Official Transcript of Proceedings

NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards
Thermal-Hydraulic Phenomena
Subcommittee

Docket Number: (n/a)

Location: Rockville, Maryland

Date: Tuesday, April 18, 2017

Work Order No.: NRC-3022 Pages 1-310

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

+ + + + +

THERMAL-HYDRAULIC PHENOMENA SUBCOMMITTEE

+ + + + +

TUESDAY

APRIL 18, 2017

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 1:30 p.m., Michael Corradini, Chairman, presiding.

COMMITTEE MEMBERS:

MICHAEL L. CORRADINI, Chairman

RONALD G. BALLINGER, Member

DENNIS C. BLEY, Member

WALTER L. KIRCHNER, Member

JOSE MARCH-LEUBA, Member

JOY REMPE, Member

GORDON R. SKILLMAN, Member

JOHN W. STETKAR, Member

MATTHEW W. SUNSERI, Member

ACRS CONSULTANT:

WILLIAM SHACK*

DESIGNATED FEDERAL OFFICIAL:

HOSSEIN NOURBAKHSH

ALSO PRESENT:

HOSSEIN ESMAILI, RES

ED FULLER, RES

DON HELTON, RES

LARRY HUMPHRIES, Sandia National Labs

RICHARD LEE, RES

KYLE ROSS, Sandia National Labs*

ANDREA D. VEIL, Executive Director, ACRS

CASEY WAGNER, Dakota, LLC*

*Present via telephone

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

(1:30 p.m.)

CHAIRMAN CORRADINI: The meeting will come to order.

This a meeting of the ACRS's Thermal-Hydraulic Subcommittee. My name is Mike Corradini, chair of the subcommittee.

Members in attendance today are Ron Ballinger, Dick Skillman, John Stetkar, Jose March-Leuba, Walt Kirchner, and Joy Rempe. We may have another member joining us later. Hossein Nourbaskhsh is the Designated Federal Official for this meeting.

The purpose of today's meeting is to discuss the recent improvements to the MELCOR code and the impact of those improvements on the recent applications of MELCOR for the state-of-the-art reactor consequence analysis, aka SOARCA.

Today we have members of the NRC staff and Sandia National Laboratories to brief the subcommittee.

The ACRS was established by statute and is governed by the Federal Advisory Committee Act, FACA. That means that the committee can only speak through its published letter reports. We hold meetings to gather information to support our deliberations.

Interested parties who wish to provide comments can contact our office requesting time after the meeting announcement and as published in the Federal Register Notice.

That said, we set aside 10 minutes for extemporaneous comments from members of the public attending or listening in to our meetings. Written comments are also welcome.

The ACRS section of the U.S. NRC's public website provides our charter, bylaws, letter reports, and full transcripts of all full and subcommittee meetings, including slides presented there. The rules participation in today's meeting were announced in the Federal Register Notice of April 12, 2017.

The meeting was announced as an open meeting. No written statement or request for making an oral statement to the subcommittee has been received from members of the public.

A transcript of the meeting is being kept and will be made available as stated in the Federal Register Notice. Therefore, we request that participants in this meeting use the microphones located throughout the meeting room when addressing the subcommittee. Participants should first identify themselves and speak with sufficient clarity and volume so they can be readily heard.

We have a bridge line established for the public to listen to the meeting. To minimize disturbance, the public line will be kept in a listen-in-only mode. To avoid disturbances, I request that attendees put their electronic devices, like cell phones, in the off or noise-free mode.

We will now proceed with the meeting. I'll call upon Hossein Esmaili of the NRC's Office of Nuclear Reactor Regulatory Research to give us our kickoff for today's presentation. Dr. Esmaili?

MR. ESMAILI: Thank you, Mike. So I'm going to be just giving a brief overview of what we do here in terms of severe accident research on MELCOR computer code.

So NRC has always been engaged in severe accident research. The objective is to support risk-informed regulations, emerging issues for new reactors, and support for new reactor design certification. To do this, we must maintain expertise in phenomenological knowledge and validated computer codes.

Given the complexity of the issues and the costs associated with the research to support experimental and analytical, we do rely on international collaboration. This provides access to experimental data for code development and assessments, as there is limited experimental programs sponsored by NRC at this time.

Over 20 years ago, NRC, with help from some international research organizations, established the NRC Cooperative Severe Accident Research Program, CSARP. It has now 27 countries participating in the program, and we host a meeting once a year in September to exchange progress in severe accidents research.

In addition to domestic use, MELCOR is provided by NRC to international organizations through bilateral agreements under CSARP. And there are currently several MELCOR-related technical review meetings, one in September called MCAP, MELCOR Code Assessment Program. And we have two others, one in Europe, the European MELCOR User Group Meeting, and one in Asia, the Asian MELCOR User Group Meeting.

There are other 900 licensed code users worldwide. So if you look at the MAAP, there is somebody doing something with MELCOR at any instant in time. And so what these meetings try to achieve is provide training in the use of the code and inform of the new code features, listen to user suggestions and problems, and provide a means for users and co-developers to discuss issues.

So, and you are also participating in some of the NEA/CSNI and European Commission programs, because they are using MELCOR code in their -- some of their projects.

CHAIRMAN CORRADINI: So, Hossein, I guess I wasn't aware that you do a European meeting and an Asian meeting yearly.

MR. ESMAILI: Yes. We do that. We actually came back two weeks ago from Spain. It was the ninth -- it was the ninth. The ninth one was in Madrid, Spain, so it's every -- every year it's in one European capital. Next year it's going to be in Croatia, so they just rotate.

And this is easy for the code users over there because they can come to the meeting instead of traveling all the way to the United States for it.

CHAIRMAN CORRADINI: So it's a replicate of what might occur here in D.C. in the fall.

MR. ESMAILI: It's --

CHAIRMAN CORRADINI: Approximately.

MR. ESMAILI: Approximately. It's a two-day meeting, and it's mostly, you know, we provide access to the code development, and so that's -- and so the code users can have -- talk to Larry and, you know, so it's --

CHAIRMAN CORRADINI: Okay.

MEMBER REMPE: So as I recall hearing somewhere, and I don't remember where, you guys actually had fees for access to the codes, and so this is like a cost neutral thing for NRC. Is that a correct statement?

MR. ESMAILI: Not for the code. We do have the CSAR -- under CSAR program, we do have bilateral agreements with several organizations. As I said, there are 27 countries, and so we do have fees. Participating --

MEMBER REMPE: Some sort of fees that offset --

MR. ESMAILI: -- that's right. that's right.

MEMBER REMPE: -- the European --

MR. ESMAILI: That's right. That's right.

MEMBER REMPE: -- access and the Asian access --

MR. ESMAILI: That's right.

MEMBER REMPE: -- et cetera.

MR. ESMAILI: That's right.

CHAIRMAN CORRADINI: But if you want it,

you can have it.

MEMBER REMPE: I think it's worth mentioning that some of those fees help offset the costs to the NRC.

MR. ESMAILI: That's correct. That is correct.

MEMBER REMPE: That's what I'm trying to make with --

MR. ESMAILI: That is right.

MEMBER REMPE: -- that point.

MR. ESMAILI: Yes. Okay. Next slide?

So this is simplified picture of what goes on into the code. And in terms of data and experiments and what comes out in terms of code applications and support for regulatory decision-makings.

So I'm not going to go in detail because I don't have time, but you have been involved, you know, the members obviously have been briefed on a number of these projects. And depending on the nature of the application, MELCOR can also provide the source term for MACCS through the consequence analysis.

So on the left-hand side, some of the major domestic and international programs are identified in the dark blue boxes. This is the PHEBUS test, the MCCI test, the zirconium fire experiments. Next to them you can see, you know, the phenomena, and what these experiments try to do is provide us a basis for validating our code and also code development, you know, how we model the code.

And then on the right-hand side, on the green, is the type of project that we -- that we work up.

So, at this point, it is my pleasure to introduce Dr. Larry Humphries. He is a distinguished member of the technical staff in the Severe Accident Analysis Department at Sandia National Laboratories. He has more than 25 years' experience in severe accident phenomenology as an experimentalist, analyst, and model developer. He has served as the principal investigator for MELCOR code development for more than 10 years, leading a team of scientific code developers in advancing physical models and computational techniques for simulation of severe accident phenomena, including advanced applications and reactor design such as spent fuel pools, liquid metal reactors, and high temperature gas reactor designs.

The led the MELCOR code assessment program, participating in several international standard problems and benchmark calculations. He also developed software quality assurance guidelines for maintaining MELCOR. In addition, he has led numerous MELCOR users' workshops for international audiences, some I was mentioning before, and has been an invited speaker at international symposia.

So before I ask Larry to go over his slides, I just want to mention that this is -- the meeting this afternoon is going to go over, you know, MELCOR modeling approach, et cetera. It is not going to be SOARCA Sequoyah-specific application, because for that we are going to come in June and give you a full picture of, you know, the changes we have made since.

We are going to touch upon some of the modeling changes in how it might or might not affect the SOARCA Sequoyah, but by and large it is going to be mostly MELCOR-related stuff.

CHAIRMAN CORRADINI: So if I might -- because I figured Hossein would say something. So for the members, we're going to come back with Member Stetkar for SOARCA sometime in June. Right, June? June?

MEMBER STETKAR: June 6th.

CHAIRMAN CORRADINI: Thank you. And to make that meeting a bit more expeditious, this is your chance to ask any question you wanted about MELCOR to get a background information versus in the middle of the uncertainty and sensitivity calculations that we'll see for Sequoyah. So we can kind of split the difference here in terms of clarifications going into that subcommittee meeting.

MR. ESMAILI: Right. That was the idea.

CHAIRMAN CORRADINI: Okay. So that's the reason we are having this meeting. Larry? At the bottom where it turns green, where it says "push." Very bottom.

MR. HUMPHRIES: There we go.

MEMBER STETKAR: That's okay. We have members that we're still training after years.

MR. HUMPHRIES: All right. Well, thank you for your introduction, Hossein. I've been very fortunate over my career at Sandia to not be here in the past. I've always been the support role, and Randy Gauntt has been the face that you've seen.

And so I've been in that role where I help the person prepare for this ACRS meeting, and I've seen the fear in their eyes over the years, and I've heard their stories.

CHAIRMAN CORRADINI: There's no fear. Randy just sent me a text message to say, "Hello, and how is he doing?" And I said, "We'll see."

MR. HUMPHRIES: But it has always been on my bucket list, so this is my time to be able to actually say that I stood before ACRS.

So, as Hossein mentioned, I'm going to focus on MELCOR code, not so much the Sequoyah modeling but how MELCOR code models may relate to the Sequoyah UA modeling.

I can't speak to the details of the Sequoyah modeling. That would be the analysts that are actually performing those calculations.

CHAIRMAN CORRADINI: So just to interrupt, since Member Stetkar reminded me, so this is a subcommittee, not the full ACRS, so not only are we not ready for prime time; these are just personal opinions when we start asking you lots of questions.

MR. HUMPHRIES: Okay. All right.

CHAIRMAN CORRADINI: And you have something to look forward to.

MR. HUMPHRIES: So there's something more for my bucket list.

CHAIRMAN CORRADINI: We're going to come back -- we're going to come back just -- just so you understand, we're going to come back in June to talk about SOARCA. That will generate a letter. Some of the information here may be part of that when we get to the full committee, but this -- this purpose -- and so Larry doesn't feel too thrilled -- most of the questions will be personal questions from the members just trying to understand.

MR. HUMPHRIES: Okay.

MEMBER STETKAR: It's mostly important for the public record because the ACRS, as Dr. Corradini expounded in his opening statement, only speaks through the full committee letters. So there is often confusion, especially with the public, about is this an ACRS meeting, or is it not? And it's not.

MR. HUMPHRIES: It's not.

MEMBER STETKAR: It's not.

CHAIRMAN CORRADINI: And members' individual comments may or may not end up as a consensus opinion.

MR. HUMPHRIES: Okay.

MEMBER STETKAR: So don't take it seriously -- too seriously if somebody is, you know, screaming at you, for example.

CHAIRMAN CORRADINI: Usually from the right-hand side of my table here.

MR. HUMPHRIES: Okay. So I do have some familiarity with the Sequoyah modeling because as issues come up with the code, they come to the code developers and ask questions about the models that are in the code and explanations as to things -- how they might have changed over time.

CHAIRMAN CORRADINI: So can I -- actually, you raised a question that I thought I knew, but now I'm not so sure. So the development group of MELCOR is a separate group of individuals from the -- what I'll call the analysis group. And so if the analysis group sees -- because eventually I'm going to ask the question about 6244 all the way up to 9423, all these -- these 3,200 versions of code changes.

So is it more of an interaction that if somebody says in the analysis group, "Something doesn't look right. We've checked it out, and something needs to be improved or rechecked," they then put in a request to you -- a user need, pardon for the expression, to the development group? How is this interaction done so you can prioritize what you need to look at versus what you are always working on to improve? Do you see my question?

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: And if it fits somewhere in -- later in the presentation, that's fine. But eventually I'm kind of curious on how this interaction goes with you guys.

MR. HUMPHRIES: I'll talk to it on this

slide here, so --

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: I guess this slide I wanted to kind of summarize what is done in the development team, what are some of our priorities, what is required of a severe accident code.

First of all, the code has to have the required physics to be able to capture the physics of a severe accident. And so MELCOR has models for the thermal hydraulics, for the core heatup, for degradation models, models for oxidation of materials and relocation of materials, release of fission products and radionuclides, the transport of radionuclides through a system.

If the vessel fails, then core M can relocate into the cavity, and then you can have concrete interactions. And so there are models there to be able to model the ablation of the concrete, the off gases, and the reactions between the concrete and the debris.

So all those models have been implemented into MELCOR and --

MEMBER BALLINGER: Can I ask probably a dumb question? Because Joy probably already knows the answer. What eutectics does MELCOR deal with? In other words, the interaction between the various materials at very high temperature.

MR. HUMPHRIES: So MELCOR has a eutectics model that has -- doesn't quite work yet, and it hasn't worked since I started working with the code. So we have kind of a poor man's eutectics model where the user is required to change melting temperatures of materials to correspond to eutectic melting temperatures.

MEMBER BALLINGER: Because I'm thinking that some of these people are using MELCOR for some of these -- for ATF, accident tolerant fuels, and things like that. I'm assuming that they have data in there for zirconium and stainless steel, but maybe not others.

CHAIRMAN CORRADINI: He was at the same meeting I was at last week.

MEMBER BALLINGER: That's right.

CHAIRMAN CORRADINI: So he has been -- he has been educated only a little bit.

MEMBER BALLINGER: That's right. I'll admit that.

MEMBER REMPE: Well --

CHAIRMAN CORRADINI: Let him answer the question.

MEMBER REMPE: Okay. Well, okay, you do have a user's recommended values for standard reactor materials, right? So even though you have a poor man's methodology, you have knowledge and you have embedded it through recommended values, whereas the ATF folks don't have data, and so they're -- yes, they have limited data, okay? Would be my response. But, please, I'd like to hear yours. I'm sorry, I couldn't help but --

MR. HUMPHRIES: No, you're right. We have a set of best practices that have been established through the use of the code over the years by analysts, and it's informed by experiments that have been done. And our intention is to put in a eutectics model or make the eutectics model that we have work at some point, but there is always -- in MELCOR development there is always a list of priorities that you have to deal with, and so you have to do triage on the work that you do and the development you do.

So we have been able to satisfy our needs through this reduced melting point way of modeling eutectics.

CHAIRMAN CORRADINI: But I think Larry is being somewhat modest. It depends on the physics package of interest as to how sophisticated. If we get to -- if we're late and the accident and stuff is sitting on top of the concrete, the CAB model is quite sophisticated in its eutectic calculations. But I think -- I assume he is talking about within the core --

MR. HUMPHRIES: Within the core.

CHAIRMAN CORRADINI: -- within the core there is assumed certain things, and one can modify them. But there are defaults that are recommended in the user's guide that one can follow. Even I can understand the user's guide, so it's a -- it's fairly okay.

MR. ESMAILI: Well, I mean, yes, that's true, and all the ATF that you're referring to, those models have been developed, you know, by -- they have been put into MELCOR, earlier version of MELCOR, so MELCOR has the flexibility to do all of those things. And I think in the future what we are going to do is that we are going to put those models into MELCOR 2.2. I think that's what we are going to do.

So those models have been developed for MELCOR 1.8.6 by INL, and we are going to do -- put those into the MELCOR 2.2. So we have the flexibility to do.

MEMBER REMPE: But data are needed.

MR. HUMPHRIES: Data are needed, yes. We have the model; we just don't have --

MEMBER REMPE: But that's another

discussion.

MR. HUMPHRIES: So the physics is important. The other thing that's important is the application, to be able to apply it to different designs and different needs. MELCOR is very versatile in that way. You're able to model lots of different reactor design concepts using MELCOR's built-in control functions and control volume approach.

We have models for PWRs, BWRs, spent fuel pool models, small modular reactors, sodium containment. We're putting models in now for sodium containment. Back when the ACR-700 was looking at licensing here in the United States, they put together a MELCOR model. So here we have a horizontal design, and just using the flexibility of MELCOR you are able to do -- at least get a start to a calculation with MELCOR because of its flexibility.

And the validated physical models. So a lot of importance is placed on validation of our models. We look at ISPs, benchmarks, experiments, accidents.

We recently published Volume 3 of our manuals in 2016, early in 2016, where we updated the validation of many of our validation cases with 2.1. And in that document, we compared 2.1 calculations to 1.8.6 calculations and 1.8.5 calculations. So we had a direct reference between code versions where we could look at changes in those models over those variations.

CHAIRMAN CORRADINI: And just to remind everybody, Hossein just sent us that yesterday. It's SAN-2015-6693, right?

MR. HUMPHRIES: Yes. I don't know the number, but --

(Laughter.)

CHAIRMAN CORRADINI: You don't have them memorized? Okay. But just because I wanted to make sure that the members had -- there is always a Volume 3. I couldn't find it, and then when I got to it on the website I couldn't download it it was so big. So Hossein downloaded it, squished it, and sent it to you all.

MR. HUMPHRIES: So, in that volume, we looked at a number of different assessment calculations. We also did some -- looked at some Gedanken experiments, basically looking at some analytical solutions, comparing the code to those analytical solutions.

So those are important to us. It's not a complete set yet. We're still adding to that document. It's a living document. This year we have done two or three more validation cases, and we'll update that report.

CHAIRMAN CORRADINI: So this actually leads to a question that I was curious about. So when you guys go from X to X plus delta X version, do you rerun all these calculations, or do you rerun a subset of the calculations in the volume? Because there is a heck of a lot of -- there's like, well, 20-ish, 25?

MR. HUMPHRIES: With every revision that we do, we run a suite of test cases. And that includes all of -- most of the validation cases. Some of them run a little longer than we can support on a daily basis, and so we don't rerun those typically. But probably 80 to 90 percent of our validation cases we run every time we release -- or we update a code version. That doesn't mean that we update the documentation every time.

CHAIRMAN CORRADINI: No, I understand that. I understand that, because, as you said, this just shows 1.8.5 to 1.8.6 to 2.1. But you have what you call analytic assessments, assessment experiments, and then code version comparisons. So you pick from all three of those whenever you have X to plus -- X plus delta X version?

MR. HUMPHRIES: For any version we run almost all of the ISPs, all of the assessments.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: The only ones that we don't are the LACE tests because they take a lot longer to run, LACE and the PHEBUS tests.

MEMBER REMPE: So when you do the test cases, it would take a lot of human time to look at the different results. So do you have some program that does -- automatically compares the results? And does it look at peak values to compare, or does it look at timing to compare the peak values? Or how do you check and say, "Oh, it passed those test cases. There was less than something different"?

MR. HUMPHRIES: So on a revision-to-revision basis, we have a certain number of metrics that we follow for each revision. And so at the end of the calculation, it will create a text file that has -- first of all, to see if there is any changes at all, we look at global energy errors, because some of our code changes we don't expect it to change answers. It's an input processing change, it shouldn't change the modeling, and we have to verify that, yes, it didn't change the results.

So we look at a global energy error to see if anything has changed. And then some changes we make will -- we expect to lead to changes in calculations.

Maybe hydrogen might be impacted by the model change. And so we look at the total hydrogen. We don't look at the timing on a version-to-version testing basis because it does take a long time to be able to do that.

But when we release a public version of the code, that's when we start looking at the timing in those issues. And so we look at the validation cases. And we don't -- we try to update the Volume 3 every time. We didn't with this last MELCOR 2.2 release.

We haven't updated the Volume 3 because we felt it was important to get it into the user's hands because there were some important code changes that made the calculation run faster, and we wanted users to have access to it.

Our intention is to update that document, though, this year, so that by September we will have an updated validation report.

MEMBER REMPE: Thank you.

MR. HUMPHRIES: So validation is important. Handling user issuers, and we track those online through Bugzilla. So we -- I get repots of issues from --

CHAIRMAN CORRADINI: Through what?

MR. HUMPHRIES: What?

CHAIRMAN CORRADINI: Through what, did

you say?

MR. HUMPHRIES: Bugzilla. Bugzilla. So it's an online issue reporting tool.

CHAIRMAN CORRADINI: Oh, you know what this is? Okay. Okay.

MR. HUMPHRIES: And it's a great way of not only tracking the bugs and assigning bugs, but allowing users to know what issues are out there. So it's all public, so that users can be informed if there is an issue with a particular code model. And so we rely heavily on it.

Internally, if Kyle has an issue, he'll just come to my office. He's right next -- his office is right next to mine, and we'll talk about issues. And eventually, though, I'd like to even have those documented in Bugzilla, if possible. Sometimes a user does not want to have those issues public. Those are private issues, and so there is a capability on Bugzilla to make those issues private also. So that's important.

Uncertainty analysis. The code has to be relatively fast running. We spent a lot of time this past year looking at ways of improving the code performance, and I'll talk a little bit about some of those in the third session. And characterizing numerical variance, and I'll talk about that also in the third session.

And then just having user conveniences, being able to run on Windows or Linux systems, utilities for working with decks. When we moved from MELCOR 1.8.6 to MELCOR 2.1, we completely changed the code syntax. And so we have a plug-in for SNAP to be able to do that, and the capability to do post-processing digitalization and developing spreadsheets of results. And then finally --

CHAIRMAN CORRADINI: Is there a Bugzilla for SNAP?

MR. HUMPHRIES: There is a Bugzilla. There's an issue reporting for SNAP. I can point you to it.

CHAIRMAN CORRADINI: Good.

MR. HUMPHRIES: And they're very good about -- they're responsive to fixing those issues. And there's extensive documentation. If you've looked at the user guide and reference manual, it's very complete. We try to make sure that all of our models are documented well. Occasionally, we miss some things, but we do have a user guide, a reference manual, a validation report, and we're looking to add a fourth report, which would be a user's modeling report.

So a new user wanting to use MELCOR has access to the syntax, knows the format that is expected, has access to the reference manual, has a description of the physics, but they need to have some discussion as to how to model an actual plant situation. And so that's what the purpose of this fourth document is for.

In addition to that, as part of that, I should say, I want a working plant deck that I can share with users, a PWR and a BWR plant deck that are not proprietary. I can't share most of our plant decks with the general public, but I'd like to have something on par with a plant deck that I can share with users.

And then as part of the Volume 4, I will reference those input decks and the models that are described in those input decks.

CHAIRMAN CORRADINI: And that exists now?

MR. HUMPHRIES: It does not exist now, and that's something that's desperately needed by new code users.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: So this slide describes some of the MELCOR core structure. MELCOR is modeled in packages, physics packages. There are packages for hydrodynamics, packages for the -- modeling the core, and heat instructions, and so forth. And each of these packages are calculated independently, and then the data is exchanged from one package to another.

So, for example, the core package, which calculates the heatup of the core and the core degradation, it has to take boundary conditions from the CVH package. It has to know what the fluid temperatures are for heat transfer to the fluid.

In addition, as the core slumps, there is movement of core material that will change the value that's accessible to the CVH package. And so that information has to be transferred to the CVH package. So this is an important part of MELCOR is the ordering in which the packages are performed, and the way in which the data is shared between packages.

And for the most part, the data sharing is explicit between packages, where the core will make changes and calculate an energy -- overall energy transfer to individual CVH control volumes, and then make that available to the CVH package.

And then there are a number of support functions also for calculating material properties, handling data, equation state, and solvers.

MEMBER MARCH-LEUBA: So you're saying that all of the integration routines are explicit? That's what you mean by "explicit"?

MR. HUMPHRIES: Explicit from one package to another. So there are some implicit --

MEMBER MARCH-LEUBA: Implicit in --

MR. HUMPHRIES: -- sub-models within a package, but exchanging information from one package to another is --

MEMBER MARCH-LEUBA: Using the time step -- is there some time step control, or do you specify it, or --

MR. HUMPHRIES: The user will specify a maximum time step and a minimum time step, and then the code will reduce the time step, depending on criteria within the packages. So you have an overall system time step, and then each -- or several of the packages have sub-cycling time steps also. So the CVH package can run at a time step smaller than the system time step also to achieve convergence of its routines.

MEMBER MARCH-LEUBA: Okay.

MEMBER SKILLMAN: Larry, are the 16 blocks arranged such that the processing is always that series of events? The arrows suggest that there is a sequence or that there is a path.

MR. HUMPHRIES: I thought they were.

MEMBER SKILLMAN: Does TP always go to DCH and DCH always goes to core and core always goes to SPR?

Is that --

MR. HUMPHRIES: No.

MEMBER SKILLMAN: -- is that intended to communicate a direction of calculation?

MR. HUMPHRIES: That's not correct. But, no, it's not correct.

MEMBER SKILLMAN: Thank you. Thank you.

CHAIRMAN CORRADINI: So can I -- I think I know the answer, but maybe just for the general group. So if one were to say where the most complication comes in in terms of physics, is it the core package? I would assume it is, but is that incorrect?

MR. HUMPHRIES: The core package is very challenging because we don't have a structural model basically that models the details of the core degradation. We have a lot of empirical models and a lot of branch points where you have logical "if" tests for --

CHAIRMAN CORRADINI: So to put it a different way is you have a series of conceptual cartoons that you transition from.

MR. HUMPHRIES: Something like that, yes.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: But it is also very complicated by the amount of physics that's available in the core package also.

So this is kind of a description of a nodalization of the CVH volume. So a user will specify control volumes and also specify flow paths that connect those control volumes. All of the hydrodynamic material resides within the control volumes. Nothing resides in the flow path. The flow path is there to calculate pressure losses due to friction, informed factors, and so forth.

The user defines opening heights of those flow paths and defines the junctions of the flow paths. He can -- they can use either horizontal flow paths or vertical flow paths. And depending on the heights of the openings, it determines the fraction, the void fraction, that passes through the flow path.

MEMBER MARCH-LEUBA: And within all those flow paths, it is always one dimensional?

MR. HUMPHRIES: Yes, that's right.

MEMBER MARCH-LEUBA: So if you wanted to get like a circulation on a horizontal pipe, you'd have to do two --

MR. HUMPHRIES: You'd have to put in those flow paths to be able to capture that. And you can capture natural circulation if you properly put in the appropriate --

MEMBER MARCH-LEUBA: You have to use the mouse.

MR. HUMPHRIES: This middle picture here shows that we can capture counter-current flow in the steam generator using MELCOR through the flow paths.

CHAIRMAN CORRADINI: There was -- unfortunately, long ago there was a computer program at Sandia called HECTR, and so there was some very good work done by the group there at the time trying to at least characterize the momentum equation or the junction equation and how one can use it for various forced and natural convection approaches.

