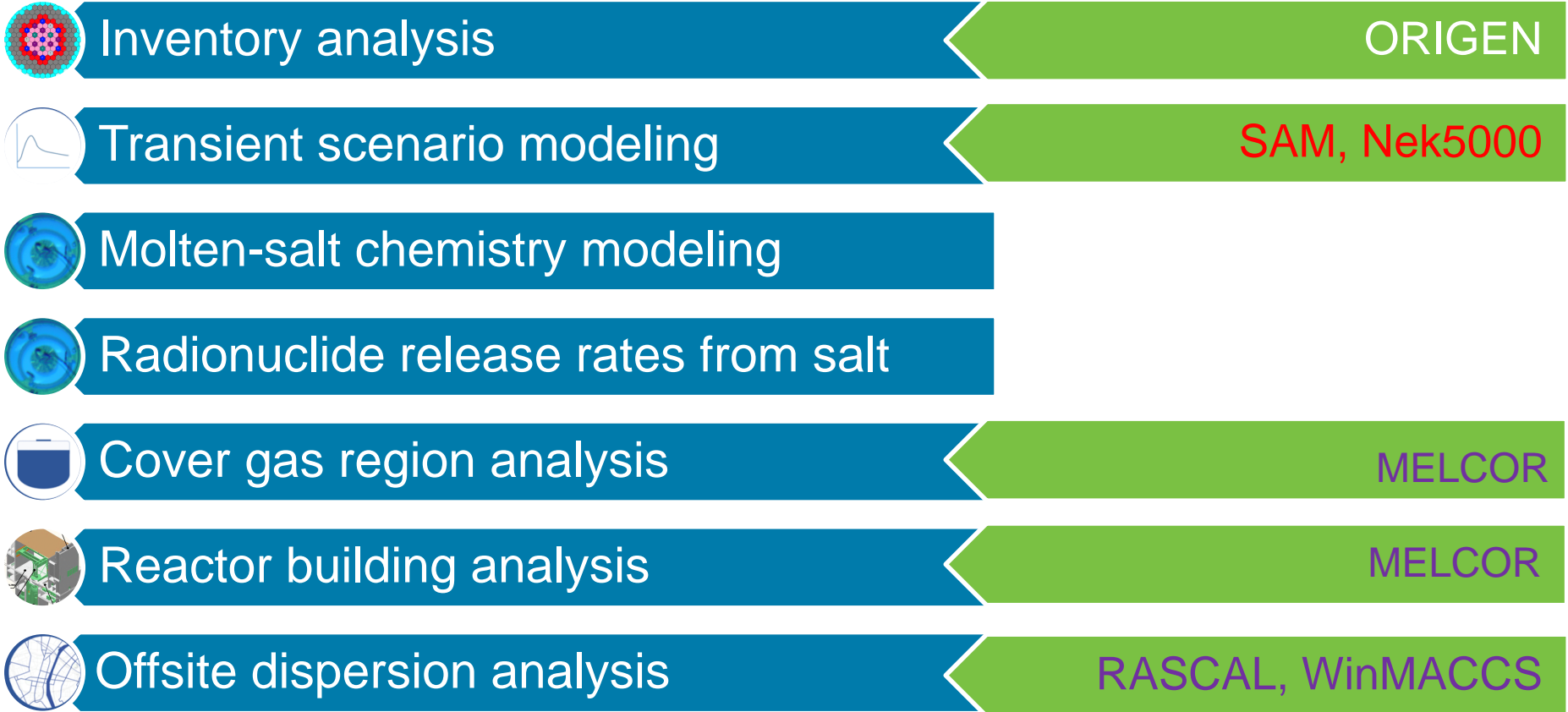
# MST Approach for MSR's

- *Functional containment* concept can also apply to MSR's (with dissolved fuel) and FHR's (with solid fuel)
  - For FHR's, coated fuel particle is also the primary barrier to radionuclide release during normal operation and off-normal events
  - For MSR's, 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 FHR's MST approach and tools used can be similar to those for HTGR's



# MST Approach for MSRs

Existing codes  
NEAMS Program Tools  
Developmental Capabilities  
NRC-supported codes



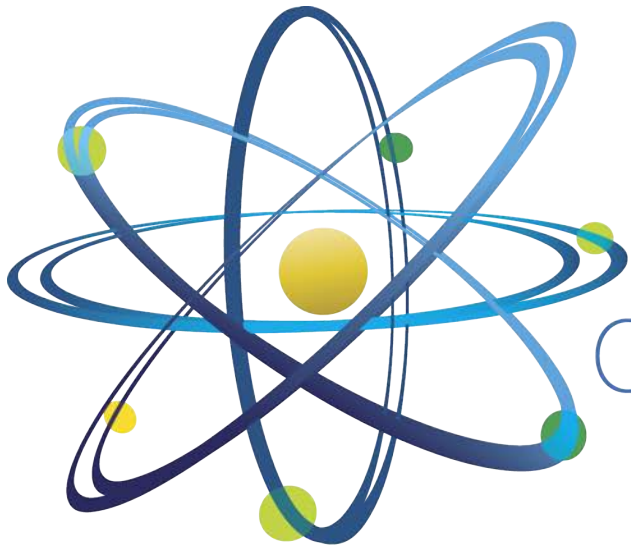


# Summary and Conclusions

- 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?



Clean. **Reliable. Nuclear.**





## 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 <sub>2</sub>	Coated cladding	FeCrAl cladding	SiC/SiC cladding	U <sub>3</sub> Si <sub>2</sub>	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