And I think that's kind of the basis of most of this in terms of the -- what I'll call a momentum equation through the junction.

MEMBER MARCH-LEUBA: Right.

MR. HUMPHRIES: So there's nodalization of the control volumes. There is also nodalization of the core cells. So the user can subdivide the core package into smaller nodalization than the CVH volume. There are models internal to MELCOR to be able to calculate temperature as a function of elevation called the DTVZ model, which will calculate those local temperatures within the CVH package.

But we look at the importance of

nodalization as part of our assessments. Nodalization is -- should be looked at not only globally, but also as for -- for individual models, because certain models were not intended to be highly nodalized. They were intended to be -- they are specific to a single control volume.

MEMBER MARCH-LEUBA: So this allows you to do radiation cooling between nodes or between pins, or how do you do it? Because, I mean, you have a hot pin surrounded by cold pins. They are too small, this -- that one will melt real fast, or are we going to spread the heat?

MR. HUMPHRIES: So I don't know if this answers your question, but so in a core cell there is -- it's a lump parameter. There is a single temperature for any of the components that are in that core cell. However, recently we added the ability to model -- it's a sub-grid model, to be able to model a number of different fuel rod types. This was really important for spent fuel pool application.

And so this is a new model that was put in for spent fuel pools, but we are also looking at it as part of our overall modeling practices, looking at maybe using these at boundaries, at the outer boundary to capture the temperature profile at the --

MEMBER MARCH-LEUBA: The problem with that, I mean, that's not the complexity. But if you don't model the hot rod in a spent fuel dryout -- drying out, the hot rod might melt whereas the others wouldn't. It would melt an hour early. So if you don't have a hot rod, it's non-conservative, right?

MR. HUMPHRIES: If you don't model the hot rod?

MEMBER MARCH-LEUBA: Yes.

MR. HUMPHRIES: That's right. Because otherwise you will never capture the ignition either and the ignition front that can go from a hot assembly to a cold assembly. It would be impossible to capture that.

MR. ESMAILI: But Larry has already developed this multi-rod within the fuel assembly. This has been benchmarked against Sandia zirconium fire experiments. As a matter of fact, that's how we found out that we had to do -- we had to do this. We had to do the -- and it showed that with just five nodes you could capture what was happening in the experiments.

We're still not modeling an individual rod. If you --

MEMBER MARCH-LEUBA: So you have five nodes in a fuel assembly?

MR. ESMAILI: Five nodes in a fuel assembly. And each of these rings that you see here are a collection of assemblies. So this is like maybe 40, 50 assemblies in one --

MEMBER MARCH-LEUBA: See, I was expecting a typical MELCOR run, a whole core may have, what, 10 nodes regularly? Five. So you have like 115 bundles per node.

CHAIRMAN CORRADINI: But I just want to make sure, because I guess I remember you guys explaining this to us when we did the spent fuel study, because we looked at the Sandia test you're speaking about. But if I take a radial position and an axial position, that could still model a number of assemblies. And then within that number of assemblies, within that radial-axial position, then you have subdivisions of temperature. That's what I'm still -- I still want to make sure I'm clear as to what the possibility is.

MR. HUMPHRIES: I think I have a slide on --

CHAIRMAN CORRADINI: You can do it orally. I just want to make sure I understand this new feature of 2.2 that I wasn't aware of.

MR. HUMPHRIES: The new feature is that --

previously, for fuel rods, you had a lumped parameter. You had a single temperature for the clad, a single temperature for fuel.

CHAIRMAN CORRADINI: Inside a radial or axial position.

MR. HUMPHRIES: Right. And it would represent a large number of fuel rods. That doesn't capture the temperature of the boundary, the temperature gradient, which is important at the boundary, to be able to capture that.

CHAIRMAN CORRADINI: Sure.

MR. HUMPHRIES: And to be able to do that, people would play around with the view factors to be able to somehow use a view factor -- modified view factor to be able to capture the temperature profile. It doesn't really quite work in all cases, especially the spent fuel pool, yes.

So we put in a sub-model. So essentially the user can add as many fuel rod types as they want within --

CHAIRMAN CORRADINI: Within a radial-axial position.

MR. HUMPHRIES: Within, yes, a cell, a core cell. You can put in as many of those components as you want. You just have to be able to define the view factors that connect those components.

CHAIRMAN CORRADINI: Okay. And then, since we're on this digression, and then to communicate with the next radial or axial position by radiation, it still probably uses a temperature.

MR. HUMPHRIES: It uses the temperature of the --

CHAIRMAN CORRADINI: Outside.

MR. HUMPHRIES: -- outer --

CHAIRMAN CORRADINI: Of the outer ring.

MR. HUMPHRIES: -- rods.

CHAIRMAN CORRADINI: Okay. And then, to go further, if I go back to my cartoons of geometry, I probably can't use the specificity that I am computing temperature to change my cartoon geometry from intact fuel rods to debris to pool.

MR. HUMPHRIES: So right --

CHAIRMAN CORRADINI: Of course, if things start moving around, they are going to move on a temperature, not on a group of temperatures.

MR. HUMPHRIES: Right now, when one of the fuel rod types determines that it's going to fail, they all will fail. And that was just the easiest first step in --

CHAIRMAN CORRADINI: So the first one to

go, they all go with it.

MR. HUMPHRIES: Yes. They all go with it.

CHAIRMAN CORRADINI: Okay. Thank you.

MEMBER KIRCHNER: Larry, how do you typically start into a calculation? Do you -- you don't do the LOCA analysis. You start with some initial conditions that are presumed from a more detailed analysis, or how do you get into actually executing a severe accident calculation? Do you see what I'm saying? Do you actually try and model the blowdown of the core in the reflood phase, or --

MR. HUMPHRIES: Yes.

MEMBER KIRCHNER: -- if it's a small break LOCA, are you trying to model where the water is throughout the system, or do you make assumptions as to the starting initial conditions?

MR. HUMPHRIES: So I'll qualify my answer first by saying that I don't -- I have never done that, actually. Because I am a code developer, I do -- I run some simple validation tests. I run all the ISPs, that sort of thing. And I -- indirectly, I run some of these plant decks because I'm debugging issues.

But a user -- code user will typically do a steady state initialization looking at water levels to establish a reference point, and then run the calculation from there.

CHAIRMAN CORRADINI: So it's no different than the wonderful world of RELAP. I do a steady state initialization or TRAC, and I then would kick it off after I do the steady state initialization.

MEMBER KIRCHNER: What I was implying was that you would use RELAP or TRAC to get your initial conditions. No? You actually try and -- you just make assumptions and start.

MR. ESMAILI: We don't make assumptions. We run the steady state initialization. So we just make sure that during the -- you know, this is the decay heat, this is the -- sorry, this is the normal power to the --

MEMBER KIRCHNER: But a LOCA is not a steady state.

MR. ESMAILI: But this is before. We want to -- we will want to make sure that the pressurizer water level is what the FSAR says, the hot leg temperature is what they say. You know, so we compare during the initializations to what -- the values that they are reporting, and from that on we introduce, you know, breaks, et cetera.

CHAIRMAN CORRADINI: So you said something -- I'm sorry I'm going back to this document.

You keep on calling them ISPs. So are all the 20 things under MELCOR assessment against experiments the ISPs?

MR. HUMPHRIES: No. No.

CHAIRMAN CORRADINI: So where are the ISPs amongst the 20?

MR. HUMPHRIES: Where are they?

CHAIRMAN CORRADINI: Because you've got -- you've got -- I'm sorry to do this to you. You've got analytic assessments, which all look very reasonable, seven of them. You've got 20 against experiment, and then you've got six on code version comparisons on physics, oxidation, blah, blah, blah.

What is -- is the ISPs buried somewhere in that grouping?

MR. HUMPHRIES: So like there is the quench ISP, ISP 45. We use that as one of our validations.

CHAIRMAN CORRADINI: So ISP 45. Because I remember that's in the 20 -- the smaller report you showed us, or you sent to us.

MR. HUMPHRIES: Yes. PHEBUS FPT-1, that's one of our validations. There is an ISP on the iodine chemistry.

CHAIRMAN CORRADINI: Okay. So it is potentially a subset of the ones we're talking about here.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: Okay.

MEMBER REMPE: So --

CHAIRMAN CORRADINI: I'm sorry. Just one last thing. So can we get that list?

MR. HUMPHRIES: It should be in that validation report.

CHAIRMAN CORRADINI: Oh, it is? Oh, excuse me. Okay. Excuse me. Okay. Thank you.

MEMBER REMPE: So while we're interrupting you, I'd like to go back to the sub-node or grid thing you're talking about. MAAP has this for containment volumes. Do you have it in MELCOR for your containment volumes, too?

MR. HUMPHRIES: For volumes?

MEMBER REMPE: Yes.

MR. HUMPHRIES: So these are for core cells, for core components.

MEMBER REMPE: Right. But MAAP, does it have a sub-node capability in their containment --

MR. HUMPHRIES: In their volumes.

MEMBER REMPE: -- volumes, yes.

MR. HUMPHRIES: We don't have that.

MEMBER REMPE: You don't do that yet.

MR. HUMPHRIES: No.

MEMBER REMPE: You've not thought it or -- because they claim it helps with stratification. I was just curious.

MR. HUMPHRIES: No. We haven't done that, and I haven't had a compelling reason to do it. I had a very compelling reason with the spent fuel pool because this was physics that we just couldn't capture with a single node. And to be able to represent those experiments, we would have to do nine rings on just, you know, simple geometry.

MEMBER REMPE: Okay.

MR. HUMPHRIES: So it was necessary for that. For stratification, a lot of our validation tests, like the NUPEC I could show you there, we --

MEMBER REMPE: I saw it in the report Mike mentioned, and all that, and you just have not seen a need to do it and --

MR. HUMPHRIES: Yes.

MEMBER REMPE: -- you've compared well with the MELCOR stuff as far as you're concerned.

MR. HUMPHRIES: Right.

MEMBER REMPE: Or the MAAP stuff. I'm sorry. Okay. Thanks.

MR. ESMAILI: Well, I think Larry has a

slide that, you know, it's not only NUPEC. We also compare it to other experiments, like HTR, CBTR for containment analysis. If you have questions about the containment, we have done a number of assessments against containment analysis, so that they show that, you know, with the reasonable number of nodes we can capture what is going on, and depending on the complexity of the -- you know, of the containments.

But like, for example, HTR is highly compartmentalized, whereas CBTR is not. So that guides us how we are nodalizing things, because at the end it's the user who has to choose what type of -- you know, how many nodes. So there is no built-in nodalization in MELCOR as it --

MEMBER REMPE: Thank you.

CHAIRMAN CORRADINI: So I think I've got it, Larry. I'm sorry. So Table 11 on MELCOR assessment studies, those list the ISPs. There's about eight of them. Does that sound approximately right?

MR. HUMPHRIES: It has been a long time since I looked at it, but I would guess it would -- it does have a list of all of the --

CHAIRMAN CORRADINI: Right. Because that's the table I think you must have been referring to.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: Thank you very much.

MR. HUMPHRIES: Okay. I cut back my slides. I'll let you know that also. So this is just a simple representation showing you how you might model something in MELCOR, so I have two control volumes, each with pool and atmosphere. So MELCOR has two fields. They have the models pool and atmosphere. The pool can also have bubbles that are in equilibrium with the pool, and it can have water droplets in the atmosphere or fog in the atmosphere.

You can model non-condensable gases. Here I've got seven flow paths where you can model a bypass, and in this case the bypass opens up when canister fails and then the flow path opens up and you can have relocation or movement of -- or flow of thermal dynamic material.

There are three by two core components, so there's three components in each of these two core cells, and then there's two core cells. And there can be also a quenched and unquenched region in each core component. So you can have two temperatures for those core components.

MEMBER MARCH-LEUBA: And how do you carry like non-condensables, fission products? Are those the property of the node and they go with the flow, or do they bubble out of the flow, or --

MR. HUMPHRIES: So non-condensables, they have simple ideal gas laws that are used to model them.

MEMBER MARCH-LEUBA: So but you don't -- do you dissolve hydrogen in the available water, or do you let it get to saturation and the rest bubbles up or --

MR. HUMPHRIES: There is a simple bubble model, bubble rise model, in MELCOR for calculating the bubbles and the swell within a controlled volume.

MEMBER MARCH-LEUBA: How about iodine? Iodine dissolves in water pretty well.

MR. HUMPHRIES: Yes. There's an iodine chemistry model that --

MEMBER MARCH-LEUBA: Oh. You have --

MR. ESMAILI: I guess non-condensables are not residing in the pool. They can pass through the pool and transfer mass and energy, but they don't reside in the pool.

MEMBER MARCH-LEUBA: Don't they get directly in the pool?

MR. ESMAILI: As they go -- pass through, they can transfer mass and energy, but they end up into the atmosphere. We don't have models for --

MEMBER MARCH-LEUBA: No hold up.

MR. ESMAILI: No hold up in the --

MR. HUMPHRIES: And fission products or radionuclides, those are handled as trace elements. They have no specific heat associated with them. They take on the temperature of the materials, and they are transported with -- and they can be scrubbed and become part of the pool also.

This is a partial list of MELCOR equations. I think we've kind of talked and touched on some of this already, but mass and energy conservation equations, equation of flow path velocity, and MELCOR will linearize the equation state for pressure, iterate on the momentum equation.

Once it's determined that the momentum equation is satisfied, convergence is achieved, then it calculates the mass and energy. So mass and energy is conserved within significant figures of the round off of the machine.

Some characteristics of the MELCOR equations -- the equations are coupled. They are interdependent on one another in many different ways. The conservation equations are written in temporal form, but generally they use time-independent closure laws like heat transfer coefficients that are calculated for time -- based on time-independent --

MEMBER MARCH-LEUBA: Are you familiar with the term "loop seals" on PWR LOCAs for --

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: -- tube that fills up with water?

MR. HUMPHRIES: Yes. Somewhat.

MEMBER MARCH-LEUBA: How do you guys model that? We have been interested in arguments or conversations on that for severe accidents.

MR. HUMPHRIES: You might have --

MR. ESMAILI: I think the only thing we would do is that we just break it out at the point of the loop seal. I don't know whether that picture shows it or not.

CHAIRMAN CORRADINI: Nothing stops them from doing it. I'm not sure you might believe it, but nothing stops them from doing it.

MEMBER MARCH-LEUBA: Page 2 has a loop seal. If you go back a couple more slides. There, you have to blow it up, but --

MR. ESMAILI: Yes. So the --

MEMBER MARCH-LEUBA: You have to talk into the microphone.

MR. ESMAILI: Okay. So on the cold leg, on the horizontal part, when we define our control volumes, so we just break it up into right at the lowest point. So there is -- this part of it is one control volume, and the other one rising to the pump is another control volume.

MEMBER MARCH-LEUBA: Yes. But it prevents the flow of gases through there.

MR. ESMAILI: It prevents the flow of gases through, that's right.

MEMBER MARCH-LEUBA: Until it boils dry, so -- and the only way to clean it is by boiling?

MR. ESMAILI: Is by boiling, right. Or pushing it out of the pump or --

CHAIRMAN CORRADINI: So you asked -- well, I have an answer, but I'm not sure it's right. Remember, MELCOR is a big pot. So if the level of the water gets below a certain -- gets below the top of the pot, then there is a path for the gases to flow. So MELCOR probably, by pure happenstance, may have a better model than TRAC or TRACE, because TRACE or -- I'm sorry, TRACE would --

MR. ESMAILI: Do you have a level on --

CHAIRMAN CORRADINI: -- have a drift flux model that will essentially assume that the vapor is intermixed with the water. MELCOR has a model that as the water level in a volume decreases, appears essentially gas space. And so I could bypass it, if I put in an appropriate junction at the top of the gas space. You could do it. You'd have to know what you're doing to do it, but you could do it.

MR. ESMAILI: Kyle or Casey, are you on the phone?

MEMBER MARCH-LEUBA: The real question I will ask is, how much confidence do you have on that model? Because it does seem to affect a lot on the consequential steam generator tube rupture whether you have a path for how the gas goes through there or not. I mean, whether the seal -- the loop seal clears or not, it may affect the result significantly.

MR. ESMAILI: That's right. I do -- I think most of the time we are talking about just hot leg natural circulation, the one that you saw in Figure 5. In most cases, we don't get these loop seals to clear. At least I have not seen it clear. So we modeled both ways.

So if the loop seal is clear, of course you have a full loop natural circulation. This is actually in some of the newer designs, in like AP1000. You don't even have a loop seal. It's just a straight through.

It's just you always end up with a full loop natural circulation.

MR. ESMAILI: Some of the designs we are reviewing now have a very deep loop seal.

MEMBER MARCH-LEUBA: And some of them, if they have loop seal, yes, the only way to get to that full loop natural circulation is somehow to get rid of that water. So that water, you know, you either have to get rid of it through seal leakage or through boiling of the water, et cetera.

MR. ESMAILI: Yes. Maybe as part of the uncertainty, when you run an uncertainty on your transient, you do it with and without the seal clear.

MEMBER MARCH-LEUBA: Okay.

MR. ESMAILI: I mean, that would be one of the uncertainty terms.

MEMBER KIRCHNER: There isn't anything stopping the user from putting multiple nodes into the cold leg, right?

MR. ESMAILI: No, there is not.

MEMBER KIRCHNER: And that's what you would want to do for the current fleet PWRs, not --

CHAIRMAN CORRADINI: But I think it would go beyond that, Walt. Not only did you put the volumes, but that's where you would put in a junction, and you want to put the junction where it is.

MR. FULLER: This is Ed Fuller. When you get talking about loop seal clearing and unidirectional flow promoting steam generator tube ruptures, you also have to bear in mind that you have to clear a path through the core, too.

So you have to get the water level down low enough so the gases can flow around the -- you know, the periphery down and then through the core. So it's not quite so simple.

MEMBER MARCH-LEUBA: Yes. That's why we use computer codes to -- to calculate it for us.

CHAIRMAN CORRADINI: Yes. You want the code to do that.

MR. HELTON: This is Don Helton, Office of Nuclear Regulatory Research. At the risk of giving Dr. Stetkar and others plenty of rope to hang me with, the issue of modeling loop seal clearing in consequential steam generator tube ruptures has been looked at over the last 20 years using SCDAP RELAP5 for MELCOR, and there have been some comparisons of the two.

And my recollection is that the draft NUREG right now on CSGTR that I think the ACRS is going to have a meeting on in May also has some discussions of the modeling of that within MELCOR.

MEMBER REMPE: And we discussed quite a bit about it last December, and they've got an appendix. There's -- actually, the latest version has added some of the exact things to the main text.

MR. LEE: This is Richard Lee from Research. As Don mentioned, back in the SCDAP RELAP5, which I was in charge at that time, we did a lot of sensitivity studies looking at loop seal occurring. Whether we believe it or not, it is a different matter.

With respect to loop seal, you need to recognize that the connection to the loop seal is -- varies all over the place. So there are no generic calculations that the staff can do that can close this loop seal occurring.

Coming back to the CEs, geometry for the severe accident into steam generator tube rupture, as you can see, the results is that the CE -- because of the way that the hot leg connect to the inner plenum are very close, you have -- the tubes are -- in general, see a much higher temperature than when we compare with Westinghouse type connections that we did 10 years ago.

So it's already high degree of -- of the tube can fail. So if you have a loop seal clear, the case is it will get worse. So it doesn't help to resolve the CE. It just make it worse for the CE geometry.

CHAIRMAN CORRADINI: So will the staff tomorrow when we talk about APR1400?

MEMBER REMPE: It might be a good idea.

MR. LEE: You can ask them.

CHAIRMAN CORRADINI: Do you mean you -- this staff won't join the other staff to help?

MR. LEE: No. We don't have to show up here.

CHAIRMAN CORRADINI: Okay. Fine. It was an invitation; not a requirement. Okay. Go ahead.

MR. HUMPHRIES: Okay. So hydrogen burns within the MELCOR code are calculated within the burn package. And to be able to make these calculations, there are essentially three things that MELCOR calculates.

It determines an ignition criteria, so based on mode fractions of hydrogen and oxygen, it determines whether spontaneous deflagration can occur. You also have limits that are used for igniters, if you have igniters present.

In addition, the code allows the user to be able to override those using control functions for determining when a burn would occur. And I believe that in the Sequoyah run they are using that, but they're -- it's because they have modified the criteria slightly. And I think they will describe that as part of their presentation in June.

Then you calculate a rate of burn, and it's based on the HECTR calculation. And so you determine a burn completeness, the duration of the burn, and then from that MELCOR calculates a rate, and then it will distribute that burn over time steps based on that rate of burning.

And then there are criteria for propagating from one control volume to another control volume.

MEMBER KIRCHNER: So, Larry, may I ask, what is your experience with this? Because when you have numerical techniques like this, then time step and volume dimensions and such sometimes become important. Have you found that there is a recommended -- how should I put it? Nodalization that leads to convergence?

Do you see what I'm getting at? Because you're passing things. Like pick the last bullet, the propagation criteria is dependent on, you know, the next -- the neighbor. And you've got a cutoff, and so it's a go/no-go thing.

I'll just pick a number -- four percent, right? But what if it's 3.9, but then it's 4.1. You know, then it goes and it doesn't. So my question to you is, nodalization and time step such -- do you find issues in convergence for this kind of --

MR. HUMPHRIES: I don't know whether there's issues of convergence, but it becomes an issue of uncertainty, and I believe that they do -- that's one of the things that they vary, and it's part of their uncertainty analysis is they --

CHAIRMAN CORRADINI: Would it be fair to say -- I guess what Walt is asking, too, is, would it be fair to say that -- I was going to say timing. That is I think the way the MELCOR -- at least the way I understand it's organized -- is that once you pick your total volume, you want to slice it up, you could get an odd timing where, if I slice it inordinately, I might get a much more benign calculation than if I wait and I have a big volume and waited, grow, grow, grow, and then have a big --

MEMBER KIRCHNER: Big bang.

CHAIRMAN CORRADINI: Or larger, but yes. I'm sure timing would be affected because they have this -- again, just from doing it, they have an event sequence where you can actually look at how events progress. And on nodalization, you can get slightly different timing of the events.

MEMBER KIRCHNER: Right. But my question there would be, how is the numerical convergence of such a discretized approach to the treatment of the gas burning problem? Do you run a -- let me make something up here in real time. Do you run just a pipe with a combustible gas in it? Do you do kind of a test like that to see if you can get convergence based on a convergent time step?

MR. ESMAILI: I have to go back -- sorry, have to go back and look at this. There are a number of experimental validation. The Nevada test site -- so there has been some. And he --

MEMBER KIRCHNER: I didn't get to study that. Pardon.

MR. ESMAILI: I think it's in Volume 3. Some of it is in Volume 3, and we are talking about deflagrations. So they are not very, very fast, you know, flame speeds that we are talking about. So what the code will do is that if you have a big volume, you allow the flame to propagate to this other volume.

And as Larry mentioned, you know, depending on the energy deposition in that volume, you know, the time step and the code chooses -- trying to choose whether it can advance in time. So that's part of the time stepping.

But even within a single system time step, a flame might not have reached. So if it's initiated here, it might not have reached to the other end of. So the next time step it -- so it is trying to complete that flame that is -- that started in one control volume going all the way to the other end of the control volume, and in the meantime it's depositing energy, correct? Based on that.

And then so -- so it's kind of connected to how the code will choose the time step necessary to make sure that it satisfies this pressure, you know, within one time step to the other time step. Am I answering your question or --

MEMBER KIRCHNER: Sort of. Obviously, it's -- the solver algorithm, then, has to look at the conditions, and then adjust the time step size. But it also could be a function of nodalization.

MR. ESMAILI: That's right. It could be a function of --

MEMBER KIRCHNER: And just my generic -- a general question is one of, how do you -- are you confident that you're getting convergence, or does the nodalization and time step selection result in a significant --

MR. ESMAILI: I think in terms of nodalization we are guided by whatever assessment we have done, and these are the type of things that we carry when we are going to -- so I guess Nevada test site is in in Volume 3? I think there is --

CHAIRMAN CORRADINI: It's test -- experimental benchmark 314 is the Nevada test site burn test.

MEMBER KIRCHNER: I saw it was there, but I didn't have time to dig in.

MEMBER REMPE: So to be a little more basic in the question I think that Walt is asking is, I saw the -- I looked more at the NUPEC one than the Nevada test site one. But basically you've come up with this nodalization scheme and shown how your results match.

But what if you had picked a different -- maybe you did, you tried a bunch of different nodalization schemes and you only documented one. But did somebody at some point try a bunch of different ones and look and see if any of those results changed? Because I didn't find that in the write-up.

MR. ESMAILI: Absolutely. As a matter of fact, there is a contain qualification report, you know, remember. So we -- basically, we started with containment. We're doing containment analysis with contain before we shifted to MELCOR. I don't have the ML number. I will find it for you, but there is a contain qualification report that discusses all these issues, you know, the type of nodalizations, the type of sensitivity to the nodalizations that you use, and so those are documented, or they tell you how to do things in terms of nodalizations in terms of choosing flow paths, et cetera, to actually use a log parameter core to do this type of analysis.

And then when we went to -- there is actually another report when we went to GSI-189, you know, during that -- in terms of, you know, putting igniters for that, there were -- and even during the DCH study, there is a NUREG that we actually reference in this Sequoyah document, that there were many nodalization studies, you know, that looked at, you know, how you want to nodalize, for example, the ice chest, how you want to nodalize the dome, et cetera, and what is the effect of those nodalizations.

So those are all documented. They are -- and what we are doing with MELCOR is just really following what has been done with contain that showed --

CHAIRMAN CORRADINI: I think, Joy, the reference you want is SAN-94-2880. That's the contain assessment of NUPEC.

MEMBER REMPE: Okay. Say it again? I'm not --

CHAIRMAN CORRADINI: SAN-94-2880.

MR. HUMPHRIES: Yes. I think that was the original one Casey did years ago. And there was a lot more detail in those reports. We can't include all those details in the Volume 3 report --

MEMBER REMPE: That's fine.

MR. HUMPHRIES: -- because it's already too big. But we do reference those old reports, and they did a lot of sensitivity studies with those.

CHAIRMAN CORRADINI: It's on page 244 of the Volume 3.

MR. HUMPHRIES: I think in the interest of time I will kind of get ahead. So in the core package, the core package will model conduction, both axial and radial, and then also within a core cell there can be conduction between components also. A component that rests upon another component is an example.

And then convection, heat transfer, from surfaces of components. MELCOR uses a local cell temperature, so, as I mentioned earlier, the CVH nodalization may be coarser than the core cell nodalization.

And if you have steam rising through a forest of fuel rods, that local steam temperature will change as it rises. MELCOR has a model to be able to calculate that local steam temperature, atmosphere temperature.

MELCOR doesn't use a critical Reynolds number to determine laminar or turbulent flow regimes. Instead, it calculates both and then it will take the maximum of the two. The reason for this is it gives the code more stability because you're not changing regimes.

The convective heat transfer from contiguous molten pools is treated separately. There is a model for -- a Stefan model for modeling conduction to a support, and then there's a convection model from the upper pool, upper surface of the pool.

There are also radiation models within MELCOR. There is the simple radiative exchange model that MELCOR uses based on a global radiation exchange factor. As I mentioned, also, we have added a multi-rod model, and there is also a geometric radiation exchange model, which kind of tries to account for the fact that the temperature at the outer surface of the ring is not the same as the average temperature of the ring. And so it tries to calculate that gradient and use that as a basis for radiating from one ring to another.

In MELCOR, there are a lot of different oxidation models or several oxidation models. MELCOR will oxidize Zircaloy and steel by water vapor and by oxygen. We can have oxidation of boron carbide in BWRs, and it models the heat generation as well as the release of hydrogen in the creation of other gases.

MELCOR models two layers, an oxide layer and a metallic layer. And modeling the kinetics is -- by default, it uses an Urbanic-Heidrick model, but there are also other models built in, like the Cathcart-Pawel, Urbanic-Heidrick, and so forth.

Modeling oxidation is probably not that difficult in terms of temperature and reaction rate. The thing that really is challenging is the fact that you have a core that's degrading, and surface areas are changing.

You have material that is candling and draining on other surfaces and freezing up, and that's what makes the oxidation modeling a challenge.

CHAIRMAN CORRADINI: I guess I'm kind of intrigued. Since we -- I think long ago you helped us model CORA-13, why did you pick that one of all of them? Because they did like 37 tests, and CORA-13 kind of pops up all the time. It's a PWR. Is there a BWR equivalent that you guys have used to --

MR. HUMPHRIES: So I picked it because it's an ISP.

CHAIRMAN CORRADINI: Oh, okay. All right. So it's one of your ISPs.

MR. HUMPHRIES: Right.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: I mean, I could also have picked PHEBUS FPT-1, too. MELCOR does really well on PHEBUS FPT-1.

CHAIRMAN CORRADINI: Right. And, sorry, I have a purpose for my questions. So there is none of the CORA tests that have what is an acceptable quench water readdition? You kind of jumped to the later quench tests, I guess they're called, at -- in Germany. Is that just because the older tests didn't do a good job of the reflood?

MR. HUMPHRIES: Well, if you look in the slides at the end, the supplementary slides, I actually have a slide that shows the CORA-13, I think. Don't I? I thought I did.

CHAIRMAN CORRADINI: Oh. So these are more supplementary sides than we were sent.

MR. HUMPHRIES: No. I think you were sent my backup slides.

CHAIRMAN CORRADINI: This looks like more than 72. This looks like 172.

MEMBER MARCH-LEUBA: Are you sure? There were like four packages.

MEMBER KIRCHNER: We had four files.

MEMBER REMPE: Yes. He gave us three sets of viewgraphs from Larry, and then one from --

MR. ESMAILI: It's on Slide 40, if you go to Slide 40, in the first set. Right here. Here we go. It's for the ISP-31.

MR. HUMPHRIES: So this shows what you're talking about, this quench, where MELCOR is not able to capture that sudden rise of hydrogen.

CHAIRMAN CORRADINI: Right. So I guess my question is --

MR. HUMPHRIES: The reason I didn't put it in there is because this is physics that is missing.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: MELCOR is not going to be able to capture that. We suspect that the reason that this happens is because you have a shattering of the oxide layer, and so you now have steam that is able to make it into the metallic layer.

CHAIRMAN CORRADINI: In deference to the

quench test where you might not, and you get a better --

MR. HUMPHRIES: So there we can actually validate the oxidation models. This one, up to that point, we can make use of the validation data. But after that point forward, MELCOR doesn't have a physics model there, so there is no point in comparing it.

CHAIRMAN CORRADINI: Okay. Very good. Okay.

MR. HUMPHRIES: That's why I didn't include it, but it's a good point to make.

MR. ESMAILI: Okay. So the other thing we want to mention here is that when we come back in June, you will see that we are going to be exercising some of these other correlations. And so it's important that -- that's why I think Larry is showing you that, you know, whichever correlation you choose, you are basically on the same line.

There are differences between these different correlations, but not by much. And some of it may be because of the way, you know, candling and other core degradation processes are occurring.

So this is something to keep in mind, that before we went on and looked at these other correlations, we did, you know, comparisons to the experiment to see, you know, whether we are going to see differences in terms of different correlations.

MR. HUMPHRIES: Right.

MEMBER KIRCHNER: Doesn't it suggest there is a bigger question, obviously, how, when you put so many complicated models together, you come up with any uncertainty assessment. But just on this one alone, it suggests you are dealing with an avalanche or a cliff phenomenon. So it really doesn't matter which correlation you use, because I would submit that that -- without doing any statistical analysis, just that spread, any of the correlations work.

MR. HUMPHRIES: Yes. Yes. I agree.

MEMBER KIRCHNER: So, then, what's going on? Are you --

MR. HUMPHRIES: Until the water comes --

MEMBER KIRCHNER: You've just gotten to a cliff.

MR. HUMPHRIES: But that's physics.

MEMBER KIRCHNER: You're at a cliff, and that's why it doesn't matter which correlation you go to. Off it goes. You're oxidizing --

MR. HUMPHRIES: That's right.

MEMBER KIRCHNER: -- at a high rate. Do you see what I'm saying, Mike?

CHAIRMAN CORRADINI: Yes. But I was

going to say, the difference is that 4800 is when the water comes in. So all three of them are overestimating the higher generation. Water comes in, and the data shoots up, and they hang out.

MR. ESMAILI: But, you know, experiments, these are all the different experimental -- you know, we are not talking about uncertainties in the experiments at this point and how the experts were conducted, et cetera. We're just trying to get a sense of, you know, if we are on the right track, at least we can get the trains right.

MR. HUMPHRIES: So I'll talk a little bit about core degradation. MELCOR doesn't have a ballooning model. There is a model for gap release when a temperature criteria is met. It is assumed that the clad ruptures, and the contents of the gap is released. So there isn't a modeling of the change in the flow area that results from ballooning, local changing.

Candling -- MELCOR has a simple candling model. When material reaches the melting point, it can drain on other surfaces, and then transfer heat and freeze up on surfaces. One limitation of this model is that it does it within one time step, so it doesn't have a field that tracks that molten material in motion.

So it will do so all in one time step.

So you could argue that there may be some oxidation that might be missing as it -- as it relocates, but it typically candles very quickly as it moves down to a colder region where it can then freeze up.

MEMBER KIRCHNER: Larry, going back to the first bullet, so you release the fission gases at that juncture. What do you do with the fuel -- the fission gases and fission products and fuel at that point? Do you assume some kinetic rate of release or --

MR. HUMPHRIES: Yes. So they are then limited by a release model based on diffusion of surfaces.

CHAIRMAN CORRADINI: So, I'm sorry, I'm still stuck on water. So in CORA-13, you missed it. In quench, you got it. So does that mean if I turned around and said -- and I won't pick on you guys only; I'll pick on MAAP and MELCOR, since I know about the crosswalk phase 2.

So if I'm going to the crosswalk study, phase 2, which MELCOR and MAAP are being looked at together, and I start asking the questions, "Where can I interdict with water to recover as time marches along?" am I uncertain high, low, or I'm just totally uncertain as to if the models are going to catch when I can actually cover from event as I proceed to more and more damage, more and more damage, and then add water later in time. Do you understand my question? Hossein knows what I'm talking about for the crosswalk.

MR. ESMAILI: Yes. But the rest of it --

CHAIRMAN CORRADINI: Well, I mean, if I understand the crosswalk, the thing that NRC is doing with DOE, together, is you're looking at -- and I thought it was Peach Bottom. I can't remember what it is. It's one of the -- it's either Surry or Peach Bottom. I forget which one it is.

And I thought phase 2 was to essentially look at parametrically adding water at later and later times to look at the ability to show recovery from a damaged core beyond the design base and then how far out before things are unrecoverable. And what I guess I'm asking is, at what point, since you guys are the model developers, do I simply not believe the calculation because I'm not sure if I'm estimating high or low in terms of the effective water addition. Do you see my question?

MR. LEE: Mike, this is Richard from Research. We only have finished crosswalk phase 1 funded by DOE. The phase 2 have --

CHAIRMAN CORRADINI: Hasn't begun yet?

MR. LEE: No.

CHAIRMAN CORRADINI: Oh, okay.

MR. LEE: Hasn't been started.

CHAIRMAN CORRADINI: Oh, it hasn't started. I thought it had started.

MR. LEE: No. I don't know what that phase 2 is. At least we don't know about it.

CHAIRMAN CORRADINI: Okay. Excuse me.

MR. FULLER: This is Ed Fuller from Research again. I don't know about the crosswalk phase 2, but I've done quite a bit MAAP recovery calculations, and in my judgment -- in my opinion -- and it looks pretty strongly held, particularly for the PWR -- if you can get the recovery before relocation of the core molten material to the lower plenum, the chances are really good you're going to recover.

For the BWR, sometimes you can after relocation to the lower portion of the vessel, and sometimes you can't.

CHAIRMAN CORRADINI: So not to tease -- not to pick on you, but at TMI we didn't recover and the water got there before it went to the bottom of the lower plenum.

MR. FULLER: Yes, I know that. And my

view is, we were damn lucky.

CHAIRMAN CORRADINI: Okay. All right.

MR. HUMPHRIES: As part of the slides that you've got there, we also have some slides from some work that was done a number of years ago with IRSN where we looked at an alternate TMI scenario looking at recovery. And so they took a stylized PLI accident --

CHAIRMAN CORRADINI: What was the study? I'm sorry.

MR. ESMAILI: It's on Slide 41.

CHAIRMAN CORRADINI: 41?

MR. ESMAILI: This is just to show how different codes, you know, can do this. This is a CSNI report. I listed the report number on the top.

CHAIRMAN CORRADINI: Oh, at the top. Okay. Thank you.

MR. ESMAILI: Yes. Right there.

CHAIRMAN CORRADINI: Got it.

MR. ESMAILI: And so this was a series of calculations done to the same set of conditions.

MR. HUMPHRIES: Same conditions, so that there was very little room for modelers to make changes to try to simulate the ATMI -- or TMI. We were looking at the same scenario. Several codes were looked at. We essentially had similar results, but there were notable differences in TIP.

CHAIRMAN CORRADINI: So the reason I'm motivated to ask all these questions is Ron and I were at the same meeting last week, and there is a lot of buzz -- I can't come up with a better word -- about accident tolerant fuels, and it seems to me one would want to come up with a series of what-ifs and exercise them on some sort of system tool like this.

And the one that comes to mind -- back is I come back to water -- water injection and system recovery as I proceed out of the design base into beyond the design base, and how far can I go, and when do I stop believing even what I can compute?

I can compute it, but I may not believe it, and that's where I am -- the reason I'm asking the questions. So they did this for TMI?

MR. HUMPHRIES: Yes.

MR. ESMAILI: Okay. Mike, so this was an alternative TMI. So this was a TMI plan, but the accident was well defined. In the previous page, you see it was a loss of main feedwater, and it was a small LOCA in the hot leg. So people knew exactly what they should do. And the idea behind this was that they thought that some of these codes -- you know, ASTEC, ATLEE, DECOL, you know, MELCOR -- they have shown, all of these codes, when you compare them to experimental data, all these --

CHAIRMAN CORRADINI: They're all good.

MR. ESMAILI: -- they're good. But what happens when you scale them up to a reactor application? How well do these codes do? So this was the objective of this exercise, and, as you can see, is that even here there are divergences. You know, most of the code, of course, you know, when you lose cooling, you know, it's going to melt for particular debris. But depending on the code, you know, the --

MR. HUMPHRIES: We all take a different modeling approach.

MR. ESMAILI: Right.

MR. HUMPHRIES: Some of -- one code in particular doesn't have a rod collapse model. So rods are forced to melt and relocate through melting. So you'll see rods hanging at the top of the core; they never collapse completely.

So we all take -- make different choices in our modeling approaches. Between MAAP and MELCOR, there is differences in the way we view the porosity of a crust, whether steam can make it through a crust and cool the debris that's above the crust or not.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: So there's differences in the way we make those impressions, but we still get very similar results. But there are notable differences that can affect things like the total amount of hydrogen that's generated in a calculation.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: So MELCOR has a candling model, and then formation of particular debris. And then as part of MELCOR 1.8.6, we added a molten pool model which then allows a convecting molten pool to form, and has some models for heat transfer from a molten pool to the lower plenum or to the lower vessel head or to a support structure.

This is kind of a sub-grid model that we added to determine the blockage of molten material. So when material candles on surfaces and relocates, depending on the amount of super heat that it has determines how far it can penetrate and where it will eventually freeze on surfaces.

And based on that sub-grid model, we determine when bridging might occur and a blockage might form. And at that point, then molten pool can form above that blockage, and we have a TMI type of geometry with a crust and a particular debris and molten pool.

CHAIRMAN CORRADINI: But -- sorry. But in crosswalk phase 1, gases still can go through it.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: In deference to MAAP, where gases go around.

MR. HUMPHRIES: And part of the reason is is it's hard to envision, in a large reactor core --

CHAIRMAN CORRADINI: I'm not saying what's right. I'm just -- I want to make sure I'm remembering correctly. That's all.

MR. HUMPHRIES: I mean, that's one of those modeling choices that you have to make, and that's one of the choices that we've made because we -- we feel that to be able to -- to completely block the flow of hydrogen would be very difficult to do in a large scale like TMI.

And then this slide treats the molten pool --

CHAIRMAN CORRADINI: Before we go to molten pools, would this be a good time for a break?

MR. HUMPHRIES: This is the last slide, yes.

CHAIRMAN CORRADINI: Oh. You're on the

last slide.

MR. HUMPHRIES: I think so. Yes.

CHAIRMAN CORRADINI: Oh. Excuse me. Go ahead then.

MR. ESMAILI: Delayed by half an hour, but --

MR. HUMPHRIES: So MELCOR has a stratified molten pool model where you can have metallics that are stratified, and you can have partitioning of radionuclides between the oxide and the metallic layer. This way you can capture a focusing effect, if you're looking at in-vessel retention.

One thing that we are looking at is improvements to our lower head model, looking at in-vessel retention. One limitation that we have in MELCOR now is that the steel structure can melt, but that molten steel remains part of the lower head structure and can't become part of the debris or the molten pool. So we're looking at a melting model to allow that molten lower head -- that head to melt and the debris to become part of the core.

MR. ESMAILI: Can I say something about that? I think it -- can I say something? On the last slide, I think this is very important. And because this is going to come up -- no, the previous slide.

We always talked about, you know, how much hydrogen is being generated. I mean, this slide clearly, to me at least, shows that -- what happens. You know, like you have part of the core being relocated, being changed into a different geometry, so every little thing, however you are modeling these things in terms of surface area or the amount of water that is available, is going to affect how much hydrogen you produce.

And these are like sudden events. For example, if you look at going from the top left to the top right, you can see part of the core has collapsed. Okay. So this is a modeling choice because, you know, we have to do -- make these modeling choices because when we run experiments, you know, you close them off, and then at the end of the experiments you open them and see everything is gone, right?

So you have to make some, you know, conceptual picture of what happened going through this. But every decision that you make is going to affect how much surface area you have available, so like you have a molten -- you know, the red line shows a molten pool. That has less surface area than if you have particular debris that is shown by the -- I'm just trying to ask Larry to actually explain a little bit more.

So all of these things are going to affect how much hydrogen you are producing. So it is a very, very difficult --

MR. HUMPHRIES: And we'll see that in the next presentation in particular. I'm going to focus on two particular models that affect hydrogen, and some of the work we've done to be able to assess what effect they have on Sequoyah and the results of Sequoyah. So --

CHAIRMAN CORRADINI: Okay. Sorry I miscounted. So you're done with Part 1 of your three-part trilogy. Okay. So we'll take a break until 3:15.

(Whereupon, the above-entitled matter went off the record at 3:02 p.m. and resumed at 3:16 p.m.)

CHAIRMAN CORRADINI: Okay. We're back in session.

Larry, you're up.

MR. HUMPHRIES: So in this presentation I wanted to focus on a couple of models and changes that we've made to the code recently, and particularly focus on how those changes to the code have affected some of the Sequoyah analyses.

And I want to also point out that some of the changes that they've seen in the recent calculations are partly due to code changes and partly due to input modeling changes. So it's kind of a mix of both, and I will focus my attention today on the code changes that we've made and how those might impact.

So we've recently released MELCOR 2.2, and you should have received a quick look overview report showing a summary of the new modeling capabilities in the code. And in addition to the modeling -- new models that we have added, we have corrected some older models and addressed some user issues, and we tried to, in this quick look, give the user an idea as to what kind of effect these changes might have on a calculation.

It is hard to be able to say how it's going to affect a specific plant calculation because there are so many ways that those can be -- that can be impacted. But what I did was I looked at some simple cases and looked at how it might have affected hydrogen, and also gave kind of a couple of examples of some of our validation tests, specifically hydrogen I think I looked at.

CHAIRMAN CORRADINI: And the thing at the left goes all the way, 6342 is 1.8.6, right?

MR. HUMPHRIES: This one here, 6342?

CHAIRMAN CORRADINI: Yes.

MR. HUMPHRIES: That's not 1.8.6. It's 2.1.

CHAIRMAN CORRADINI: Oh, it's 2.1.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: Oh. And there will even be more of these things.

MR. HUMPHRIES: So the --

CHAIRMAN CORRADINI: Heaven forbid.

MR. HUMPHRIES: -- number of revisions -- let me also explain this. The number of revisions does not necessarily indicate a code change.

CHAIRMAN CORRADINI: But something changed.

MR. HUMPHRIES: Because the repository is used to manage not only the code, but it is used to manage all of our documentations, as well as input decks. And one person at Sandia, when they were doing some uncertainty analyses, they checked in 500 realizations from an uncertainty analysis. And so our number incremented 500 overnight.

CHAIRMAN CORRADINI: Oh. You mean the input models are --

MR. HUMPHRIES: The input models are also managed in subversion.

CHAIRMAN CORRADINI: If they run a

calculation.

MR. HUMPHRIES: Well, not necessarily by calculation, but usually like a base case that they --

CHAIRMAN CORRADINI: I'm sorry. Okay.

MR. HUMPHRIES: -- they keep in the subversion. In this particular case, they added all of their realizations. Every permutation that they included in their --

CHAIRMAN CORRADINI: Okay. So it's not just a code change.

MR. HUMPHRIES: Right. It's not just code change.

CHAIRMAN CORRADINI: When I looked at that, I thought --

MR. HUMPHRIES: Yes. We're not that busy.

CHAIRMAN CORRADINI: A word came to my mind, which I can't go on record --

MR. ESMAILI: You will see that on Slide 5.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: In addition to that quick look report, we updated our manuals also, the user guide and the reference manual. Just to give you some significant code changes, I won't go through all the models that we've added because they really aren't pertinent to Sequoyah, and so -- but these could possibly have some impact.

Some new defaults -- we added a new fuel rod collapse model. Typically, the SOARCA analyses, they have already used a fuel rod collapse model as opposed to what MELCOR was using by default previously was a temperature at failure. So it was a temperature criteria for failing and collapsing fuel rods.

We added this as a default, so that new users would not have this -- this large sensitivity that would result from a temperature failure criteria, because there are times when you have a calculation that just approaches the failure criteria and doesn't quite meet it, and then you can rerun it by making a small change to your calculation, and this time it exceeds that temperature criteria and it becomes very sensitive.

And so by default now, we use this fuel rod collapse model.

MEMBER KIRCHNER: So what's different?

MR. HUMPHRIES: It's a time with temperature base, and I've got a slide here that will address that.

Melt spreading model also was added for the cavity, and then there was a number of code corrections. There was a mass error that associated with the hydroscopic model and the flashing model. I don't think that plays into the Sequoyah calculation because I don't think they were using the flashing model.

And a revised candling model for BWRs and canisters, which doesn't play -- isn't pertinent. But the ones that I would focus on are the corrections to the reflood quench model and the Lipinski dryout model, and they could have impact on hydrogen generation. And so I'll talk about those in this presentation.

One of the things we do is we run some simple test decks to look at the effect of code revision and change to a code and monitor certain metrics. And so, in this case, I'm looking at hydrogen generation as a function of revision number.

And I have a PWR case and a BWR case. These are very, very simple test cases that we ship with MELCOR. The nodalization is very, very fine, or very, very coarse, and a lot of models are activated, and it's very sensitive. And so it will pick up on things like differences in hydrogen.

MEMBER REMPE: So before you leave that slide, I was curious because it kind of looks like whenever there's a change that the next version comes in and that change decreases. And I was thinking about, well, what does this mean here?

And does that -- I mean, when you did this analysis, you did something that you thought was the best approximation of experimental data to implement it in your code, and then now you've made a change and like, if I look at the BWR one, the hydrogen generation went from like 350 to 450 with a code version. And then the next version it came back down to something closer, and is it because you've --

MR. HUMPHRIES: You're very astute. That is the case at times where you make a code correction and you thought that you had the code corrected properly, and then you continue your testing, and then you realize, oh, that was not quite right, and there was something else I needed to do that I missed. And you fix it, and then you get back to where you were before.

So this shows some of that churn that you would get in normal code development that you expect. I mean, it's typical of all codes where you get some of that churn. But these don't represent external releases either. These are internal code releases, and so they're not submitted to users.

And so once we reach a point where we feel that the churn is sufficiently diminished that we're satisfied with our models, then we release it and use it in a study.

MEMBER REMPE: The other thing I thought was bizarre was that whenever the hydrogen went up for the BWR, it seemed to go down for the PWR, and I --

(Laughter.)

MEMBER STETKAR: So, Larry, pertinent to that, I hope that your story here is going to give me confidence that the current down tick for this particular version release for PWRs is -- why do I have confidence that the next time you correct it it ain't going to go back up again?

MR. HUMPHRIES: Well, and I would also add to that --

MEMBER STETKAR: I hope you can give us confidence in that because that's a big deal for what we're going to hear about for Sequoyah SOARCA, right?

MR. HUMPHRIES: Right. I think so. And I think, also, that -- I can't remember what I was going to say next. It will come back to me when I get to it.

MEMBER STETKAR: Okay.

MEMBER MARCH-LEUBA: Going back to Mike's original question on this slide, the number of modifications, this is the revision number in subversion, right?

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: Right. So, but that updates every time you save a file or you --

MR. HUMPHRIES: You've committed.

MEMBER MARCH-LEUBA: -- you commit the file. Do you keep branches like this typical working -- so is this when the branch gets put back into the trunk or --

MR. HUMPHRIES: Yes. So branching occurs on major code development. So if we're adding a new model, we'll create a branch for that person to work on that model.

CHAIRMAN CORRADINI: But then it goes -- but to his point, it goes back in somewhere. Eventually, it loops back in.

MR. HUMPHRIES: Yes. Eventually it loops back in. So, for example --

MEMBER MARCH-LEUBA: That may have been 10,000 lines of code. It counts only as one in the rev number.

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: It is branching. If you are working on the trunk, I can say 20 times a day and I never even reveal the code.

MR. HUMPHRIES: Right. For example, the homologous pump model, this was a new model that was added to the code. And it was a developer; I wanted him to work on a separate branch, and that model should have no impact on MELCOR results.

And so he made a number of revisions to the branch. It is always good to keep that branch up to date and check in your work, and he followed that. And then when it comes time to merge his branch back into the trunk, you have to test it to be able to verify that it makes no impact on the trunk.

CHAIRMAN CORRADINI: Except where a pump is used.

MR. HUMPHRIES: Except on a case where a pump is used, on a homologous pump.

CHAIRMAN CORRADINI: So I guess I'm -- maybe I am more forgiving about uncertainty, but John's worry is if -- if something is of a concern where there is a plus or minus of 50 kilograms, then I'm worried because the uncertainty on 350 is easily plus or minus 20 percent, the way I -- that's my interpretation of this.

It has been 350 plus or minus 50 or more for 3,200 versions. So if I really am worried about some source term that is closer than that, I don't think

I have an answer. I'm highly uncertain within that band. That's how I would answer John.

MEMBER STETKAR: Well, yes. Thanks.

MR. HUMPHRIES: Well, we'll look at --

CHAIRMAN CORRADINI: And if -- then if --

MR. HUMPHRIES: And this isn't capturing modeling uncertainty as part of the Sequoyah analysis. I ought to be capturing that level of uncertainty.

CHAIRMAN CORRADINI: Well, but the other thing I wanted to make sure is I assume something here. This is hydrogen generation from the core, not from plunking into the lower plenum or plunking in --

MR. HUMPHRIES: This is the core.

CHAIRMAN CORRADINI: This is just the core. Because in 1.8.6 there was no hydrogen generation outside of the core, if I remember correctly. When it popped into the lower plenum, it forgot that there was --

MR. HUMPHRIES: You can still have hydrogen generation.

CHAIRMAN CORRADINI: Oh, you did? Okay. Because I thought it flattened out after -- okay. Then I am forgetting. Excuse me. Excuse me.

MR. HUMPHRIES: Okay. So this shows a large change in the results that we saw between an older version of MELCOR, MELCOR 7317, and MELCOR 9321. This case that we're looking at, I am showing the hydrogen generated from oxidation of stainless steel.

The red curve shows the old code version, 7317; the blue one shows the newer version. This is a case where you have intact fuel when you have the accumulators dumping into the pressure vessel. In that case, it's very sensitive to the quenching of the core support plate.

And in the case of the situation on the right, with the configuration on the right, we have accumulators coming in discharging after you've had a safety relief valve that's stuck open and then the core has degraded, and at that point the surface areas are much smaller, and at that point you don't see that quench.

The case on the left where we see these large differences in hydrogen are those types of cases that we would expect to lead to early containment failure. And so they're very important, and it's very important for us to understand why we're getting differences in the hydrogen generated.

MEMBER BALLINGER: So this is for Zircaloy fuel, but stainless steel, other structures; is that what you're saying? Or is it all stainless steel?

MR. HUMPHRIES: This is just a hydrogen that is generated from the stainless steel.

MEMBER BALLINGER: They have already subtracted away all of the other hydrogen.

MR. HUMPHRIES: So it's not included --

MEMBER BALLINGER: Back to the way the other --

MR. HUMPHRIES: It's not included in the inventory from -- of hydrogen generated from --

MEMBER BALLINGER: Which is 350 or some number like -- some number like that. But what if the fuel was stainless steel clad?

CHAIRMAN CORRADINI: Then you'd get a hell of a lot more.

MEMBER BALLINGER: Well, what if the fuel was FeCrAl?

CHAIRMAN CORRADINI: You'd get a hell of a lot more.

MEMBER BALLINGER: You'd get a hell of a lot more.

CHAIRMAN CORRADINI: Well, because if -- I don't mean to answer the question. I'm sorry. But I think your question is more as to, but if it was stainless steel, I think MELCOR's modeling would consider -- you could. Nothing stops you from telling

MELCOR that your cladding -- it doesn't know about criticality, so it may not be critical, but, by God, you can put in stainless steel cladding and watch what would occur. And I would think you'd probably get a lot more hydrogen generation from the stainless steel. It --

MEMBER BALLINGER: Millstone started up with stainless steel cladding.

CHAIRMAN CORRADINI: But nothing stops -- unless -- I can turn to Larry, but I think the flexibility in the tool is such that you could put in stuff. You'd have to be careful how you did it, but nothing stops you from flexibly putting in, with the appropriate oxidation rate laws.

MR. HUMPHRIES: You can change the oxidation or --

CHAIRMAN CORRADINI: Right. With your sensitivity coefficient.

MR. HUMPHRIES: -- sensitivity coefficients, yes.

MR. ESMAILI: I just want to -- I don't think you should extrapolate what happens for other cases because this is one realization. So we just want to make sure that this is one realization in the SOARCA.

MEMBER KIRCHNER: Can we go through this

again, though? You lost me. Are these two different accident sequences?

MR. HUMPHRIES: These curves here are for one accident sequence. This is --

MR. ESMAILI: Okay. So this one on the left-hand side that you see, this was realization 225, one of the original realizations that we did. So what you see is that in this -- in this case, up until the time of the hot leg failure, there was intact fuel. So the fuel did not fail. It did not form a debris bed.

And so when the hot leg failed, you can see that the accumulator injection, you see water has come up to half of the core. Okay?

So last year in MELCOR 2.1, which is the red line, we were producing a lot more hydrogen because we were not properly quenching old steel structures. And now with the revised quench model, when we are quenching correctly, we are producing less hydrogen.

But this is not -- this is what happens after -- you know, after you have -- after hot leg failure. So you have already -- this is always stainless steel. We have produced hydrogen from --

CHAIRMAN CORRADINI: But it's you guys' fault that you put it up there, so explain by proper --

MR. HUMPHRIES: I'm going to actually have --

CHAIRMAN CORRADINI: -- and improper quenching.

MR. HUMPHRIES: Okay.

CHAIRMAN CORRADINI: I think that's what -- Walt is going to go to that.

MR. HUMPHRIES: If you'll just indulge me for the next couple of slides, because that's what I wanted to show in these next couple of slides is this one advances the question. What's causing this difference in these two oxidation curves? Why are we getting more -- less hydrogen now than we did with an older code version? The next slides I'd like to answer that.

MEMBER REMPE: Just to further distract you, when I saw Slide 4 where you say "corrections to reflood quench model," I thought you were talking about the fuel. But you're talking about the fuel and the steel --

MR. HUMPHRIES: All components.

MEMBER REMPE: -- the whole -- everything. Thank you. Thank you.

MR. ESMAILI: And the other thing is that what you see on the right-hand side where it says "debris bed," where the core has collapsed and everything, that one, it does not correspond to any of those lines in the figures. That one we just put in there.

MEMBER KIRCHNER: What is it doing up there then? That's what --

MR. ESMAILI: We just wanted to point out -- yes, yes, yes. That's what -- just to confuse you.

(Simultaneous speaking.)

MR. ESMAILI: Well, let me explain this. So this one is -- this one is just there to show that if the core is not intact at that time, if it's in the debris bed form, whether you run it with the old version of MELCOR or the new version of MELCOR, we are not going to get a difference, because we don't have much surface area, because the core already has collapsed and it's in that form. I'll surely not put that one in the figure, but --

MEMBER MARCH-LEUBA: You could have an extra line with the results for that one.

MR. ESMAILI: That's right. It is going to be -- it's going to be documented as part of the SOARCA, but we just wanted to let you know that this is -- let me actually go online with Kyle or Casey. Can you hear us?

MR. WAGNER: Yes.

MR. ESMAILI: Okay. Do you want to add anything, Casey?

MR. WAGNER: Yes. I think you've clarified what I wanted to say, in that that second vessel picture probably shouldn't be on that graph.

(Laughter.)

MR. HUMPHRIES: The majority rules.

MEMBER BALLINGER: Yes. Where I come, that's letting your alligator mouth overload your humming bird something.

MEMBER REMPE: Casey, you need to say your full name for the transcript. Sorry.

MR. WAGNER: This is Casey Wagner.

MEMBER STETKAR: And your affiliation?

MR. WAGNER: My affiliation is Dakota, LLC.

MR. HUMPHRIES: Okay. So this is showing an impact of a code change on hydrogen generation.

MEMBER KIRCHNER: Specifically, what is the code change?

MR. HUMPHRIES: Well, that's what I want to talk about next. That's the question is: what is the code change that led to this? And we looked at possible candidates from this previous slide, and the ones that appear to be most likely are changes that we made to the quench model, and changes that we made to the Lipinski model, the dryout model.

And so I want to go through both of those models and talk about the changes that they have on hydrogen generation.

There are also changes to the modeling in Sequoyah that also impact hydrogen, and also impact the effect of the hydrogen that is being calculated. And one of the things that is important in hydrogen is the amount of hydrogen that makes it to the containment, regardless of how much is generated internally in the core and how much of it makes it into the containment dome.

And for a deflagration to occur, and possible containment failure, Kyle has looked at this -- Kyle Ross has looked at this and found that 150 kilograms of hydrogen has to make it to the containment where 375 kilograms is generated in vessel. And for this to happen, a pressurizer safety relief valve needs to fail to close in order to vent that hydrogen to the containment. And the lower flammability limit for hydrogen needs to be greater than five percent.

And so small numbers of early failures in the recent calculations is due to smaller likelihood of safety valve failing to close. So they've changed the way they've sampled the failure of a safety valve because of changes in interpretations of the data from the plant. And so those are more impactful on the amount of hydrogen that makes it to the containment than the actual source of containment within the pressure vessel.

MR. ESMAILI: So I just want to emphasize this point, that what you saw in the previous picture that shows there is like 200 kilograms of hydrogen being generated from stainless steel vessels 50 kilograms from the new version, all of these things are happening after you have hot leg failure and in a few hours after that.

So these are things that are happening after you have had the potential for a hydrogen deflagration. So all the code changes that he has made, that's why it says that the reduction in hydrogen generating vessels, use of quotients is not as important as model changes, is because it is affecting what is happening afterwards. Okay? After you had the hot leg failure, after you have accumulated dumping gain, and after you have those extra hydrogen.

By the time that you have the hot leg failure, and even before that, you have potential for hydrogen combustion. So it's more driven by how much you are releasing those hydrogen that is being generated up until the time of, you know, RCS breach, that makes it to the dome rather than things are being affected by the quench model.

CHAIRMAN CORRADINI: Okay. I thought I had you, but you lost me.

MR. ESMAILI: Okay. So, in that case, I'm going to ask, Kyle, can you explain what I just said, if you disagree?

MR. ROSS: Yes. This is Kyle Ross with Sandia Labs. First, I wasn't quick enough on my mute button here, but on that slide that shows the increased stainless steel produced hydrogen, I don't think it's particular to stainless steel. Stainless steel just happened to be what's there, what's available to oxidize at the time that this happens.

But it could have been -- you know, if there was zirc around, you could also see the increased hydrogen generation. It's not specific to material type. It's just specific to, you know, the metal that is available, if that makes sense.

CHAIRMAN CORRADINI: Okay.

MR. ROSS: And then on the hydrogen burn being large enough to fail containment or not, what shows to be real important is how much hydrogen is in containment when you get the initial burn. There's the first burn and the accident, and so -- so the amount of hydrogen that is vented from the RCS to containment by the time you get that first burn is real -- is a critical thing. And that's -- this increased hydrogen generation that we're seeing with the -- or decrease in hydrogen generation we're seeing with the new code, that's coming after this first burn happens.

So it's not directly adding to what's available in this first burn that's so critical to containment.

CHAIRMAN CORRADINI: I'm sorry, Kyle, but you confirmed what Hossein said, but I'm still not -- I'm still not catching the significance. I apologize. I'm not getting it.

So let me repeat it back to you, so maybe we get closer. You're saying timing is important, and this difference in hydrogen production is after the fact of the first burn, which occurs due to safety valve opening and closing prior to the RCS essentially failing open and accumulators dumping. That's what I thought you said.

MR. ROSS: Yes. That's right.

CHAIRMAN CORRADINI: Okay.

MR. ESMAILI: So, in other words, whatever code changes he has made that --

CHAIRMAN CORRADINI: Don't change the signature of the accident up to this point.

MR. ESMAILI: Up to that time.

CHAIRMAN CORRADINI: Okay.

MR. ESMAILI: Up to that time, because he only changed the code -- the reflood model, that is when the accumulators come in. But most of the cases where we have the first burn, these are occurring before that time. So that's what -- that's why he's saying that there is --

CHAIRMAN CORRADINI: It's an interesting way to show how that's important.

MR. ESMAILI: Yes. So I think we can go over this, you know, in June a little bit more, but this is important to point out, that the code changes from last year to this year is affecting the reflood, the quench model. And this reflood quench model does not come into play until you actually have your first burn and you actually have failed the RCS, and you start injecting --

CHAIRMAN CORRADINI: So let me say it to you differently. So if I were to do a LOCA, it would affect it.

MR. HUMPHRIES: There's still a difference in hydrogen.

CHAIRMAN CORRADINI: Yes. Or if I had a LOCA and I didn't get the ECC in soon enough and I delayed it, it would affect it even more because I --

MR. ESMAILI: Yes. It -- yes, yes. Because those -- that red line that you saw is that -- the core components, whatever it is, it's pretty hot. When the water comes in, it doesn't quench it, and that's what he corrected.

MR. HUMPHRIES: So there's still a change in results, a change in the hydrogen that is being generated because of changes to a model, a code change. And so I want to address what models have been -- have been modified and how they can impact hydrogen.

CHAIRMAN CORRADINI: I got it. Thank you.

MR. ESMAILI: It's not as important for --

MR. HUMPHRIES: But as far as Sequoyah, this is probably more important than the issues that I'm going to talk about.

MEMBER KIRCHNER: That doesn't give me a lot of confidence. Put the Sequoyah results aside for a moment. You've got a very large change in hydrogen generation. So are you going to talk about the model change and why you're confident the new model --

MR. HUMPHRIES: I just really intend to talk about the model changes.

MEMBER KIRCHNER: -- more physical result.

MR. HUMPHRIES: Right.

MEMBER KIRCHNER: And take Sequoyah out of it. Yes. I think I get it, yes. If it comes later, you already had the first burn, so it doesn't -- it's not as critical. But that's an extremely divergent result.

MEMBER MARCH-LEUBA: What he's saying is one of them quenches; the other one doesn't quench.

MR. ESMAILI: That's right. So for one of them it was like sitting at 1500 K. The other one, as soon as the accumulator came in, quenched to whatever the saturation temperature was. And so whatever we were doing before was we were producing more hydrogen versus less hydrogen now.

MEMBER BALLINGER: But I think what Walt is saying is, how do you know which one is right?

MR. HUMPHRIES: That's what I'd like to talk about.

MEMBER BALLINGER: Okay.

MR. ESMAILI: What we are doing right now is right.

CHAIRMAN CORRADINI: They have just simply motivated the heck out of us.

MR. HUMPHRIES: But I think you'll understand when I get to it. I hope. Okay.

MEMBER KIRCHNER: I would, in the future, put the model improvement first, and then the results because it --

CHAIRMAN CORRADINI: Yes. But you haven't been on the committee long enough. If they did that, we would want to see the results first. We would just torture them anyway.

(Laughter.)

MEMBER KIRCHNER: I thought we were hearing that in June.

CHAIRMAN CORRADINI: No, no, no. I'm just saying I know -- I know for as long as I've been here that if they do it A, and then B, we want B first. Whatever A and B are.

(Laughter.)

MR. HUMPHRIES: Okay. So we added a new fuel rod collapse model. It's a time at temperature model. It's a model that was implemented previously, but only experienced users typically took advantage of it. So we added a default model that a new user could use that is based on some results from VERCORS and fitting curves to the VERCORS tests.

CHAIRMAN CORRADINI: But it is physically -- it is there for the user if they're sophisticated to use it in 2.1.

MR. HUMPHRIES: It has always been there. It was in 1.8.6, yes. Yes.

CHAIRMAN CORRADINI: Okay. So a time at temperature model.

MR. HUMPHRIES: So it's a time at temperature model using a damage function, and the coefficients are fit to data from VERCORS.

CHAIRMAN CORRADINI: So, I'm sorry, but now you've got me interested. For SOARCA, Surry, 1.8.6 was used. SOARCA, sensitivity -- or, sorry, excuse me, uncertainty, 2.1 was used. Was this used in both of them?

MR. HUMPHRIES: This particular model? It's slightly different because this -- this study was recently done where they fit these curves. And so it is slightly different.

CHAIRMAN CORRADINI: Does that lead one to ask the question --

MR. ESMAILI: Can I confirm with that?

CHAIRMAN CORRADINI: Yes.

MR. ESMAILI: Okay. Let me just confirm, Kyle or Casey, I think it's -- this time at temperature was already in 1.8.6 that you used for the original SOARCA, correct?

MR. WAGNER: Yes. And in 2.1, Surry UA, we sampled. We sampled the shape of this curve.

MR. ESMAILI: So it was always there. You just had to specify that there is --

CHAIRMAN CORRADINI: Okay. But to get to Kyle, I want to make sure I understand Kyle, that in SOARCA, because you guys had an Appendix A in some of -- one of the reports -- I get so confused -- for Surry, and you showed 2.1 versus 1.8.6, this -- the internal core -- the core sell model for fuel rod collapse was buried in that already.

MR. ESMAILI: Yes.

MR. HUMPHRIES: Yes.

CHAIRMAN CORRADINI: Okay. Okay.

MR. HUMPHRIES: For the Sequoyah UA, they are also sampling the distribution. They are not using the time at temperature model, but they're sampling a temperature for failure, just as a means of convenience for replicating this time at temperature.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: Okay. So this is kind of

an illustration of the reflood quench model. We made a lot of changes to the reflood quench model, but I don't want to characterize them as model changes, because they are mostly corrections to an existing model that we had in there.

And some of them are more subtle than others, but they have impact on a calculation. We found in doing some other work where there were cases where the quench front would get stuck in a nodalization scheme, where it was trying to pass from one core cell to another and it couldn't make that pass. That was important. That's what I'll point out as being most important.

MEMBER BALLINGER: So it just sat there and cooked.

MR. HUMPHRIES: It just sat there and couldn't advance to the next cell.

MEMBER BALLINGER: Well, that's just a plain, old-fashioned error.

MR. HUMPHRIES: It's a plain, old-fashioned error, yes. But it doesn't show up on every calculation. It shows up under specific conditions.

MEMBER BALLINGER: So that's the worst kind of plain, old-fashioned error.

MR. HUMPHRIES: It is kind of a risk.

CHAIRMAN CORRADINI: So a boil down, you wouldn't see it; but a reflood, you'd see it.

MR. HUMPHRIES: A reflood, you could see it.

CHAIRMAN CORRADINI: So station blackouts, you'd never see it. I'm asking.

MR. HUMPHRIES: Probably not. I don't know. This is one of those things, unless you're looking for the quench front, you wouldn't see it.

CHAIRMAN CORRADINI: I see. But let me it differently. So if I had a station blackout and -- with SOARCA, the station blackout occurs, I have -- the steam generator boils dry. I repressurize. I sit there; I pump -- I punch a hole in the hot leg; it depressurizes; accumulators dump; this would come in.

MR. HUMPHRIES: Possibly. Possibly, yes.

CHAIRMAN CORRADINI: Okay.

MEMBER BALLINGER: But you would never know it.

MR. HUMPHRIES: Not unless you were looking at the quench front. If you were looking at the quench front, you would notice there was a discrepancy.

CHAIRMAN CORRADINI: But would I see a surge in the hydrogen unphysically?

MEMBER BALLINGER: That's what I'm trying to get at. How -- if you go merrily along and accept the results, with no way of knowing that there's something odd, it's not a very good thing.

MR. HUMPHRIES: Well, you wouldn't -- I mean, it wouldn't be unphysical. Because you'd have hot temperatures, you would expect it to oxidize, right? It's just that it shouldn't be that hot because it didn't quench properly.

CHAIRMAN CORRADINI: Okay.

MEMBER KIRCHNER: Then, in this model Larry, how do you avoid the problems with nodalization in the axial direction? Do you do a separate side calculation of mass that you think is liquid and then get the quench front location and velocity from that, independent of the nodalization?

MR. HUMPHRIES: So the quench front is calculated from a correlation. So it's a velocity that is calculated from a PCLT number and --

CHAIRMAN CORRADINI: This is a FIN calculation from long, long, many moons ago, the Japanese paper from long ago; is it not?

MR. HUMPHRIES: This was implemented --

MEMBER KIRCHNER: No, that's Dua and Tien. That's a long time ago.

CHAIRMAN CORRADINI: It came from essentially a FIN, where I have a film coming up and it's cooling ahead of it, and I prescribe a temperature and I watch the water advance. If I --

MR. HUMPHRIES: It was implemented in MELCOR 1.8.5 actually, at the tail end of the MELCOR 1.8.5 development around the year 2000. It has been in there for a while. It's based on Dua and Tien's model for the -- but then there are a lot of conditions where it tests to determine whether that quench front can advance from one core cell to another. And we changed that in the recent -- and I have a slide where I talk about that.

Some of the observations on the model is that all of the thermal energy associated with the change in temperature across the quench front is -- was transferred directly to the vaporization of the liquid water. We don't believe that to be exactly right. We would suspect that some of it would be transferred to the pool as bubbles that rise through the pool.

So we've modified that slightly so that we partition that energy so that a fraction of it goes to the pool rather than to the steam. The thermal --

MEMBER KIRCHNER: But once you do that, then you'll get a swell. So are you tracking somewhere else a swell?

MR. HUMPHRIES: We are tracking a swell using a simple bubble rise model.

MEMBER KIRCHNER: Okay.

MR. HUMPHRIES: The thermal capacitance of the core components is very, very large compared to the water, and so to quench the core components you can create a lot of steam, and so that can lead to sensitivities.

And we were running into some issues where the code would drop time steps and run very poorly because it was trying to put too much heat into the production of steam. And so that was one of the first motivations we had looking at this quench model was to try to improve the code performance because it would tend to thrash on time step when it got into these situations.

MR. ESMAILI: So right now the problem is really aggravated because the way we are applying this is for accumulator dump, which actually dumps a lot of water in a very, very short time. And so, you know, we don't see these when we are doing the --

MEMBER KIRCHNER: That's the whole

problem with control volume approach, to have a solution to begin with. You're assuming things happen very slowly. Once you dump things in quickly, this is going to create all kinds of problems for this.

MR. ESMAILI: Right. And all of our experimental validations that Larry is going to talk about is under controlled conditions where you bring in water, it's actually -- you know, you can measure how it goes, and this is just like a really, really fast event.

MR. HUMPHRIES: Because the quench velocity is based on the steady conditions, it doesn't -- you can have a case where the quench velocity might be changing very rapidly. There is also a case where the quench velocity catches up with the water level, and you could have it overshoot the water level. And so that was another thing that we looked at that was causing problems with our numerics.

CHAIRMAN CORRADINI: Just for the sake of -- I looked back. For the SOARCA -- unless I misfound it. For the SOARCA calculation -- now I lost it. Shoot. Failure -- the event failure for SOARCA for the loop or for the pre-rupture of the hot leg is about three hours and 45 minutes, whereas you start getting hydrogen generation before that. You start coming up on the curve before that.

MR. ESMAILI: Yes. That's what we were saying is that -- is that by the time you get to the hot leg failure, you produce a lot of this hydrogen, and that was what Slide 7 was meant to convey is that whatever code changes it was doing, this was affecting things after 3:45. You are talking about Surry, Appendix A in Surry, right?

CHAIRMAN CORRADINI: I happen to have the event table in front of me, so I don't know where it's from.

MR. ESMAILI: Is it the same?

CHAIRMAN CORRADINI: Yes. It's Surry for SOARCA.

MR. ESMAILI: Okay. So, yes, but the actual hydrogen production happens. So by that time, you actually had your hydrogen combustion in Sequoyah.

CHAIRMAN CORRADINI: Okay. I'm only focusing -- I'm sorry, I apologize. I'm only focusing on the quench model about Walt's point about where it takes off. But it starts taking off before the accumulators dump, because first I have the hot leg failure, depressurize, and the accumulators dump about less than a minute later.

And then you -- so you see the hydrogen

coming up in the calculation. And then a few minutes later, then it goes up like gangbusters. I was thinking of a different word, but a lot, right when the accumulators dump, which would essentially mimic the -- so I'd be curious, if you redid this for SOARCA base case, what you would get for the quench on the accumulator dump. That's what I'm asking to --

MR. ESMAILI: We're going to do that.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: So this slide summarizes two of the changes that were made to the quench front model. One of them was we do a temporal relaxation on the quench front velocity, so that the rate of change of the quench velocity is limited. And then we drive the quench velocity to zero as it approaches the pool surface. And both of these corrections were done in order to improve the code performance.

I don't think either of these have any effect on the hydrogen that we're getting from steel. In fact, I've changed these, and I don't see any changes in the hydrogen that's generated from steel.

There were a lot of different changes to the quench front, but these didn't play into that. The important changes were the corrections that we made to allow the quench front to advance from one core cell to another because it wasn't properly quenching a component.

So one of the things we looked at was ISP-45, the Quench 6 experiment. So here is a depiction of the quench experiment. In this facility, they can either do top quenching or bottom quenching. This experiment was done in -- as a bottom quenched test. The fuel rods were electrically heated, and they were oxidized to -- at 1500 Kelvin.

There was a pre-oxidation, and then at about 71, 79 seconds, reflood begins. And I wanted to show you some of our validation of that experiment, both before and after the changes that we've made to the quench model.

So in this depiction, I have two curves that are plotted. The red curve is the old version of MELCOR's version -- Revision 6342, and the blue curve is Revision 9641. And right now they are sitting at a time just before reflood, and so on this plot I show the clad temperature. This is an axial temperature profile, so at the bottom here it's at quench temperatures. And then there's a peak at about one meter, and --

CHAIRMAN CORRADINI: Did you say this and I forgot? What are you assuming in the simple model as the quench temperature?

MR. HUMPHRIES: I'm sorry?

CHAIRMAN CORRADINI: Well, you don't have to go back, but I thought in Tien's model you pick a temperature when I change heat transfer coefficients, and that's specified in the model; is it -- or am I misremembering?

MR. HUMPHRIES: No. The model predicts the velocity of the quench.

CHAIRMAN CORRADINI: But you have to --

MEMBER MARCH-LEUBA: It's not a mean model. I mean, he calculates the velocity of the wet front.

CHAIRMAN CORRADINI: But I have to switch heat transfer coefficients, and that's based on the temperature.

MEMBER MARCH-LEUBA: No, it's based on whether it is wet or not.

CHAIRMAN CORRADINI: Which is based on the temperature.

MEMBER MARCH-LEUBA: No, it's based on where the front is.

CHAIRMAN CORRADINI: Which is -- again, I only advance it if I fall below a temperature because I have FIN cooling; don't I?

MEMBER MARCH-LEUBA: This is going to move at one centimeter per second.

CHAIRMAN CORRADINI: Oh.

MEMBER MARCH-LEUBA: That's the correlation, right?

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: This is the way TRAC used to do it.

CHAIRMAN CORRADINI: So the velocity is not computed; it's input?

MEMBER MARCH-LEUBA: Velocity --

MR. HUMPHRIES: No. Velocity is determine from the BO number.

MEMBER MARCH-LEUBA: The velocity is a correlation -- the output to the correlation.

MR. HUMPHRIES: So it's an interpolation between two relationships for the BO number.

MEMBER MARCH-LEUBA: That's a complication, but it --

CHAIRMAN CORRADINI: What's Thot and Tmax? I'm sorry.

MR. HUMPHRIES: Thot is the -- so there's a hot temperature. This is the unquenched temperature of the component.

CHAIRMAN CORRADINI: Yes?

MR. HUMPHRIES: This is the quenched temperature of the component.

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: And they transfer hear to the atmosphere or to the pool.

CHAIRMAN CORRADINI: I got it.

MR. HUMPHRIES: And there is a heat transfer coefficient. That's a sensitivity coefficient.

CHAIRMAN CORRADINI: Right.

MR. HUMPHRIES: And MELCOR is using the pool temperature here, and then the quench front is determined on the velocity. So the movement of the quench front is based on that velocity that is determined from the correlation.

CHAIRMAN CORRADINI: But the correlation -- that's why I was going back to the formula. I wanted to know what Tmax was versus -- Thot I got is the hot stuff that -- it's coming in. Tsat is the saturation temperature of the pool. What's Tmax? There's a Tmax in there. That's why I thought was a prescribed temperature at the change point.

MR. HUMPHRIES: Tmax.

CHAIRMAN CORRADINI: When I give my students this problem, I give them a temperature, and you can back compute the velocity. It's a FIN problem.

MR. HUMPHRIES: Yes. I don't recall what the Tmax is --

CHAIRMAN CORRADINI: Okay.

MR. HUMPHRIES: -- associated with it.

CHAIRMAN CORRADINI: Because my next would be, you know, I noodle with that; how much do I change it?

MR. HUMPHRIES: Yes. And we haven't noodled it -- noodled with it.

CHAIRMAN CORRADINI: All right. Fine.

MR. HUMPHRIES: It's based on the original default that was used, but the original default was based on this quench test.

CHAIRMAN CORRADINI: Okay. That's fine.

MR. HUMPHRIES: That's when it was --

CHAIRMAN CORRADINI: Okay. Sorry. Don't make fun of me.

MR. HUMPHRIES: Okay. So clad temperature on the left, atmosphere temperature on the right, and the middle diagram shows a stacked series of control volumes and the water level is tracked on here. So start that.

And the symbols represent temperatures from thermocouples. So you can see water started to enter here. The red is team. The blue and the green are water.

Initially, MELCOR can't keep up with the quench. There is probably precursor heating. It's a very violent situation when water comes in the bottom, and you would expect that there may be some heating, precursor heating.

MR. ESMAILI: Okay. So the Tmax, Mike, just looking at the reference manual, it's defined as the maximum temperature against which a quench front can progress. And it's equal to the saturation temperature plus some delta T, but delta T is user specified.

CHAIRMAN CORRADINI: Okay. So put in homogeneous inflation, and I'll believe it.

MR. ESMAILI: Right.

MR. HUMPHRIES: But there's a default, isn't there?

MR. ESMAILI: It's in a default. It's a sensitivity coefficient.

CHAIRMAN CORRADINI: Okay.

MR. ESMAILI: So the user has to specify.

CHAIRMAN CORRADINI: Specify something. Right. Okay.

MR. HUMPHRIES: So MELCOR tended to lag

slightly behind the quench front, but it did a reasonable job of tracking the quench. If I look --

MEMBER MARCH-LEUBA: Tell me, what are the blue and red lines?

MR. HUMPHRIES: The blue line is showing the latest code revision. The red line shows the oldest -- older code revision.

MEMBER MARCH-LEUBA: So what I conclude on that, that you wasted your time making the revision because it didn't change anything?

MR. HUMPHRIES: Didn't change the temperatures. So as far as the quench model, there is very minimal changes that have been made to the actual physics in the model. It is more error corrections that we have made.

MEMBER KIRCHNER: Let me ask a question now. I assume these are -- the steps are thermocouple measurements or the nodalization?

MR. HUMPHRIES: Those are nodalization.

MEMBER KIRCHNER: Do you use this nodalization for an actual calculation of a core?

MR. HUMPHRIES: Probably not quite this fine, no.

MEMBER KIRCHNER: By a lot, right?

MR. HUMPHRIES: I don't know.

MEMBER KIRCHNER: So now would you run this test with a typical core axial nodalization and see how it reproduces the test results?

MR. HUMPHRIES: Yes. And that's one of the things that I want to do. We did also look at the control volume nodalization. I changed the control volumes from a stacked series of control volumes to a single control volume, and essentially got the same results. There was no difference.

But it's more important to capture the local temperature in the fuel rod because that dictates the quench.

MEMBER KIRCHNER: But you started your calculation with the initial steady state conditions, right?

MR. HUMPHRIES: I started it back, yes, at initial steady state conditions.

MEMBER KIRCHNER: Well, that won't happen in the dynamic, the actual SOARCA, or other calculations. You'll have to come up with those.

CHAIR CORRADINI: I counted 25 nodes or --

MEMBER KIRCHNER: What's a typical axial nodalization in the core? 15 maybe?

SPEAKER: Yes, 15.

CHAIR CORRADINI: It's not that much

different.

MEMBER KIRCHNER: Okay. That's not too bad.

MR. ESMAILI: But also, this also shows you why we cannot catch this, you know. When you run against experiments, you see that results do not change that much, because these are still small-scale experiments.

It's only when you scale up, right, to the -- to the reactor application that you see, you know, some of these errors that --

MEMBER MARCH-LEUBA: Okay. So, what you're saying is in -- for other components, there is a difference between 6342 and 9641. Because here, there is no difference.

MR. HUMPHRIES: There's no difference.

MEMBER MARCH-LEUBA: There's no difference. All right.

MR. HUMPHRIES: There's no difference, but this doesn't include complicating effects like candling of material and refreezing on surfaces.

MEMBER MARCH-LEUBA: Okay. So, all those components like stainless steel components.

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: But you will see a

difference.

MR. ESMAILI: Right. So, we cannot catch this here, but we are going to catch it when we ---

MR. HUMPHRIES: Looking at the total oxidation that's generated, I compared MELCOR 186, MELCOR 2.1 and the data, and they all looked very good.

Sometimes people tend to use that total oxidation as a metric for determining whether you captured the quench, but I did a calculation in this slide where I completely disabled the quench model and ran it on the quench test to see what kind of hydrogen I got, and it was about the same.

About the same, because what's important is whether you get this peak temperature right. If you get the peak temperature right, you get the amount of -- the hydrogen and the oxidation right.

So, in this plot, I show clad temperature again only -- and blue is the latest calculation, and red is a calculation I've run where I've disabled the quench model completely.

On the right, I also show the oxidation layer. In the symbols, I show the final oxidation layer that was measured on this axial profile. And in the blue, I show what's calculated by the code.

MEMBER KIRCHNER: I think it would be

worthwhile to do a study of nodalization.

MR. HUMPHRIES: Yes.

MEMBER KIRCHNER: Because you've got 20 plus nodes over half the length of a core. A full core is four meters, right -- or three plus meters.

MR. HUMPHRIES: You can see here where there's -- the quench in the red curve is not -- there's no quench calculated, but the oxidation level -- I mean, the oxidation looks about the same.

MEMBER KIRCHNER: Yes.

MEMBER MARCH-LEUBA: Yes. That's because all the oxidation happened before --

MEMBER KIRCHNER: All happening at the hot point.

MEMBER MARCH-LEUBA: Well, it happened before you quenched.

MEMBER KIRCHNER: Well, yes. The pre-oxidation was there before, yes.

MEMBER KIRCHNER: All right.

MEMBER MARCH-LEUBA: So, what's cooling the clad if there is no quench?

MR. HUMPHRIES: Well, there's still heat transfer. There's just one temperature. It's not a -- it doesn't have a hot temperature and a cold temperature.

It's got one temperature for the clad. And then based on the fraction that's exposed to the atmosphere, it uses the heat transfer coefficient for the --

MEMBER MARCH-LEUBA: So, you're using the steam cooling -- the steam --

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: -- coefficient to the cold water that you are quenching with. You're not failing to quench.

MR. HUMPHRIES: Right. I'm using the water boiling models down in the pool, and I'm using the steam models above the pool level.

MR. ESMAILI: Let me just confirm that, Kyle, the number of actual nodes that we are using for plant calculation is, what?

I think it's about maybe -- can you hear me, Kyle?

MR. ROSS: Yes. It's there on one-foot lengths of 12.

MR. ESMAILI: 12. So, this is the active fuel -- this is 12 in the active fuel range, right?

MEMBER MARCH-LEUBA: Yes. That's the number.

MR. HUMPHRIES: This slide shows the

calculation of -- over time showing the timestep that MELCOR uses as a function of time in the calculation.

CHAIR CORRADINI: That's the key thing you're changing.

MR. HUMPHRIES: That's the key thing that we're -- by changing the relaxation, we've eliminated this numerical thrashing that was a problem.

CHAIR CORRADINI: So, you probably would have -- you probably would expect not a big difference in result, just a big difference in time performance.

MR. HUMPHRIES: Yes. Uh-huh.

Okay. So, the takeaway from here is that the model we haven't changed significantly. We're still able to capture the quench model. Though, as I showed, you could even disable the quench model and calculate the hydrogen --

MEMBER MARCH-LEUBA: Yes. What I conclude from here is that you don't have the proper benchmark data --

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: -- where it matters.

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: I mean, if you are matching benchmark against this one, everything is going to work. Even the no-quench model works.

CHAIR CORRADINI: But I think what he's -- I guess I would have said it differently is for what they're interested in, it doesn't make a difference. They're not really interested in reflood heat transfer.

MEMBER MARCH-LEUBA: In the Zircaloy clad, but on the stainless steel components, makes a big difference.

CHAIR CORRADINI: Well, that --

MEMBER MARCH-LEUBA: That's what I don't understand.

CHAIR CORRADINI: That's after the fact, though, because it's a debris -- it's a configuration difference between the two.

MR. HUMPHRIES: But as far as the fuel rods are concerned, whether I had the quench model on or I didn't, I'd still get about the same amount of oxygen -- or hydrogen.

MEMBER KIRCHNER: Hydrogen.

MEMBER MARCH-LEUBA: Yes. So, you -- as I say a moment ago, you wasted your time to do it.

So, what we're missing is benchmark for the places, what I think to know which of the two is correct.

MR. HUMPHRIES: So --

MEMBER MARCH-LEUBA: But I think --

MR. HUMPHRIES: -- I do have a slide here

--

CHAIR CORRADINI: You can fight back with us, but I guess my conclusion is if it takes them ten hours to do a simulation versus one hour and they get the same result, it would be better if it would happen in one hour.

MEMBER BALLINGER: But they also corrected the physics --

CHAIR CORRADINI: Well, I think --

MEMBER BALLINGER: -- this error.

CHAIR CORRADINI: Right. But I think the benefit, at least as I understand Larry's point -- maybe I'm misunderstanding -- is that it's -- you've corrected the error, things are behaving numerically and much more well-behaved, but the net result is the same fidelity.

It may not be the fidelity I want for reflood heat transfer, but it's the same fidelity as I had before without all the thrashing.

MR. HUMPHRIES: Right.

MR. ESMAILI: So, correct me if I'm wrong, Larry, but I think this would allow us to do those 500 hours of calculation which we are doing under the BSAF project for the Fukushima forensic analysis.

Because now, we can run the code for about

500 hours in a reasonable amount of time, whereas before like a year ago, we were not able to do that.

MR. HUMPHRIES: This is one --

MR. ESMAILI: So, in -- I don't know whether we are going to get to that, but in the next talk, that shows that, you know, we are doing calculations for 500 hours of Fukushima and this is a long time to do this type of calculation. This is what allows us to do those.

MR. HUMPHRIES: So, in this calculation, this is a different calculation, but this is where we first saw an issue with the quench front model.

And before the correction was made, we were tracking the quench front and there were cases -- there were times when the quench front would not advance from one COR cell to another.

So, if you are tracking the quench front, you could actually see that there was a problem with the code, there was a numerical issue that was happening.

So, that was corrected and so that calculation now was quenched and we get the hydrogen right and we get the quench front advancing properly.

This is what I think was the issue that was causing the problem with the -- well, with the oxidation of the steel, is that we weren't getting quench because of a numerical problem where the quench front could not advance and quench that component before the reflood came on.

CHAIR CORRADINI: So, it was two things combined, not one thing alone.

MR. HUMPHRIES: Right.

CHAIR CORRADINI: Is that what I'm understanding?

MR. HUMPHRIES: Right -- well, it was -- it was - we made a lot of different changes to quench front.

I suspected it was an issue with the quench front modeling, but I think the issue is not in terms of the physics that we changed, it's in terms of a numerical correction that we made that corrected this problem where the quench front would not -- would get stuck. And we fixed that.

It's not related to the temporal relaxation, that's a completely different issue, because I've disabled the temporal relaxation and I still get the small hydrogen generation.

Another possibility for the source of that discrepancy in hydrogen would be the Lipinski dryout model. We did make a change here.

The Lipinski dryout model is used to calculate when the debris bed would dry out because of heat fluxes.

It really was developed to model the case where you had water on top of a debris bed and in the lower plenum.

However, it was also applied not only in the lower plenum, it was applied in the -- to debris in the upper core.

In the upper core, we don't have countercurrent flow of water and steam coming up. And so, dryout is completely different.

And in addition, we ran into some issues where it would -- it would arrantly calculate dryout of particulate debris from a canister that failed.

And so, a canister would fail and it was -- and the heat flux was high enough that it would say dryouts occurred here. And the model would say, don't let any other component in that COR cell transfer heat to the water -- to the pool, because it has experienced dryout conditions.

So, you would have a case where dryout would occur because of a canister forming particulate debris, and then it would shut off heat transfer from the fuel rods.

And so, that would affect the core degradation. And so, we disabled that completely in the upper core.

This is an example of how it affected the COR degradation for the TMI-2. You can see that these are two time slices of time.

With the upper -- Lipinski model in the upper core, we don't get the particulate debris to penetrate as far and -- as far down, but it does advance radially more than it did -- it does in the new modeling.

So, we disabled the model, I've run it -- the case that I showed previously with the hydrogen from stainless steel -- oxidation from stainless steel, and I've run it both with and without the -- this Lipinski model enabled and I get the same results.

It's a -- kind of a rare occasion when you have this Lipinski model affect anything in the upper core, because the pool is down below the core. You don't have pool and contact with the particulate debris unless you have a reflood condition.

CHAIR CORRADINI: So, let me make sure I understand this.

So, there was a logic error? Is that the essence of it? I'm just trying to make sure. There was a logic --

MR. HUMPHRIES: Essentially, it was applied where it shouldn't have been.

CHAIR CORRADINI: Okay. Fine.

MR. HUMPHRIES: It was applied in the upper core where it shouldn't have been applied.

CHAIR CORRADINI: Okay.

MEMBER SKILLMAN: Larry, what is the green on the periphery on the lower portion of each of those images?

MR. HUMPHRIES: Here?

MEMBER SKILLMAN: No.

MR. HUMPHRIES: So, there's particulate debris that has made it down --

MEMBER SKILLMAN: In the wings.

MR. HUMPHRIES: Oh, in the wings?

MEMBER SKILLMAN: In the wings.

MR. HUMPHRIES: So, there are heat structures out here that are modeled -- or used to model the core barrel.

MEMBER SKILLMAN: I'm trying to relate what I know is in the -- what was in the TMI-2 reactor vessel compared to these two images.

The image on the left is very close to what we discovered, but I don't understand the green that's on the extreme periphery that say two feet, four feet, six feet off.

MR. HUMPHRIES: For this one?

MEMBER SKILLMAN: Yes.

MR. HUMPHRIES: And here also?

MEMBER SKILLMAN: Yes. That's what I'm trying to --

MR. HUMPHRIES: Those are -- that's the shroud, the core barrel. So, there's the annular region outside the shroud where material can relocate down through the formers (phonetic).

MEMBER SKILLMAN: Oh, okay. Back in the formers.

MR. HUMPHRIES: Yes.

MEMBER SKILLMAN: Fair enough. Okay. Thank you. Okay.

MR. HUMPHRIES: Uh-huh. So, I wanted to look at -- was there a question?

CHAIR CORRADINI: No. Keep on going. You're doing good.

MR. HUMPHRIES: Okay. There was a question in my mind as to what affect this might have on hot leg gases. I think it was asked by Joy in our last telephone conference when we discussed this model.

And so, I ran this model both with and without -- I ran two cases, the Fukushima case and the

TMI case, both with and without the model enabled, and compared the gas temperatures in the hot leg to see how much they differed, and they were very similar.

I see more differences in the TMI calculation, but it's hard to say which one's hotter, because at different times -- they change over time. With the case of the Fukushima Unit 1, they're both very close.

MEMBER KIRCHNER: Should you be looking at other effects? I wouldn't expect a big change on the gas temperature.

MR. HUMPHRIES: Yes.

MEMBER KIRCHNER: Because gas temperature is pretty insensitive to your --

MR. HUMPHRIES: Right. To first orders.

MEMBER KIRCHNER: Pretty insensitive to the details of your core model.

MR. HUMPHRIES: The biggest thing I would see is the changes in COR degradation.

MEMBER KIRCHNER: Yes.

MR. HUMPHRIES: Because this led to situations where you would have the wrong heat removal from core components. And so, you could lead to COR degradation differently.

MEMBER KIRCHNER: Okay.

MR. HUMPHRIES: All right. So, the last couple of slides -- few slides here, I wanted to talk about the topic of numerical variance.

MEMBER MARCH-LEUBA: Oh, wait. Are you done with --

MR. HUMPHRIES: With Lipinski? Unless there was a question I didn't answer --

MEMBER MARCH-LEUBA: Can you go back to Slide 6 -- 14. One more.

CHAIR CORRADINI: He's where I am. I'm still trying to figure out how this all fits together.

MEMBER MARCH-LEUBA: Well, that's exactly what -- so, you're saying that the change from 2.1, 2.2 changed the amount of hydrogen by the stainless steel?

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: And you concluded in your mind, that this is because of an error on the reflood quenching model. It was not really the model itself.

MR. HUMPHRIES: It was a model on a criteria for advancement of the --

MEMBER MARCH-LEUBA: So run Lipinski on and off, I will have ran quenching off --

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: -- and see if it

reproduces that.

MR. HUMPHRIES: Absolutely. However, the Lipinski model change was made in one revision. It's very simple to --

MEMBER MARCH-LEUBA: Well, you can.

MR. HUMPHRIES: With a quench model, there's lots of different pieces to it. And I did disable the time -- the relaxation and I saw no difference.

But to be able to disable this other -- I haven't done that yet.

MEMBER MARCH-LEUBA: You did disable it on one of the slides on T-clad. The red and blue lines.

MR. HUMPHRIES: Which one?

MEMBER MARCH-LEUBA: The one -- slide 16.

MR. HUMPHRIES: Yes. Without a quench model. So, I can turn it -- disable the quench model entirely.

MEMBER MARCH-LEUBA: Then you will reproduce the red line with 2.2? If that was --

MR. HUMPHRIES: No, it wouldn't, because there was a quench model there to begin with. I don't -- actually, I haven't done that with this. I could try that.

MEMBER MARCH-LEUBA: Okay. Yes. It

would help to figure out what's going on, because back to Ron's request is, how do we know which one is -- is the red good or the blue good? Is there another error that you haven't looked at?

I mean, right now you have -- show this, a number of possibilities that you have evaluated.

MR. HUMPHRIES: Right.

MEMBER MARCH-LEUBA: And you say, well, what's left is the quench model, but it would be nice to be sure that there's not another error somewhere.

MEMBER BALLINGER: Because when you get an answer which you think is correct, there's a tendency to sometimes assume it's correct and find out that it's fortuitous.

MEMBER MARCH-LEUBA: Yes, with the quench off, it would really confirm your theory on validity.

MR. HUMPHRIES: I actually was trying to do that on Friday before I left.

(Laughter.)

MR. HUMPHRIES: I didn't make it happen, though.

MEMBER MARCH-LEUBA: Doesn't it run on your laptop?

(Laughter.)

MEMBER MARCH-LEUBA: Okay. Thanks.

MR. HUMPHRIES: Okay. So, I wanted to talk a little bit about the topic of numerical variance.

So, for years, MELCOR developers and MELCOR users alike have known that there are issues with code variance.

It's not just an issue with MELCOR and variance, but it's an issue of all codes where you're looking at convergence of different models and numerics.

And so, if you change something very slightly and have a slightly different timestep, it can change your results, sometimes small, sometimes dramatically. And users are very frustrated by it, as well as code developers.

And so, it's important for us to be able to look at this. And we've looked at it before and we'll look at it again.

And I think this is something that is part of our Volume 4, which I mentioned that we're going to have for users to be able to give them some guidance in MELCOR modeling. We're going to have a section where we talk about numerical variances.

So, one of the first things we want to do is to try to find some of the sources of variances. And these can come from tolerances in your convergence criteria.

It affects, due to history, your modeling of opening and closing of valves and how that interacts with the timestep.

There are other things. There are some things that are inherent to the user model that's developed.

If a user model is not careful in how they're modeling things, they may introduce something that may lead to code variance. So, those are sources.

There are things that also may amplify those variances. There are things -- models in the core package that lead to abrupt changes in core geometry. Those things would tend to amplify any small differences in calculations.

And one of the things that motivated this was when we first released MELCOR 2.0, users found that if they added a flow path to an input deck, it would change the results.

And the reason why is because in MELCOR 186, our input was -- you would read an input and each object had a number associated with it and it was ordered by that number.

In MELCOR 2.0, they went to names. And so, there were names ascribed to things. And sometimes you weren't even required to attach -- associate a number with an object. And so, you didn't know the order in which a flow path would show up in the flow path matrix.

Basically, that's what we were trying to determine is where that flow path shows up in the flow path matrix. And that's important in terms of your calculation.

And so, they would see differences depending on whether they added a new flow path or not.

So, we wanted to assess the sensitivity of the variance to different models. We're going to look at the core package to see how sensitive it is to different models that are there. Effect of nodalization, nodalization can have an impact on this numerical variance.

More than anything, we want to be able to characterize it so that users have a better understanding of what that variance is, how large it might be, how it might affect uncertainty analyses.

And then based on what we've learned, provide some code improvements that might reduce some of these numerical variances.

It can't be eliminated. It's just part of coding is that you're going to have some level of numerical variance.

So, reduction of tolerances in the code for uncertainty analyses, addition of smart relief valves.

One of the reasons we added the time-at-temperature model in the first place, was because it tended to smooth out this process of COR degradation rather than having a step change.

And one of the other things we've added is this multi-rod model. This can also help in terms of smoothing out numerical variances.

You now rather than having a whole ring of rods collapse, you could have part -- have this done more stepwise.

So, we're looking at better characterizing it, as well as reducing numerical variance as possible.

MEMBER KIRCHNER: So, Larry, do you -- does the code kind of limit the -- what the -- you talked about one thing, nodalization and adding a different flow path.

It would seem to me that if this is a well-posed solution, at least, of the -- not the full-blown Navier-Stokes equations, but certainly conservation of mass in particular for the fluid circuits, then, you know, if they're adding additional detail or loops or piping, that should -- I mean, the user can't just do it willy-nilly, right?

It has to -- it has to connect in a logical way to say you have a core and you want to put a bypass in the downcomer for the baffle region or something, you know.

It would seem to me that at some point at the lower plenum and the upper plenum, the two paths are going to connect.

So, from that standpoint, is that constrained by how the input deck is assembled when you get to -- starting with things like nodalization?

And then, like, with things like the core, you probably have a lot of experience now as to what gives reasonable -- reasonably good reproduction of your validation set and such in terms of nodalization.

So, are you limiting them to a minimum of six axial nodes, say, and 50, if you want to add 50, and sort of the run time that goes with it, or -- in other words, are there constraints in there?

MR. HUMPHRIES: There are no constraints on --

MEMBER KIRCHNER: No constraints.

SPEAKER: There's user guidelines, though, aren't there?

MR. HUMPHRIES: There are best practices that we publish in terms of the SOARCA work that's been done. And a lot of users will base their models on those best practices.

MEMBER KIRCHNER: Okay.

MR. HUMPHRIES: That's one of the purposes of this Volume 4, also, is to be able to provide that guidance to users so that they don't, you know, willy-nilly connect things.

And sometimes, you know, you don't -- you have to do this characterization study to really understand it.

You think that just having small nodal -- course (phonetic) nodalization, that that is always a source of numerical variance.

Actually, it might be a reduction of numerical variance if you have very course nodalization, because now everything collapses at once whereas if you have more finer nodalization, you may have some rods at the periphery that stand up longer than others. And so, they may have more hydrogen generation in those outer rings.

So, there has to be some sort of a guidance to help users to be able to make those determinations.

MEMBER KIRCHNER: So, then, going to the next one after nodalization, what about timesteps? Isn't that something that should be the decision logic that the actual code execution should control, right?

MR. HUMPHRIES: And it does. It does control that. The user specifies a maximum timestep, but MELCOR will reduce that based on convergence criteria.

Now, that doesn't necessarily mean that what users use is appropriate, because they may select a timestep of two seconds and that might be too large for some calculations.

The important thing is, is that that timestep is really dependent on where you are in the transient too.

There are times in the transient where you can go to a very large timestep, and other times where you have to have a much smaller timestep.

So, it's hard to rigorously enforce that on a user. It's better to advise them through guidance reports and then let them make that decision.

MR. ESMAILI: So, the other thing I want to mention is that -- Larry has it -- is the cliff-edge effects. And then he says "Variance is extremely small prior to COR degradation."

So, it's only when you start -- you look at those pictures -- it's only when you start changing the geometry.

That means that you are changing the volume, how much volume you have available, what is the flow path.

And these things -- again, so when you are solving this equations, you know, you put in these rows, the order of the matrix becomes important, because now your hydrodynamic volume changes, because now you have a different -- and these cliff-edge effects, they can happen in one timestep.

Doesn't matter what timestep you take as long as you hit that, you know, let's say that, you know, you want to fan the fuel rod at certain temperature, at 2500. The entire intact geometry, that cell goes to a degraded cell.

And so, these are inherent into the -- and as the calculations progress, you are actually changing, you know, your convergence criteria, you know. You still have the same convergence criteria, but these things add up and you can be on a different trajectory.

So, because of this COR degradation, it's very, very difficult to remove some of these numerical variances.

CHAIR CORRADINI: Keep on going.

MR. HUMPHRIES: So, this is one source of that numerical variance. So, when we have a station blackout, the pressure starts to rise.

And that pressure would rise -- continue to rise, except there is a setpoint on an SRV valve that limits that. And so, the pressure then starts to fall as that flow path opens up.

And then it would continue to fall, but then there's a lower setpoint value. And so, the pressure rises again.

And you can have a small overshoot in that pressure based on your -- the timestep that you're running.

So, in this case, I've been running this calculation at this timestep dt1. The pressure exceeded my setpoint by a small amount and then I -- my valve opens up and so my pressure curve is offset in time.

And then for a different timestep, I might have a larger overshoot of that pressure. So, this is a source of that numerical variance that is partly in the code and partly in a user model.

I mean, you could essentially say you could just go to a smaller timestep and do a better job of calculating that.

One of the things we're looking at is

putting in a smart valve that would recognize that an overshoot has happened and then decrease the timestep so that it would hit that setpoint better.

And so, we've -- I've developed one. It's still running a little slower than I'd like. And so, that's one of the things in a future version of the code, we'll have a smart SRV valve that will capture this -- the setpoint properly so that it would remove this source of --

MEMBER MARCH-LEUBA: Is it really worth it? I mean noise to the output.

MR. HUMPHRIES: What's that?

MEMBER MARCH-LEUBA: This is noise to the calculation.

MR. HUMPHRIES: Yes.

MEMBER MARCH-LEUBA: I mean, of course you go with delta-T an hour and a half, obviously you have a problem, but I wouldn't waste too much time on this.

MR. HUMPHRIES: Yes. But they're amplified by other things in the code, also. And so, if I can reduce those sources of numerical variances, I can reduce my overall variance.

CHAIR CORRADINI: So, are you going to get to a cliff-edge example? This one I get.

MR. HUMPHRIES: I don't have a cliff-edge example here, but --

CHAIR CORRADINI: Well, the reason I guess I'm asking is, I can see where you get close, but not close enough to an operator action or a trip setpoint, and then you run another calculation and over you could actually have a branch.

So, I was looking for an example of where you've seen that that makes a difference other than eventually it's going to happen anyway.

MR. HUMPHRIES: It's going to happen, yes.

MR. ESMAILI: So, on this one, I think we can go back and look, because the times I'm seeing here is 200 to 300 seconds.

I think we are taking maybe smaller timesteps than the maximum time steps sometimes. So, this overshoot, as you said, may not be, but still it's a good idea to put these models in there just to make sure that it's not going to go to other --

MEMBER MARCH-LEUBA: Well, the proper thing for the SRV model to recognize that it missed an opening and forced the whole to backtrack one step and do it right.

But if you're going to do the correction at the SRV you're going to have to fudge something.

I mean, the proper thing to do is the

delta-T was too large, go and do it again.

MR. HUMPHRIES: Right. But you don't have to do a bisection method to find that timestep. You could use some smarts to predict the appropriate timestep and --

MEMBER MARCH-LEUBA: Try to predict it.

MR. HUMPHRIES: -- it doesn't buy you that much in terms of performance.

MEMBER MARCH-LEUBA: Okay.

MR. HUMPHRIES: I put this in here as a means of understanding how -- one of the sources of variance because people say, well, how could it be possible that just by changing the order of my flow paths I could get a difference in results.

Small changes accumulate. A small change that's calculated from a -- the ordering of a flow path can lead to a small change in timestep, which then can lead to trigger another model to have another source of variance such as this SRV.

And then eventually you lead to something much larger like the collapse of a ring of fuel rods and now we have a catastrophic event, and that leads to a much larger source of variance.

So, this was a set of calculations that were done for -- it was for a Fukushima run. And these were all identical calculations, except for changes in the order of the flow path.

So, the flow -- there's nothing magic about the flow path ordering. There are other things you could use to perturb the situation to be able to generate some kind of -- this variance, but we used the flow path as a means of doing that and these are the horsetails that are generated.

And the first thing I point out is like Jose mentioned early on, this variance is small before COR degradation becomes significant.

The curves tend to lie on top of each other as hydrogen is being generated for intact geometry.

Then as we get more and more candling and COR degradation occurring, the variance tends to increase over time, because you have more models and they tend to accumulate with each other.

CHAIR CORRADINI: So, I don't -- I mean, I know what you're saying, but this worries me, I guess.

MEMBER MARCH-LEUBA: No, what happen is, is you have irreversible events that the core triggers like I'm going to melt half the core.

CHAIR CORRADINI: Yes, but I don't think that's what he -- I don't think that's what he -- I thought that isn't what he was saying, though.

I thought he was saying how the code numbers the flow junctions will affect the solution.

MEMBER MARCH-LEUBA: There is a little noise, which under normal circumstances before core melting, it would be just noise. But this noise if you're this close to melting the core, this is not melting it and there are irreversible events happen because of noise.

CHAIR CORRADINI: Well, but let me ask -- okay.

MEMBER MARCH-LEUBA: And the conclusion from that is that the fix is not fixing the noise. The fix is saying the uncertainty of my calculation is this large, because I may or may not.

CHAIR CORRADINI: But --

MEMBER MARCH-LEUBA: I'm too close to the border. I cannot really tell.

CHAIR CORRADINI: So, I'm still not sure -- the way Jose is hearing it is different that I'm hearing it.

Are you saying that the junction loss coefficients are changing as I proceed in time, or it's just the order of which junction I solve?

MR. ESMAILI: The order of how you are putting -- so, you have this flow path, the way you are ordering them in your matrix to solve them, to try to --

CHAIR CORRADINI: So, are you inverting the matrix and where you put the junction numbers and inverting the matrix changes the answer?

MR. ESMAILI: Yes. Because you have truncations, right? You have truncation errors because, you know --

CHAIR CORRADINI: But it's not --

MR. ESMAILI: But then you have --

CHAIR CORRADINI: I just -- it's different that what Jose was saying. The way I interpret what he was saying was the loss coefficients because of the evolution of the geometry changes between them.

MEMBER MARCH-LEUBA: What I was saying is the ordering of the junctions produces noise. Something less than one percent. That one percent in error triggers a very big event --

(Simultaneous speaking.)

MR. HUMPHRIES: The flow path order is the perturbation. It could have been -- I could have changed the timestep just slightly and that would have perturbed the situation.

MEMBER MARCH-LEUBA: And it's only one percent change, but that one percent is sufficient to create a big event.

MR. HUMPHRIES: But that's amplified through other models, through COR degradation, through oxidation, through --

CHAIR CORRADINI: And this is primarily the core junctions in the control volumes --

MR. HUMPHRIES: Right.

CHAIR CORRADINI: -- in the CVH package in the core junctions.

MR. HUMPHRIES: Well, you see variances in other volumes also.

CHAIR CORRADINI: Sure.

MR. HUMPHRIES: But they're not as important and near as significant. They don't lead to hydrogen generation.

MEMBER MARCH-LEUBA: But what I read from this, is that the real uncertainty of the calculation or even larger. Because a one-percent change, a minor change in truncation error leads to a very large error.

MR. ESMAILI: Well, because now in each of these realizations, you have a different geometry of the core, because how you are -- so that the core logic is -- I mean, the COR degradation is a logic-based model, right?

So, you say I'm going to get to 1700K,

right, and then I'm going to do this. I'm going to just melt everything in there or do that.

And what it does is that, as I just said before, it's just going to change the volume available, the flow that, you know, whether it's going to be, you know, like the open flow path or it's going to be closed up. So, it changes a lot of those things in those flow path.

And those truncation errors, those convergence errors, you know, because we also have convergence errors that, you know, we say, you know, and I think Larry did some calculations to show that if he tightens the convergence, it's going to tighten this --

MR. HUMPHRIES: I can tighten it a little.

MR. ESMAILI: He could tighten it. So, this is clearly because of a degraded core. So, each realization has a little bit less surface area available, a little bit more hydrogen available. So, this goes through this.

It is -- but the important thing is that up until the time that you are probably intact about you are producing about 400 kilograms, like 40 percent of the hydrogen, it's very, very tight. You are not diverging as long as --

CHAIR CORRADINI: So, let me ask the question differently. So, if I did a numerical experiment in the containment, I wouldn't see this?

In other words, if I were --

MR. ESMAILI: You're not even seeing this, Mike, as long as -- you're not even seeing this until you get to COR degradation.

CHAIR CORRADINI: But that's why I'm asking. So, if it's geometry-related, I could pick another sample problem and not see by -- because I want to go back to the ordering of the junction.

So, if I have a containment and I have the upper dome and I connect all of these by numbering them in a different manner, same junctions, but I change the order in which I input them into the deck, the input, you would not expect to see this because it's not geometry-related?

MR. ESMAILI: You haven't done --

CHAIR CORRADINI: I'm trying to ask the question as, okay, I'll buy off on this if you now do it for containment and I see no change and I do it for the primary system for a LOCA, no geometry changes, then I'll buy it. But until I see other examples, I'm not sure if I buy it.

Because I would just say turn down the

tolerance on the matrix solution technique until the damn thing gives me the answers -- convergence, yes.

MEMBER BALLINGER: Assuming you are getting convergence.

MR. ESMAILI: Well, we haven't done it for containment. I guess we could go ahead and do it. We don't expect things to change much in the containment because what we are seeing, the evidence here --

MEMBER BALLINGER: But I understand what you're saying.

MR. ESMAILI: -- is suggesting that --

MEMBER BALLINGER: You're saying the source of this is geometry changes, which changes loss coefficients, which changes flow.

Those errors tend to typically balance each other out, those types of things, correct?

CHAIR CORRADINI: Microphone.

MEMBER BALLINGER: Those types of things tend to go negative here, positive there, negative here and kind of balance each other out, don't they?

CHAIR CORRADINI: All I know is -- so, here's where I'm coming from. All I know is when I use MELCOR in not such a complex environment, I don't get these problems. So, I'm trying to decide what's the root cause.

If the root cause is geometry changes, then somehow there ought to be another sample problem that shows indisputably that I can get the same answer again and again.

MEMBER REMPE: But you would never sample the ordering, which is what he did there.

MR. HUMPHRIES: How would you know that you didn't see any variance in your calculation?

CHAIR CORRADINI: I would just -- I would just have multiple decks. I would -- I'm telling you that's how I input the junction numbers. I would --

MEMBER MARCH-LEUBA: But, Mike, in this calculation up to, say, it's 1,500 before they start diverging, there is the 500 runs in there that they don't diverge. They don't diverge. It's only when they start melting the core.

MR. ESMAILI: Everything here is just pretty tight, actually.

MR. HUMPHRIES: There's variance there.

MR. ESMAILI: There is lots of flow path.

MEMBER MARCH-LEUBA: There's noise.

MR. HUMPHRIES: And early on, it's quite high, actually, because you have small masses to begin with. So, slight deviations lead to large variances.

MEMBER MARCH-LEUBA: What this tells me is that a little bit of noise makes a big difference on the output.

MR. ESMAILI: Noise, because now you're changing the higher --

MEMBER BALLINGER: I'm sure I don't know what noise is.

CHAIR CORRADINI: Allowable air.

MEMBER BALLINGER: Okay. That's what you mean by noise?

MEMBER MARCH-LEUBA: Yes.

MEMBER BALLINGER: Okay.

MEMBER MARCH-LEUBA: Whenever you run your calculation, you have delta-Ts and you have truncation errors and that gives you noise.

MEMBER BALLINGER: Don't they have a tendency to sort of average out?

MEMBER MARCH-LEUBA: Well, you have on a variable.

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: And that gets you into melting something and that creates a big change.

MR. ESMAILI: So, this --

MEMBER MARCH-LEUBA: The problem is, I mean, do you -- you might be able to get a code that will always give you the same answer, but it won't be the true answer, because that's the real answer.

MR. ESMAILI: The problem is that we don't have differential equations describing what happens to the -- everything, you know, how these materials flow.

It has to rely on logics. It says that, okay, so now I have this thing melted, right, I have this melted, so I'm going to -- once it's melted, I'm going to move it to the next action level.

Once it goes into the next action level, because he just reached, you know, 2600K, then that volume that's below it is just going to produce sometimes blockages that nothing can go through.

CHAIR CORRADINI: I get all that.

MR. ESMAILI: And so, it just changes --

CHAIR CORRADINI: I get all that, but we need to move on. But on the other hand, I want to make sure I understand what I'm getting out of this.

What you did was machine-wise took -- if there was -- I'll just pick a number -- if there were 50 junctions in the core, you reordered the 50 junctions randomly as many ways as you possibly could.

MR. HUMPHRIES: Yes. I use a random number generally.

CHAIR CORRADINI: And you then had a fixed convergence criteria for the matrix inversion.

MR. HUMPHRIES: Yes.

CHAIR CORRADINI: So, now if you have to reduce the tolerance by a factor of ten, would this shrink?

MR. HUMPHRIES: A little. Yes. There's a lot of different places where MELCOR calculates convergence on different routines and --

CHAIR CORRADINI: Okay.

MEMBER BALLINGER: So, there's different convergence criteria for different places?

MR. ESMAILI: Well, we cannot have statements inside the code that says if this happens, do this. If this happens, now I don't have an intact geometry, create a thing. These are things that are happening, the cliff-edge effects.

I cannot get rid of this, because I don't have any way to smooth -- I mean, we are thinking about doing smoothing later, but at this present time things are not so smooth.

MR. HUMPHRIES: That's one of the reasons that we want to use this multi-rod model. I want to be able to use it to try to smooth out effects due to nodalization and --

CHAIR CORRADINI: Well, I mean, the only -- my only other conclusion is that I'm still within plus or minus 20 percent.

If hydrogen is the measurable of interest from version 6300 to 9400, so I went 3,200 revisions, and it's still plus or minus 20 percent. That's what I'm --

MR. HUMPHRIES: Let's finish the slides and then we can continue the discussion.

CHAIR CORRADINI: Yes. I'm sure.

MEMBER BALLINGER: And this is -- but I could see why -- what you're saying. You just can't avoid those kind of things and you have a very nonlinear oxidation model.

So, you change by five degrees centigrade, you change by a factor of two on the rate for any of these things, and so it's very nonlinear. Especially at the high temperature, you can see it in your -- where most of the hydrogen is generated at one node.

MR. ESMAILI: The only story here is that we are bounded by how much we can actually do, right? I cannot just shift these things up and down, you know, because we have -- we have certain amount of water, we have certain amount of steam, we have certain amount of material. So, it's still within that bounded --

MR. HUMPHRIES: So, one of the things we wanted to do was to see if this kind of error is additive, whether it accumulates.

So, we took three of these situations, three of these realizations at the extremes; one at the lower end, one at the higher end, and one at the medium, and we did a sensitivity analysis.

So, we varied a number of parameters based on the UA that was done for the Fukushima work. And we did that variation on each of these three different realizations to see if they gave me the same distribution or if the distribution changes depending on the order of the flow path.

And so, I did that using a ten percent variation in the UA parameters. So, I just varied all of the UA parameters by --

MEMBER MARCH-LEUBA: What is UA?

MR. HUMPHRIES: Uncertainty analyses for the Fukushima work.

MEMBER MARCH-LEUBA: Okay. Got it.

MR. HUMPHRIES: So, I took those variations that they used and I varied all of them by ten percent, and then I created a distribution for each of those realizations.

And if you look at this curve here, it shows them, they all lie on top of each other. The one in blue was my distribution here from my flow path shuffling.

So, this was -- this one in blue is basically the inherent numerical variance associated with either flow path shuffling or some sort of perturbation. And these other curves show the variance that's associated with this variation study.

I did it again, I changed it to 20 percent and looked at that variance. And now you see, again, all three curves lie on top of each other. They're not showing any kind of additive error that's associated with them. They all reproduce the same uncertainty.

But in addition, these uncertainty variations moved -- shifted down to lower hydrogen production. So, it's showing me something that's physically changed in the UA analyses.

MR. ESMAILI: So, this is -- okay. So, let me -- this took me a while to understand what's going on here.

So, I think maybe we can -- so, the blue line that you just did that changes in the input parameters.

MR. HUMPHRIES: It's like a background --

MR. ESMAILI: Just a background. So, he didn't change anything in the -- in terms of modeling parameters and such. That's what the blue line is.

That shows the range with that blue line.

But then the other curve that show wider range, what he did was that he didn't change the input parameters.

He stuck with one of his realization, but he actually did uncertainties the way we are doing uncertainties. That means that he changed, you know, like the eutectic melt temperatures, et cetera, right?

And those shows -- so, this is showing you that -- how much value it is in doing the uncertainty analysis, because knowing that we have this noise because of this COR degradation, et cetera, but then we are doing the uncertainty analysis, we are capturing a wider range of, you know, some of these parameters. In this case, would be the hydrogen mass.

So, the blue line is just the parameter changes, it's the same thing. The other lines are modeling parameters, you know, temperature changes, you know, some of these things that we are going to talk about next month, correct?

So, knowing we have this noise, this is what we are going to --

MR. HUMPHRIES: Okay. So, this one shows for several levels of variation ranging from a half a percent to 20 percent, that for low variations it's hidden in the noise.

There's no -- it's hard for you to discern any differences between the noise and the sensitivity analysis. It's hidden in the background.

We did a plot here showing the signal-to-noise ratio for these various realizations and you can see that as the variation becomes smaller, the uncertainty -- the overall variation becomes that of the full path shuffling.

So, it doesn't go to zero. It goes to the nominal background noise that's associated with the numerics.

CHAIR CORRADINI: So, what is the scenario that was run that you did the initial randomized junction ordering?

MR. HUMPHRIES: This one. This is station blackout Fukushima 1.

MR. ESMAILI: This is actual Fukushima Unit 1 is with a short-term station blackout. And these are the kind of results you get.

CHAIR CORRADINI: Okay. So, I interpret this -- so what I interpret this to mean that is as long as I'm uncertainty with 0.5 percent, it's the equivalent of shuffling the deck.

MR. HUMPHRIES: Right. So, I think this

actually is a good story for MELCOR that shows that we're able to characterize the variation that's associated with the numerics and that that isn't so high that it overwhelms the uncertainty that we see from an uncertainty analyses.

And so, I think that's an important conclusion to draw.

MEMBER MARCH-LEUBA: Say that again, because you said something different.

MR. HUMPHRIES: That we're able to characterize a base level of a noise associated with MELCOR numerical variance, and that that numerical variance can be -- is not so large that it overwhelms the uncertainty that we might see by varying parameters in the code so that we can make some physical conclusions from an uncertainty analyses because it is -- it's above the noise level.

MEMBER MARCH-LEUBA: What you said makes sense. What Mike said --

CHAIR CORRADINI: No. I just said that I have to -- if I'm uncertain less than 0.5 percent, I can't tell the difference of how I made the deck versus how I have my uncertainty.

MEMBER MARCH-LEUBA: Okay.

CHAIR CORRADINI: I'm saying the same

thing, just --

MR. HUMPHRIES: I'll also point out that we're kind of on the leading edge here. Other codes have asked us about our numerical variance and they're interested in working with us on that.

CHAIR CORRADINI: The one that I'm still back at that you mention in your words, but I'm looking for an example, is the cliff-edge one, which is I'm moseying along here and there's neither an operator action or a setpoint. And depending on how I --

MR. HUMPHRIES: Let me show you one. Let me show you one. This was a bug that we fixed in the code that led to a cliff-edge effect.

So, here we had a candling model. In --

CHAIR CORRADINI: You're on your extra slides?

MR. HUMPHRIES: Extra slides, yes.

CHAIR CORRADINI: Somewhere in there.

MR. HUMPHRIES: So, this is showing candling from particulate debris. And on the left I show particulate debris that's in a cell that has no intact fuel rods.

When that particulate debris starts to melt, that molten material will then candle on the fuel rods, which is good. That's what we want.

Then there's a situation where we have particulate debris in a cell with intact fuel rods. And all the logic in the previous -- before we corrected this issue, this particulate debris did not see particulate debris in the cell below it.

And so, it couldn't candle on itself because there's intact canisters down there. There is no particulate debris down there, so it has to candle on another component.

And so, it would use the same logic and it would candle on fuel rods in that COR cell, which is not what you'd want to do. It would lead to a failure of the fuel rods. And so, you would have a cliff-edge effect that occurred.

And we revised this model so that now that molten material will now candle on the canisters where it makes more sense and is a much more logical thing.

So, this was one that led to some variance. When I was looking at sources of numerical variance, I found that a certain set of my calculations would be these outliers. And they were associated with this error in the model logic.

CHAIR CORRADINI: Okay. We're right on time.

MEMBER REMPE: So, before we leave this,

because I looked ahead and there's another set of slides, but it's talking about new applications and I want to think about SOARCA and Sequoyah for a minute.

And I mentioned this a little bit before the meeting, Hossein, to -- but I haven't talked to you, Kyle.

And a while ago when we did some things with the Surry SOARCA analyses, there were some significant changes in timing of the pressurization of the containment and the dryout of the steam generator timing. And that was from the original SOARCA analysis for Surry and the uncertainty analyses.

And I think I mentioned that also to you, Tina, one time. And you said, yes, you're aware of it. And you went and had them redo the things for the uncertainty analyses.

And, Kyle, I believe you said it was due to changes in the code, as well as changes in the model.

And so, since we're going to be talking about Sequoyah and changes that are specific to it at our full committee meeting -- or I guess it's a subcommittee meeting the next time, could we see something that shows us timing, not just peak values of hydrogen produced, but if -- something that would give us an understanding of are these timing of events going to change because of differences in modeling.

And I know informally, again, this was on a different project, but I think you told me, Kyle, that there was a better steam generator model that was implemented and there were a lot of change in how the model for Surry had changed.

And I'm not sure if that happened with Sequoyah or not, but I just would like to know the timing of the sequences have stayed the same as well as some of the peak values.

CHAIR CORRADINI: Do you understand her question?

MR. ESMAILI: Kyle? Are you online, Kyle?

CHAIR CORRADINI: I'm sure he's there.

MR. ESMAILI: Kyle?

CHAIR CORRADINI: Bridge line is coming open.

MR. ESMAILI: They have to unmute him.

CHAIR CORRADINI: I think he should be --

MEMBER STETKAR: The bridge line is open if he's not muted on his end. It's supposed to be open as long as Theron is back there.

MEMBER REMPE: But he doesn't have to answer it today.

MR. ESMAILI: Casey, can you hear us?

CHAIR CORRADINI: They've all given up on us.

MR. ESMAILI: He has to do something back there.

MEMBER REMPE: Five o'clock, so they're done.

(Laughter.)

MEMBER REMPE: It doesn't matter if he answers today. But before we have the next meeting on this, you guys understand my question. I showed you the plots of what I'm thinking of and why I'm concerned.

CHAIR CORRADINI: Knock on the window.

(Comments off record.)

MR. WAGNER: Can you hear us now?

MEMBER REMPE: Oh, there you go. We can hear you now.

MR. ESMAILI: Kyle, you are here?

MR. ROSS: Yes. Hello.

MR. ESMAILI: Did you hear Dr. Rempe's question?

MR. ROSS: Yes. Yes, I did. So, these would be modeling differences between when we presented to you about Sequoyah a while back and what we'll present in a month from now?

MEMBER REMPE: Yes. Okay. Do you remember this interaction we had about Surry and how the timing of the events changed --

MR. ROSS: Yes.

MEMBER REMPE: -- pressurization, steam generator dryout, and it was significant, like, 24 hours different and things like that.

MR. ROSS: Yes.

MEMBER REMPE: And I just want to know is that going to happen with Sequoyah or not and can we -- I'm from Missouri and so I like to see plots. Even if they're made falsely, it gives me confidence to see that the timing is the same.

CHAIR CORRADINI: So, what changed? I'm sorry. What -- can you just start again? What change that you saw that maybe we haven't --

MEMBER REMPE: Okay. And actually -- it was actually in the -- one version of a NUREG report, but, like, the containment pressure, originally it was done and it would reach its peak value a little bit after a day.

And then there was a plot shown for, like, going up to 50 hours and the pressure was still going up and it never leveled off.

And I know that Kyle and I talked about it a bit. And he said, yes, the peak values are the same, it's just the timing changed and it was changes to the code, changes to the --

MR. ESMAILI I think Dr. Rempe is referring to how you change the containment leakage model, Kyle.

MEMBER REMPE: Well, he had said it was the steam generator at the time.

MR. ESMAILI: Is the steam generator?

(Simultaneous speaking.)

MR. ESMAILI: Because you are showing me the containment pressure which was drastically different.

MEMBER REMPE: Right. But there was also the steam generator dryout time. And, again, I -- it may have been other things.

He said there were a lot of changes to the code, as well as the input decks. And I just would like to --

MR. ESMAILI: So, I think what I saw, Kyle, was that the original SOARCA, which was 186, this was the original SOARCA back in 2008, the containment pressure based on that.

And then in the figure below that, Dr. Rempe was showing me the new containment pressure in the UA, correct?

MEMBER REMPE: Yes.

MR. ESMAILI: And I think you changed the containment leakage model.

Can you explain a little bit about that for the Surry? For the Surry. We're not talking Sequoyah.

MR. ROSS: Right. So, that is one of the modeling changes that we made to Surry, but there were -- there were a number of changes we considered to be enhancements to the modeling. So, that one, as well as others, could have moved the peaks from here to there.

And we do have -- we certainly do have such modeling changes in Sequoyah now compared to when we presented a year ago or so. And we are going to lengths to describe what those changes are and what the impacts of them are.

We have an appendix that's dedicated to that and we can certainly address that with plots in the meeting in June.

MEMBER REMPE: That's great. That's what I wanted to hear. Thank you.

MR. ROSS: Certainly.

CHAIR CORRADINI: Okay. Before we go on

to -- so, we have a decision point. It's just about the shank of the afternoon.

So, we do we want to hear the fourth talk on new applications?

MR. HUMPHRIES: We can do it real short.

MR. ESMAILI: He can just -- he can just do a couple of slides on that one.

MR. HUMPHRIES: They're not even my slides, so I can't talk much about them.

MEMBER KIRCHNER: Just quickly, I'm sorry for this, but could you explain this viewgraph here a little more?

The green is canisters in the BWR or --

MR. HUMPHRIES: Yes.

MEMBER KIRCHNER: Okay. So, this is -- or control rod guide tubes in a PWR, or what are we looking at?

MR. HUMPHRIES: So, this was -- this is specific to a BWR calculation where we were -- and I was looking at variances in the results similar to those horsetail plots that I showed you before.

And I found a couple of realizations that were -- several realizations that were outliers and I attributed them to this error and the way things were modeled.

So, typically when something melts in MELCOR, a component melts, it will candle on itself. So, a canister will candle on canister.

MEMBER KIRCHNER: Right.

MR. HUMPHRIES: Particulate debris will candle on --

MEMBER MARCH-LEUBA: By "candle," you mean melting --

MR. HUMPHRIES: Drain on.

CHAIR CORRADINI: Drain down like a melting candle.

MEMBER MARCH-LEUBA: Because I actually checked the definition on Google and I couldn't get anything.

MR. HUMPHRIES: So, yes. It's a MELCOR term, I guess.

So, it will try to find a component in the cell below it that is the same and it will try to candle on that.

If there is no component there, then it has to candle on something else. And so, the logic previously was that if canister -- if you had particulate debris formed by canister or by anything, it would -- it would candle onto fuel rods.

And the -- you can see the geometry is that it's in the bypass sitting on top of the canister. The logical place for it to drain would be onto the canister walls.

Instead, it was distributing that mass on the fuel rods and leading to blockages and failure in the fuel rods.

MEMBER BALLINGER: When you say "canister," you mean the --

MR. HUMPHRIES: Channel box.

MEMBER BALLINGER: Channel box. Okay. In my world, it's a channel box.

MR. ESMAILI: Yes. Channel box.

MR. HUMPHRIES: Channel boxes.

MEMBER BALLINGER: And there's not a whole lot of distance between the -- in fact, there's almost no distance between the fuel rods and the channel box.

So, isn't it -- I mean, I see it's realistic to want to drain straight down, of course. But to say that it only drains on the channel box, I don't know since they're both zirc --

MR. HUMPHRIES: Right.

MEMBER BALLINGER: -- all right, they're both zirconium --

MEMBER KIRCHNER: And one's hotter, actually.

MEMBER BALLINGER: -- and one's -- and the rod's hotter, actually --

MEMBER KIRCHNER: Are there experiments or --

MEMBER BALLINGER: -- I'm going to have to -- I've got to think a little hard about that.

MEMBER KIRCHNER: Is there some experimental data to substantiate that model?

MR. ESMAILI: So, now you see the problem. We are talking about how you go about, you know, conceptualizing what -- how you want to degrade this core.

MEMBER BALLINGER: But we have to be a little bit careful about our conceptualization should we want to call confirming -- well --

MR. ESMAILI: Because --

MEMBER BALLINGER: -- artificial conceptualization, let's put it that way.

MR. ESMAILI: We don't see this thing happening. We see, you know, where we start to heat up and we see where it ends up. So, we don't have intermediate stages of what's going on during this core relocation process.

So, you have to start somewhere. I think that's what --

MEMBER BALLINGER: So, there's data that actually shows that that's what happens; is what you're saying?

MR. ESMAILI: No. I'm saying that there is no data, that this is our -- we are assuming that when it candles, it just candles on the same component below, correct? We don't have any data to prove that.

MR. HUMPHRIES: We did XR reactor -- XR experiments where we looked at drainage and --

CHAIR CORRADINI: The XR, do you have two -- the DF experiments?

MR. HUMPHRIES: DF experiments also, I think.

CHAIR CORRADINI: And they showed preferential drainage --

MR. HUMPHRIES: Drainage between the -- in the bypass region.

CHAIR CORRADINI: I mean, my -- but I didn't want to get into this. So, these are radial rings. So, this isn't just one place. These are like a --

MR. HUMPHRIES: Right.

CHAIR CORRADINI: -- lot of these.

MR. HUMPHRIES: Yes.

CHAIR CORRADINI: And so, it's simply a

matter of where this stuff goes, but for sure it was wrong that it started here and it ran to the fuel rods.

MR. HUMPHRIES: I would say so, yes. It makes more sense.

CHAIR CORRADINI: Whether or not it runs to the fuel rods and the local near a cold wall is different than it --

MR. HUMPHRIES: And you could see partitioning in between them and --

MEMBER BALLINGER: But it would stay within the channel box, right?

CHAIR CORRADINI: It stays within the radial ring. Think of this as you've got a whole core and you're bringing this up into a series of rings. And most of the time unless you want to stay for weeks at a time, you'll do two, three, four, five radial rings of a whole core versus ten or 20 or whatever.

MEMBER BALLINGER: Oh, okay.

CHAIR CORRADINI: And then, still -- and those -- those are tens of assemblies.

MEMBER REMPE: We don't have tests with tens of assemblies.

CHAIR CORRADINI: Huh?

MEMBER REMPE: And we don't have tests with tens of assemblies.

CHAIR CORRADINI: You have tests with a fraction of assemblies --

MEMBER REMPE: Yes.

CHAIR CORRADINI: -- and a fraction of the height.

MEMBER REMPE: Uh-huh.

MEMBER KIRCHNER: So, the -- then conservative would not be the right way to characterize the last --

(Laughter.)

MEMBER KIRCHNER: It would be disastrous and sooner with more energy hydrogen release. So, how critical, then, is the change in the model to the overall results both in time and release?

So, I'm curious what Larry has to say about this.

(Laughter.)

MR. HUMPHRIES: Well, it was critical enough that it showed a difference in the hydrogen generation.

MEMBER KIRCHNER: Oh, yes.

MR. HUMPHRIES: It was a noticeable outlier in our hydrogen production.

MEMBER BALLINGER: How much of an outlier?

MR. HUMPHRIES: It's been a long time

since I looked at it, so I can't really tell you, but it was enough that just visually I could see that these were -- these stood out from the others.

And interesting enough, a user -- another user pointed this out to me also that he had found the same issue and felt it was an error that the code had and wanted it changed.

MEMBER KIRCHNER: What if the reality is somewhere in between the left and the right? You get a mixed bag of -- yes, maybe the --

MR. HUMPHRIES: I would say --

MEMBER KIRCHNER: -- duct wall collapses, but maybe it runs down in the fuel rods.

(Simultaneous speaking.)

MR. HUMPHRIES: MELCOR does not have that kind of granularity.

MEMBER KIRCHNER: No, but what I'm asking -- I understand that. So, if the reality is somewhere in between, you're programming it to go to the right-hand side of that picture -- your right-hand side, which would have it candle on the duct walls, not the fuel rods.

So, what's the difference between the left side of the picture and the right side of the picture in terms of impact on overall results? Is it dramatic?

MR. HUMPHRIES: No. It wasn't the sort of thing that was dramatic, but it wasn't significant enough that --

CHAIR CORRADINI: So, this is where I guess I was going. So, off the things that you've done, at least give me personal confidence that you've caught errors, made changes, but doesn't the crosswalk that you guys did with our -- your -- not our, your colleagues in the MAAP world versus the MELCOR world, isn't the whether the gas goes into the disrupted geometry versus it goes around the disrupted geometry create a bigger change than anything else we've seen today?

In other words, if I apply -- if I were to put your very first plot --

MR. HUMPHRIES: Yes.

CHAIR CORRADINI: -- your very, very --

MR. HUMPHRIES: What you're saying is that this is in the noise compared to whether we have debris that holds up and --

CHAIR CORRADINI: Whether you have gas bypass or gas through the disrupted geometry.

MR. HUMPHRIES: Right.

CHAIR CORRADINI: Okay. Because here Larry has it in his first set of slides, is that it's plus or minus 20 percent, but it's more like a plus or minus a factor of two whether or not the gas goes in or it goes around. So, instead of 400, you get 200.

MEMBER KIRCHNER: I would assert that in a PWR it's going to go around it. Don't know how, not in any -- with any, you know, precision, but to assume everything just collapses or debris is intact, that was highly unlikely.

MEMBER BALLINGER: In a BWR, it might be different.

CHAIR CORRADINI: You're off again. But the only reason I'm bringing this up is, is that this, to me, is a small effect compared to other effects that when the MELCOR people have done supposedly side-by-side calculations with the MAAP calculations, there are bigger differences.

But I think this is a lot of -- I won't call it all error correction, but you've caught inconsistencies and cleaned things up substantially, is what I hear.

MR. HUMPHRIES: The Lipinski model is another example and a lot of that comes from looking at these variance studies. Doing that sort of study helps us find these kind of outliers that lead to different results.

Do you want to go through the final --

CHAIR CORRADINI: Yes.

MR. HUMPHRIES: Okay.

CHAIR CORRADINI: Give us a sampling.

MR. HUMPHRIES: Okay.

CHAIR CORRADINI: The dessert for the day.

MR. HUMPHRIES: So, these are calculations that were performed by Jeff Cardoni at Sandia Labs, Fukushima Unit 1 calculations that are run out -- are these Unit 1? Unit 3. Fukushima Unit 3 calculations that were run out to three weeks.

Prior to this work, they were run out to a hundred hours. And this is with an older code version.

And to run it out to a hundred hours, I can't remember exactly how long it took him to --

CHAIR CORRADINI: 500 hours.

MR. HUMPHRIES: It was a long run, but we've recently extended those calculations out to three weeks and the calculations were run under a week's time.

Due to changes in code performance, what they talked about earlier, like, the relaxation models for the quench velocity, all these things have had an impact on how fast the calculation runs.

So, this presentation talks about some of the things that were learned from doing the three-weeks calculations.

CHAIR CORRADINI: How do you -- the moment you start showing this stuff, a lot of questions. How do you know the initial and boundary conditions -- well, forget about the initial. I know how you start the initial, but the boundary conditions on, like, water inventory of what's going on, where it's going.

MR. HUMPHRIES: Yes.

CHAIR CORRADINI: I mean, goodness gracious.

MR. HUMPHRIES: Yes. You don't know. And so, you do -- you end up doing a lot of sensitivity analyses looking at varying your assumptions as far as how -- as those boundary conditions.

And so, in this example, it shows a surge in the pressure that was probably due to a change in the injection rate, but MELCOR needed some modifications to enable it to capture the pressure -- depressurization of the calculation.

So, this was probably just an error in the data, this series of symbols here, but this was something that MELCOR needed -- wanted -- to be able to capture it, you had to be able to capture the correct boundary conditions.

So, one of the things that they did was they looked at the depressurization curves and tried to capture that. You couldn't do that without making some assumptions about leakage. There had to be a leakage from the containment.

And so, they -- there could be either leakage from the containment, there could be melt-through of the base mat and there could be leakage there. That would be a possibility, but somehow there had to be a leakage in order to get the depressurization curves that they saw.

CHAIR CORRADINI: So, can we go back? Can I go back? So, what you're focusing on is the orange dots.

MR. HUMPHRIES: Yes. Uh-huh.

CHAIR CORRADINI: Okay. And so, the question is, how do I get a calculation to match the orange dots?

MR. HUMPHRIES: Yes. From here down to these orange dots, yes.

CHAIR CORRADINI: Okay.

MR. HUMPHRIES: And to be able to do that, you have to make assumptions about leakage and some assumptions about the injection rate.

So, they did a series of -- there series of calculations where they assumed different leakage rates. So, they assume a fraction of the area fraction for the leakage rate and they changed it by one order of magnitude.

And so, each of these series of calculations represents a different leakage rate. And the individual curves represent assumptions that were made for the injection rate as a function of time -- actually there were constant injection rates, is what they're assumed. They didn't assume a variation over time, but just a constant value that changed.

And so, they did these variations and found that in order to capture the depressurization, they had to have a 0.1 drywall head flange leak fraction.

CHAIR CORRADINI: When you say "0.1," 0.1 what?

MR. HUMPHRIES: Yes. It's based on the --

CHAIR CORRADINI: Like, percent per day or what? What --

MR. HUMPHRIES: It's an area fraction, basically. So, it's an area --

CHAIR CORRADINI: Oh. Oh. So, this is a whole size.

MR. HUMPHRIES: A whole size, yes. Uh-huh.

CHAIR CORRADINI: Oh. So, ten percent of

the flange area would be leaking?

MR. HUMPHRIES: Yes.

CHAIR CORRADINI: Am I understanding that correctly?

MR. HUMPHRIES: Yes. And the flange area is not, you know, the cross-sectional area of the containment. It's the --

CHAIR CORRADINI: It's the gap.

MR. HUMPHRIES: Yes, it's the gap. That area. So, they assumed a ten percent flange leak rate to be able to get that.

Whether it was due to the leakage of the flange or whether it was due to something else like a melt-through of the cavity, they've had to assume something in order to -- some sort of a leakage.

CHAIR CORRADINI: Is this in support of Dr. Rempe's forensics -- Joy's --

MR. HUMPHRIES: I think so. I don't know for sure.

CHAIR CORRADINI: I can ask that question of Dr. Rempe.

MR. LEE: Excuse me. This is Richard Lee from Resource. This has to do with the NEA Fukushima benchmark.

CHAIR CORRADINI: Oh, this is a benchmark calculation?

MR. LEE: Yes.

CHAIR CORRADINI: I see.

MR. LEE: At different countries. This is the US and Aussie one.

CHAIR CORRADINI: I thought you do what Dr. Rempe asked of you.

MR. HUMPHRIES: So, this one was showing the generation of gases due to metal in the cavity. I'm not sure what exactly to say to this other than since then they revised the model.

This didn't include rebar in the cavity and so they are actually calculating larger release of gases.

MEMBER REMPE: So, can we -- we didn't talk about what you're doing with the spreading model and the cavity stuff. And you're grinning like --

MR. HUMPHRIES: It was in the report.

MEMBER REMPE: It was in the report, but all they basically said was they're going to do what's in MELSPREAD, is what I saw.

And so, right now, I mean, you're aware of how the -- sometimes Mitch talks about what MAAP would predict with spreading and what MELCOR would predict with spreading.

Are you going to see spreading more -- will it be more fluid and spread further, the results of the model, or what are you doing, actually?

MR. HUMPHRIES: So, we implemented a spreading model that's looking at viscous forces and gravity forces to spread the debris.

We added a new model. By default, MELCOR does not have a spreading model. So, by default, if you had debris that relocated in the cavity, it would spread and cover the entire cavity floor immediately in the first timestep. However --

CHAIR CORRADINI: But you can cheat.

MR. HUMPHRIES: Yes. We have a control function that can be used by users to dictate the spread radius as a function of time.

So, you -- and that's what they do in the analyses --

CHAIR CORRADINI: But you're still 2-D symmetric.

MR. HUMPHRIES: Yes. Yes, we are.

CHAIR CORRADINI: But, I mean, this all goes back to -- unfortunately, it goes back to the ray system that MELCOR or CAV or CORCON or whatever you call it, was developed on.

You can essentially put a ray with variable elevation to make it fill like a bathtub and do it that way and that's it -- kind of it's own automatic spreading. You know what I'm saying?

Because I know that was tried by some people -- again, we're back on the crosswalk, phase 1, back before you were doing the MAAP/MELCOR comparison. And if you just change the elevation and you make it slightly deeper and slightly higher, you can make it just fill up like a bathtub and it will just essentially its own hole.

You know what I'm -- you know?

MR. HUMPHRIES: Yes. But typically --

CHAIR CORRADINI: And it works, actually, quite well.

MR. HUMPHRIES: But typically we just use the control function to control that. We're not as clever, I guess.

CHAIR CORRADINI: But it's built inside the code. Nobody uses it. It's built in from when Dr. Muir (phonetic) wrote CORCON back in 1970 something.

MR. HUMPHRIES: So, there's capabilities to do that. But for a new user, you really need to have some kind of model there for you.

CHAIR CORRADINI: Yes.

MR. HUMPHRIES: And so, that's why we

added this spreading model so that they didn't have to have a correlation for the spreading as a function of time.

So, we put in this model, we've done some comparisons. It's really hard to validate it against experiments because of that limitation of we're assuming pancake spreading.

And a lot of these experiments are channels. You're looking -- like the volcano experiments, it's looking at spreading through a channel. How you do that with MELCOR? It's very, very difficult.

We've done some -- try to do some validation by making some assumptions to do that, but really what I -- what I'm more satisfied with is looking at the comparisons between a pancake spread model by MELCOR and a pancake spread model by MELSPREAD and doing a code-to-code comparison and letting the burden of the validation lie on MELSPREAD, though we do look at the CCI -- we've looked at the CCI tests and used them as part of our validation.

MEMBER REMPE: So, again, I'm looking at a plot right now -- or a picture, and it has MELSPREAD/MAAP predictions and the stuff's all over, and whereas MELCOR kept it in a small region out of --

this is Fukushima 1F1 and it didn't spread as far, and will it spread further?

MR. HUMPHRIES: Part of that is not all due to the spreading model. Part of it is due to the condition of the debris when it reaches the cavity.

If it's really, really hot and liquid, then it's going to spread more. And if it's colder, then it's not going to spread as much.

MR. ESMAILI: And I think MAAP always predicts that what comes out is always much hotter than what comes out of MELCOR, because --

MEMBER REMPE: So, you won't see a lot of difference, is what you're saying, because of the way the debris is. Okay.

MR. ESMAILI: So, yes, the different temperatures are very --

MR. HUMPHRIES: And we've actually compared this new model against what they were using as a correlation for the spread rate, and we get good agreement there also.

MEMBER REMPE: Okay. Thanks.

MR. HUMPHRIES: Uh-huh. So, this is looking at containment using our latest model for Fukushima. So, the containment pressures.

So, this is -- the pressure rise is a

function of time and it's dictated by the pressure that's received by the SRV cycling and RCIC operation and recirculation pump leak.

And I asked the person that did this modeling, "Well, how were you able to get such good agreement?"

And he said, "Well, there are certainties in the way you would model the suppression tank." There would be temperature gradients that we're not able to capture in MELCOR, because we don't look at -- we didn't look at stratification.

We do look at possible -- a hot spot looking at annular nodalization of the suppression tank so you could have a hot spot, but we don't look at the axial temperature profile that might exist.

And so, he felt that there was some luxury for some changes to the assumed recirculation pump leak. So, he was able to capture it by changing the recirculation pump leakage to be able to get the pressure response.

And then at 20 hours, we see a drop in the -- and if Jeff Cardoni is on there, if there's anything you want to correct me as we talk, that would be great.

And then at 20 hours, the wet well sprays and the dry well sprays come on and we see a drop in the pressurization. And then, main steam line rupture occurs at about 45 hours.

And you'll see that in the MELCOR calculation, you see a spike that corresponds to the spike, but there's an early increase in the pressure that wasn't picked up.

And Jeff pointed out that he did some uncertainty runs to look at what might be the reason for this and looked at some variations that resulted in earlier oxidation, and he was able to attribute this early pressure response due to an earlier onset of oxidation in the core.

And then core slump occurs, and MELCOR captures that. And then there are a series of pressurization followed by depressurization, and MELCOR has to assume some leakages to be able to capture those depressurization events.

MR. ESMAILI: Before you go off, so I think this is something that shows that if you just take away the MELCOR plots and everything else and you are just looking at the data, it's very, very difficult to figure out what's going on.

So, this is where a code like MELCOR, or any other code, can become handy in trying to explain why we are seeing these peaks and valleys, et cetera.

So, you know, we have to make some assumptions in terms of, you know, how much, you know, like, you have leakage, et cetera, that shows that, okay, so if this leak occurs, we think -- and we have to still prove it, we think it's because of the main steam line rupture, or this other peak is that we got this peak, but we also get it in the MELCOR.

And so, this is important in terms of being able to explain what happens during the accidents.

MEMBER KIRCHNER: So, what model of MELCOR predicts the main steam line rupture?

MR. ESMAILI: It's just the --

MR. HUMPHRIES: The creep model. It's the Larson-Miller creep model.

MR. ESMAILI: It's a type of temperature creep model. It looks at the pressure inside the steam line and looks at the temperature. So, we actually calculate the temperature of the steam --

SPEAKER: (Speaking off mic.)

MR. ESMAILI: We, you know, here, you have to be -- Jeff, are you online? Jeff Cardoni? Okay. We are taking -- so, I want to say we are trying -- we are trying to see what changes we have to make to the code to be able to predict this and does this -- do these changes, you know, it's not like we are blindly predicting this.

So, we want to see that -- does this creep that we get at this particular -- timing was not important for us. Whether we get this peak at that time, it was not that important, but --

MEMBER KIRCHNER: You input the main steam line rupture to get that pressure --

MR. ESMAILI: No, but we did put in some modeling parameters, right, to induce -- do you remember, Richard? I don't know how best to say.

MR. LEE: I just remember the MELCOR calculations, the flow coming through.

So, you remove a lot of heat from the core. So, that's why the outer part of the containment, the piping, is very hot.

So, as Hossein said, parameter is used for the -- melting the hot leg, the steam line. Once you satisfy the criteria, it opens it up and that's all in the calculation. There's no predetermine when you should open it up.

So, if you don't assume that for other -- for example, the Japanese, other people really don't believe in the so-called main steam line break. They assume other rupture in order to look at the so-called peaks, for example.

MEMBER KIRCHNER: They assume an SRV failure.

MR. LEE: They assume SRV failure. So, right now we still do not know -- of course, no one knows which is -- who is right.

MEMBER KIRCHNER: Right.

MR. LEE: So, every code does it differently, except the MELCOR is the only one calculating the main steam line break at this time.

MR. ESMAILI: So, we are not saying that this is exactly what happened and MELCOR predicts it at exactly that time, but --

MR. LEE: And meet that criteria at time-at-temperature.

MR. HUMPHRIES: So, this is the RPV pressure as a function of time.

CHAIR CORRADINI: So, these are all part of -- these are all part of what you started -- no, no, I understand, but these are all part of the benchmark.

MR. LEE: The benchmark --

CHAIR CORRADINI: Okay.

MR. LEE: -- which is ongoing.

CHAIR CORRADINI: Okay. But you didn't -- you had to do something to make this timing come out exactly right. Let's just -- let me say it directly.

MR. HUMPHRIES: I think there are places -- there are, like, milestones that they want to meet. And so, they force certain things at certain times.

I believe that vessel failure, they were able to calculate it, you know, within a certain range, but they ended up in a calculation forcing it at a particular time so that they could go and make some sense out of the subsequent realization.

MR. ESMAILI: So, it's a forensic study. We tried to see what happens by making --

CHAIR CORRADINI: You know where the body is, you're just trying to figure out --

MR. ESMAILI: Right. And then once you open it up and see if it happened the way it's stated.

MEMBER REMPE: But it helps guide us on what to look for when you open it up. So, it does help the other way.

MR. ESMAILI: Right.

MR. HUMPHRIES: This was one thing that Jeff pointed out that was very important, was that these depressurizations, you see that there's a trend here that it follows.

Jeff had to make some assumptions about the main steam line rupture. Rather than assuming that it was a double guillotine break, he assumed a fraction of the area to break. And that was necessary in order to get that depressurization curve.

I think that's it.

CHAIR CORRADINI: Okay. Questions by the committee. We haven't asked you many yet. So, let me go around the table. I guess we have to first -- thank you. I think we first have to have public comments.

So, if we have anybody left in the room and, Theron, can you open up the public line? And if somebody is on the public line, can you please --

MR. WAGNER: Hello.

CHAIR CORRADINI: Yes.

MR. WAGNER: Casey Wagner, Dakota. I'm just identifying that the line is open.

CHAIR CORRADINI: Thank you. Okay.

Is anybody else a member of the public wanting to make a statement?

Okay. Let's close the line -- mute the line and let's go around the table.

Member Ballinger.

MEMBER BALLINGER: No.

MEMBER SKILLMAN: Hossein and Larry, thank you.

CHAIR CORRADINI: You've not asked any questions, Member Stetkar.

MEMBER STETKAR: No, I haven't, but thanks. That was -- I actually learned stuff today. I can't repeat it because I don't speak that language, but one of the things I did learn -- and that's why I ask Tina when we do have the SOARCA subcommittee meeting in June, we're going to be really interested in hearing the story about how they changed the uncertainty analyses for the safety -- the pressurizer safety valve.

Because what I learned today is not so much hydrogen related to MELCOR, a lot of hydrogen related to how they're modeling the safety valves. So, that's what I learned today and thank you for that.

MEMBER MARCH-LEUBA: No comment.

MEMBER KIRCHNER: Thank you both.

MEMBER REMPE: I also would like to thank you both, as well as the folks on the line, because I learned a lot too.

I again would like to better understand if there are any changes in the actual Sequoyah analysis and to see some plots that way and understand what caused the changes if they occurred. Thanks.

CHAIR CORRADINI: So, since everybody else has thanked you, I won't, but I think it's been very illuminating.

I do want to make sure that, then, when you have John's meeting in June, that you can at least refer back to some of these things, because I think the key thing for the Sequoyah uncertainty is going to be hydrogen production and the timing of the combustion event.

So, you've got to help us as --

MEMBER STETKAR: But, again, that's not going to come from anything we heard today. That's literally going to come from -- the amount of hydrogen produced early is the same amount of hydrogen that was always produced early, it's just not as much as getting released early. And then, therefore, you're not burning as much early.

CHAIR CORRADINI: Early.

MEMBER STETKAR: Early. All the later stuff doesn't affect the large early release frequency, which is what we're interested in at Sequoyah, right?

CHAIR CORRADINI: Right.

MR. ESMAILI: So, it was important to say what they did in MELCOR --

MEMBER STETKAR: Right.

MR. ESMAILI: -- is not going to greatly affect --

MEMBER STETKAR: Right. I mean, you

know, I'm sure there's a numerical --

MR. ESMAILI: Right. And we are trying to show you --

MEMBER STETKAR: Yes. From the late hot leg rupture stuff, but --

MR. ESMAILI: So, we can make that June meeting like two-hour meeting?

MEMBER STETKAR: No.

CHAIR CORRADINI: No, I don't think that's going to happen. So, I don't have any other comments. We'll see you again in June. Hossein will be here.

MEMBER REMPE: We'll ask for you.

(Laughter.)

CHAIR CORRADINI: All right. With that, we'll adjourn.

(Whereupon, at 5:46 o'clock p.m. the meeting was adjourned.)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

NRC Severe Accident Research and MELCOR Computer Code

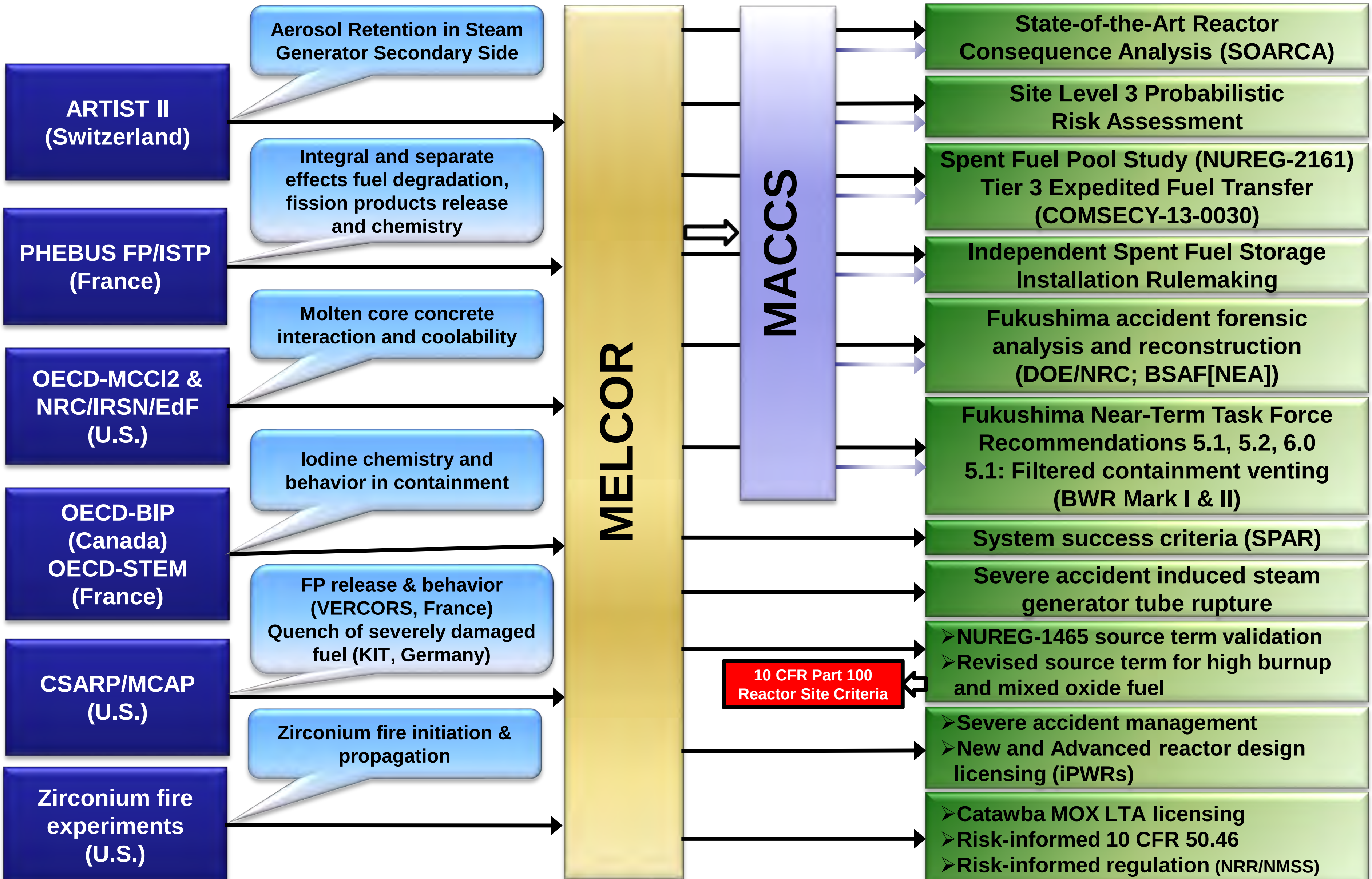
Office of Nuclear Regulatory Research

April 18, 2017

Severe Accident Research Activities

- Support Risk-informing Regulations and Address Operating Reactor Issues and New Reactor Design Certification
  - Maintenance of expertise of severe accident phenomenological knowledge and validated analytical tools
- International Collaboration
  - U.S. NRC Cooperative Severe Accident Research Program (CSARP)
  - Annual MELCOR Meetings
    - MELCOR Code Assessment Program (MCAP) - (Fall/USA)
    - European MELCOR User Group (EMUG) – (Spring/Europe)
    - Asian MELCOR User Group (AMUG) – (Fall/Asia)
  - NEA/CSNI and European Commission

Code Development & Regulatory Applications



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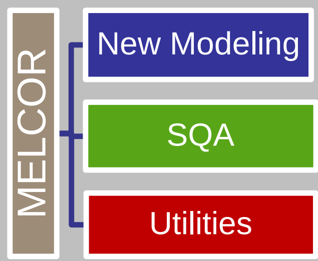

Overview of MELCOR and Selected Models

ACRS Briefing on MELCOR Modeling - April 18, 2017

Presented by Larry Humphries
llhumph@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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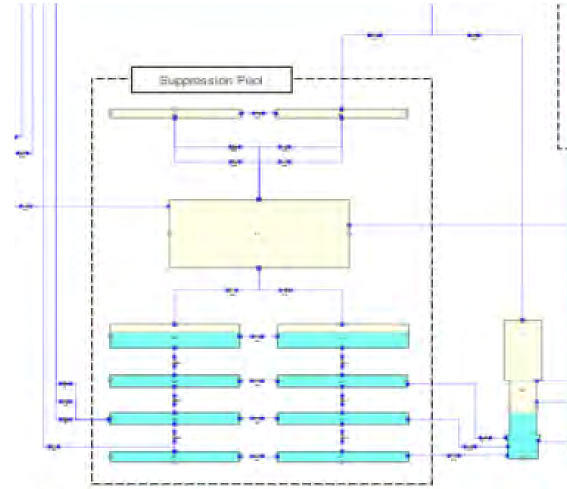
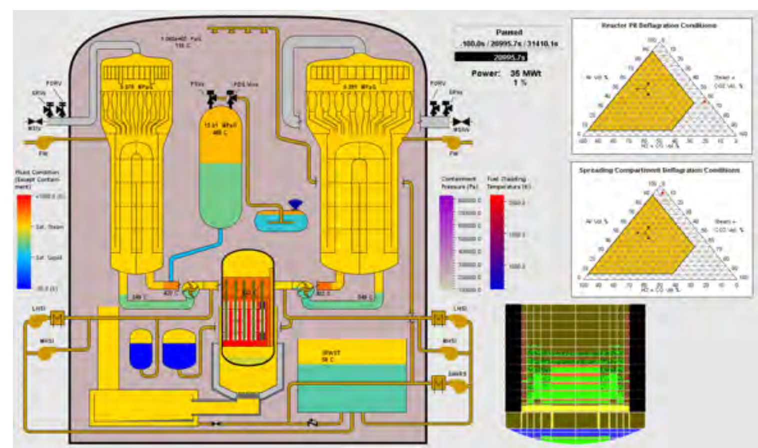
What is Required of a Severe Accident Code

- Fully Integrated, engineering-level code
  - Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
  - Core heat-up, degradation, and relocation;
  - Core-concrete attack;
  - Hydrogen production, transport, and combustion;
  - Fission product release and transport behavior
- Application
  - User constructs models from basic constructs
    - Control volumes, flow paths, heat structures,
  - Multiple ‘CORE’ designs
    - PWR, BWR, HTGR (Pebble Bed & PMR), PWR-SFP, BWR-SFP, SMR, Sodium (Containment)
  - Adaptability to new reactor designs
- Validated physical models
  - ISPs, benchmarks, experiments, accidents
- Uncertainty Analysis
  - Relatively fast-running
  - Characterized numerical variance
- User Convenience
  - Windows/Linux versions
  - Utilities for constructing input decks (GUI)
  - Capabilities for post-processing, visualization
  - Extensive documentation





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MELCOR Code Structure

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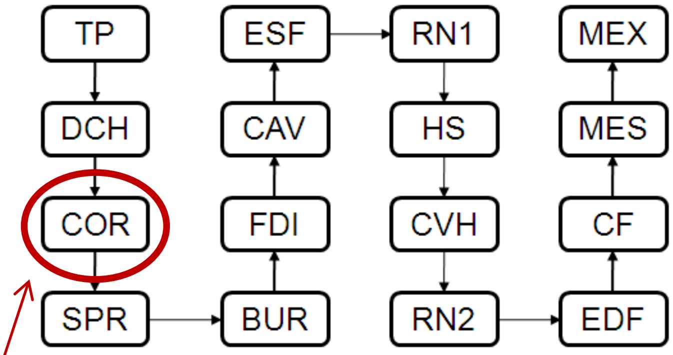
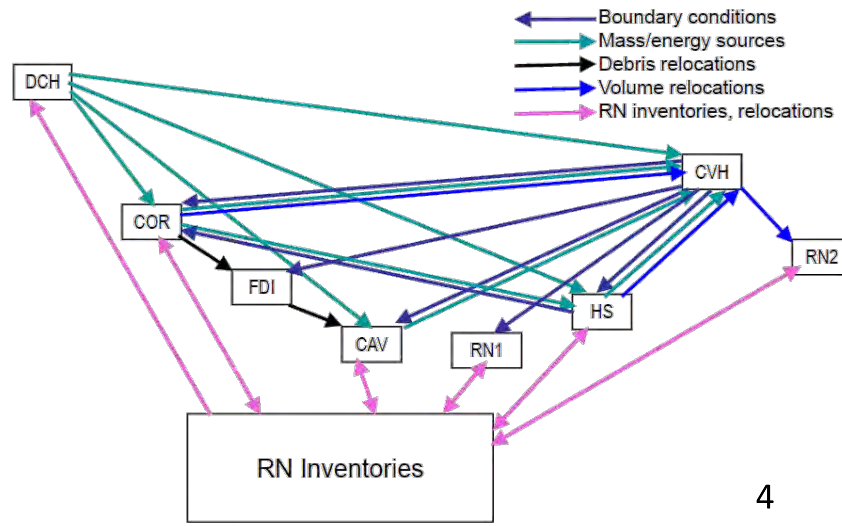
- Maintainable code structure
  - Modular architecture, portable to new systems
- Major pieces of MELCOR referred to as "Packages"
  - **Basic physical phenomena**
    - Hydrodynamics, heat and mass transfer to structures, gas combustion, aerosol and vapor physics
  - **Reactor-specific phenomena**
    - Decay heat generation,
    - **core degradation and melt progression**
    - ex-vessel phenomena (e.g., core concrete interactions)
    - sprays and engineered safety features (ESFs)
  - **Support functions**
    - Thermodynamics, equation of state, material properties, data-handling utilities, equation solvers

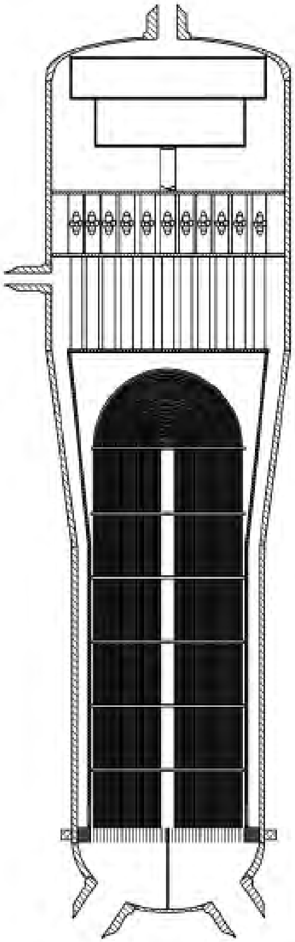


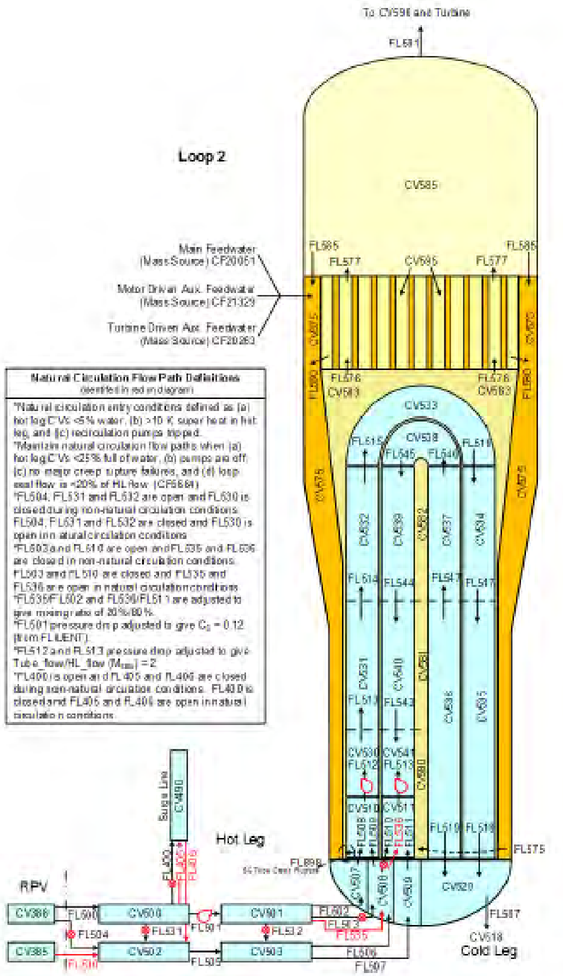
TP = Transfer Process
DCH = Decay Heat
COR = Core
SPR = Containment Spray
BUR = Gas Combustion
FDI = Fuel Dispersal Interaction
CAV = Cavity (MCCI)
ESF = Engineered Safety Features

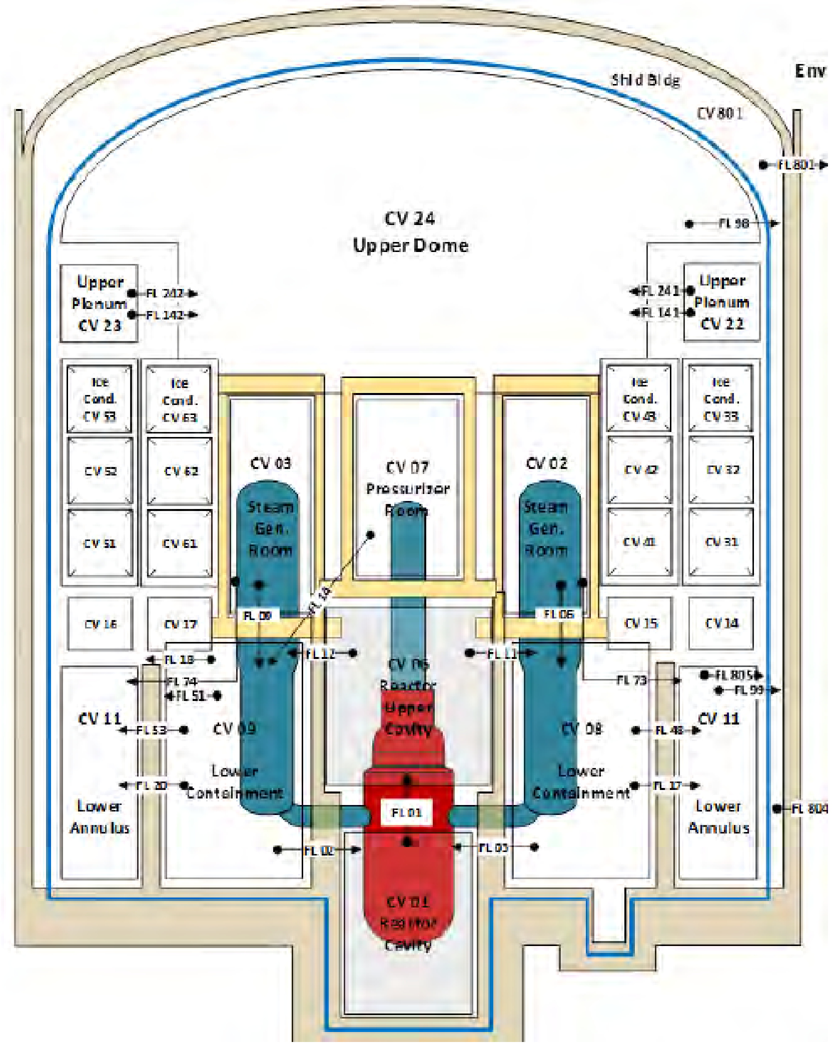
RN = Radionuclide
HS = Heat Structure
CVH = Control Volume Hydrodynamics
EDF = External Data File
CF = Control Function
MES = Special messages
MEX = Executive



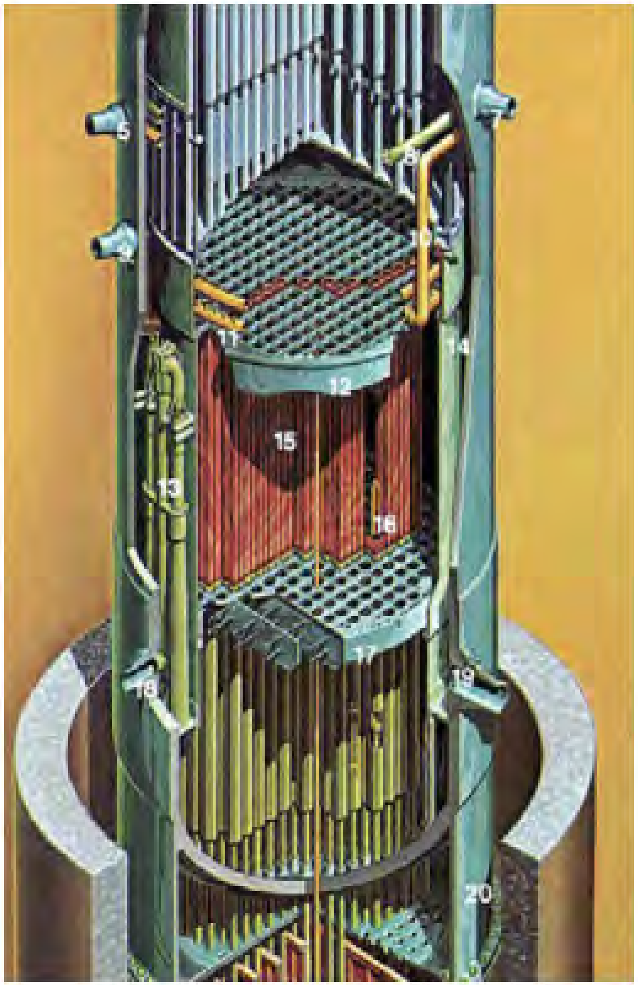
MELCOR discretizes problems into an interconnected set of CVH volumes







The in-vessel core region is further subdivided into “COR package” cells



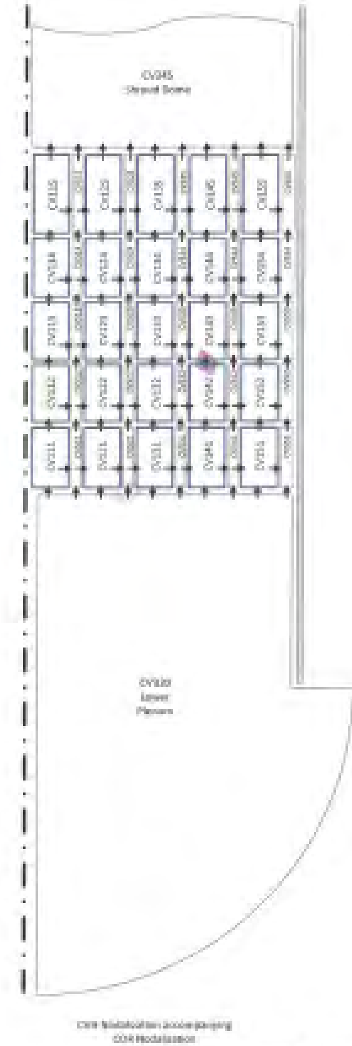
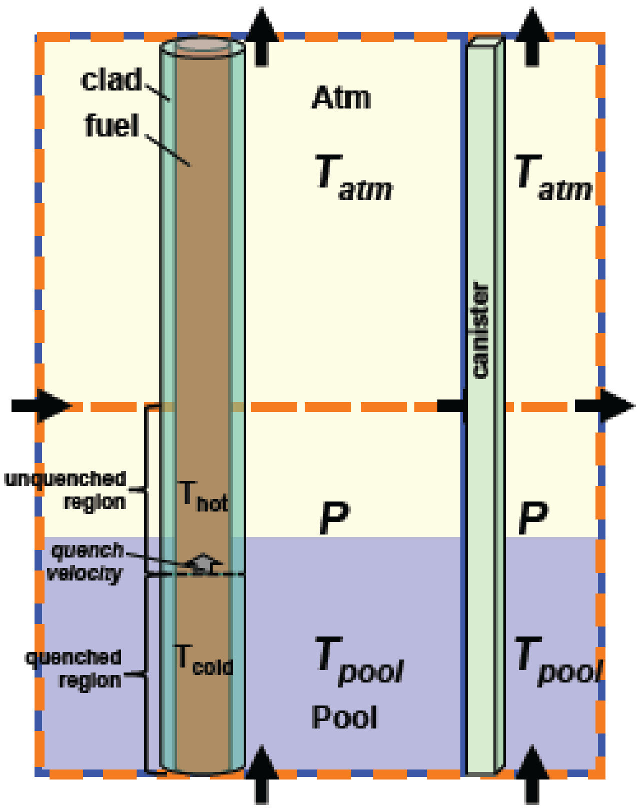


Illustration of modeled items in two simple MELCOR CVH control volumes



- 2 CVH Control Volumes
  - Each with “Pool” and “Atm”
- Pool
  - Water and vapor bubbles in thermo equation
- Atm
  - Vapor, NC gases, water droplets
- 7 Flow Paths
- 3(x2) Core Components
  - Clad, fuel, and canister represent multiple copies
- Quenched and unquenched regions in each core component

MELCOR CVs represent finite-size regions within which a large set of coupled non-linear equations (i.e. models for conservation laws, transport rates, etc.) are active.

A Partial Listing of MELCOR Equations

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- **Mass and Energy Conservation Equations**
  - **CVH: for each of two fields**
  - **COR: for each component**
  - **. . . Other “packages”**
- **Equations of State (Thermodynamics)**
- **Flow Path Velocity Equations**
- **Mass/Energy Release and Transfer Rates**
  - **Convection, conduction, radiation, fission heating, oxidation, . . .**
- **Material Form Transfer Equations**
  - **Clad failure, debris formation, etc…**
- **Material Property Equations**
- **Geometric Form (Morphology) Equation**

Some Characteristics of MELCOR Equations

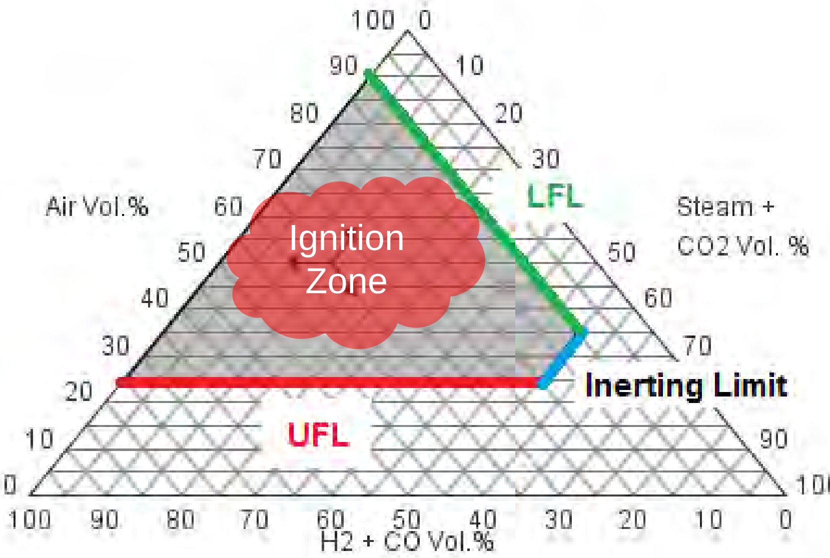
- The equations are "coupled", i.e. they are interdependent on one another in many different ways.
- The conservation equations are written in temporal form, but generally use time-independent closure laws to represent transfer rates (convection, friction, etc.)
  - This means temporal accuracy is "zero" order accurate, i.e., the direction is correct, but has no error bound on time-step accuracy
- MELCOR solves discrete "numerical" approximations to the modeled equation set that uses a mixture of "explicit" and "implicit" temporal integration schemes.
- Different types of physics are modeled in distinct packages (CVH, COR, HS, RN1, …). These are solved sequentially and separately during each system time step.

BURn Package

- Burns in MELCOR involve the following determinations
  - Ignition Criteria – Mole fraction criteria permitting a burn to occur
    - Two limits may be defined (burns may also be disallowed in user specifies volumes)
      - Spontaneous deflagrations / Igniter initiated deflagrations
        - » Control function (CF) may be used to actuate an igniter
          - » Recent SOARCA modeling use the igniter CFs to incorporate all of the ignition criteria
      - Irrespective of flame direction front
  - Burn Rate – Moles of gases reacted during a time step (HECTR 1.5)
    - Burn Completeness – Mole fraction of combustible left at end of burn (solved at start of burn)
    - Burn Duration – Duration of a given burn (solved at the start of burn)
      - = Characteristic volume length / Flame Speed (HECTR Correlation)
    - Rate = (X(t) – BurnComplete)/(BurnDuration – TimeSpentBurning)
  - Propagation Criteria – Mole fraction criteria permitting a burn to transfer to another control volume
    - Propagation directional ignition criteria (4%/6%/9%)
    - Ignition criteria check after Const(def=0.0)*BurnDuration

MELCOR BurnPackage Ignition Criteria

- Shapiro Model – Spontaneous Combustion
  - Constant limits
    - Lower Flammabiltiy Limit (LFL)
      - 10% H_2 (+CO adjusted)
    - Upper Flammabiilty Limit (UFL)
      - 5% O_2
    - Inerting Limit
      - 55% CO_2 + H_2O
    - Control volume mole fractions are evaluated against these limits
- Note the use of "Air" implies set N_2/O_2 concentrations



COR Heat Transfer

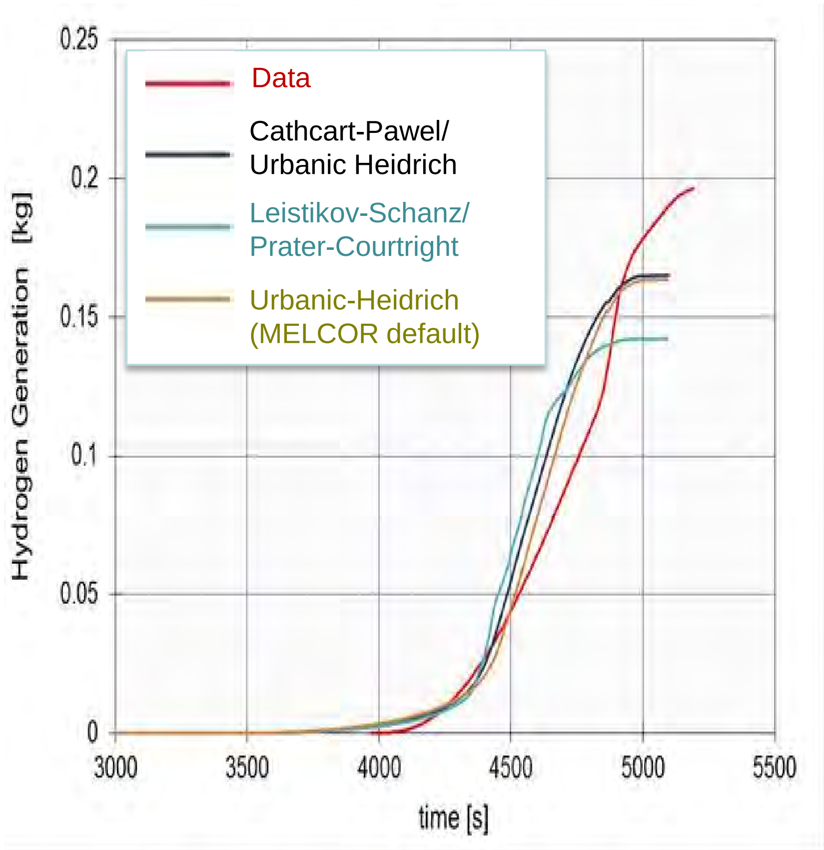
- Conduction
  - Axial Conduction
  - Radial Conduction
  - Intracell
- Convection
  - Heat transfer rates calculated for each component using heat transfer coefficients
    - Uses Local cell temperature predicted from dT/dz model
  - Does not use a critical Reynolds number to determine laminar or turbulent flow regimes
    - Maximum of laminar/turbulent, forced/free
  - Convective heat transfer from contiguous molten pools treated separately
- Radiation
  - Simple radiative exchange model
    - Global radiation exchange factors
    - Local radiation exchange factors
  - Geometric radiation exchange model
  - Multi-rod model

$$A_1F_{12} \equiv A_2F_{21} \equiv AF = \min(A_1, A_2, A_{cell,x})F_{cell,x}$$
$$= A_{cell,x}F_{cell,x}\min(A_1/A_{cell,x}, A_2/A_{cell,x}, 1)$$

Oxidation Models - General

- Oxidation behavior for COR components
  - Oxidation of Zircaloy and steel by water vapor and/or O_2
  - Oxidation of boron carbide (B_4C) in BWRs
  - Heat generation by oxidation
  - Release of hydrogen (and other gases) to CVH package
- Oxidation kinetics models
  - Urbanic-Heidrich
  - Cathcart-Pawel/Urbanic Heidrick
    - CP when T< 1853K
    - U-H when T> 1873 K
  - Leistikov-Schanz/Prater-Courtright
- Several air oxidation models to choose from
- Several options for enabling breakaway

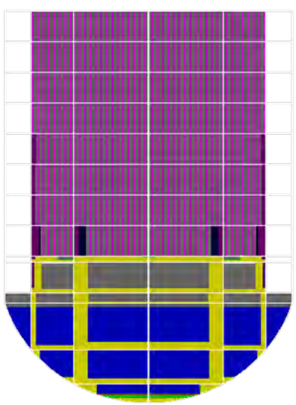
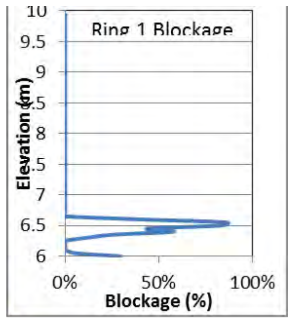
CORA-13



COR Degradation Models

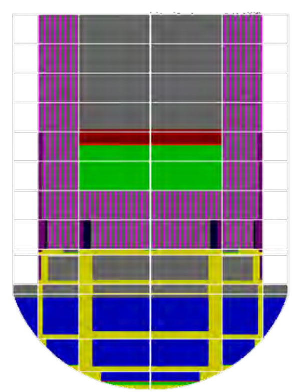
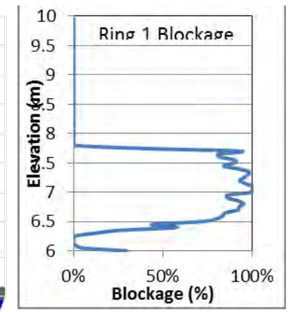
- Ballooning Model
  - There is no comprehensive model for clad ballooning in the code though MELCOR provides limited capabilities for simulating the effects.
    - Gap release model
      - Gap release at user temperature (1173 K default)
- Candling
  - Thermal-hydraulic based
    - (does not account for viscosity or surface tension)
    - Does not have a separate field (temperature)
  - Simple holdup model for melt inside an oxide shell
  - Formation of blockages from refrozen material
- Formation of Particulate debris
  - Failure temperature / component thickness / CF / support structures
  - Clad optional time at temperature modeling (best practice)
  - Downward relocation of (axial and radial) by gravitational settling
    - not modeled mechanistically but through a logical sequence of processes through consideration of volume, porosity, and support constraints.
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates
  - Support structure modeling for COR components leads to failure of supported intact components when support structure is lost
- Molten Pool Modeling
  - Forms when downward candling molten material reaches a blockage and still has superheat
    - Settling similar to particulate debris but particulate debris displaces molten pool
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates

Sub-Grid Model Prediction of Blockages

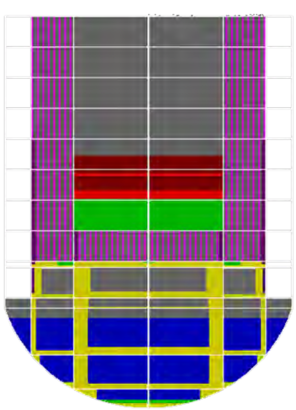
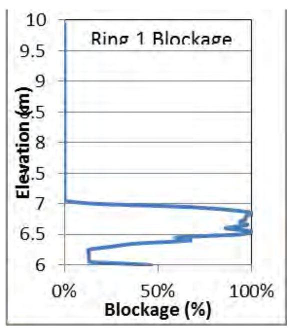
Candling of low melting point metals to lower fuel rods

1998 (sec)

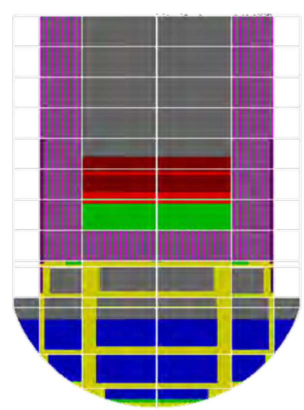
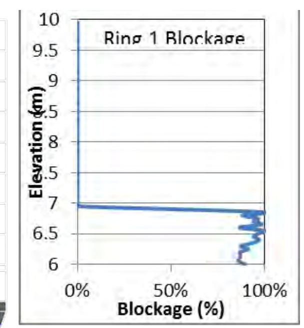
Formation of PD and conglomerate filling interstitials

2008 (sec)

PD slumping and maintaining blockages

2414 (sec)

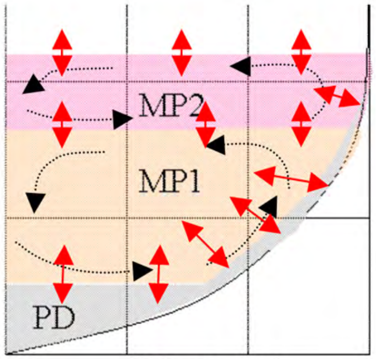



Melting of PD 'crust' and freezing on lower fuel rods

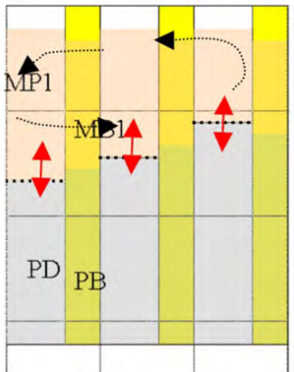
2462 (sec)

MELCOR Core Phenomenon Stratified Molten Pool Model

- Treat molten pools, both in core and lower head
  - Can contain oxidic and metallic materials
  - May be immiscible, and separate by density
  - Same approach in core and lower head
    - Requires distinguishing pool in channel from that in bypass
- Stratified melt pool - Additional material relocation models
  - Downward and radial flow of molten pools
  - Sinking of particulate debris in molten pool
    - Particulate displaces pool
  - Stratification of molten pools by density
    - Denser pool displace less dense
      - Currently oxide pool is assumed denser
  - Partitioning of fission products between metallic and oxidic phases
    - Can affect heat generation and natural convection in core molten debris.



Molten pools in lower plenum



Molten pool in upper core

Backup Slides

MELCOR Development

- Design Objectives
  - Model severe accidents and provide reasonable prediction of accident progression, source term, and their uncertainty
  - Model containment thermal-hydraulic phenomena for design basis analysis (DBA)
  - Properly scale phenomena important to DBA and severe accidents from separate effect tests and integral effect tests (SET/IET) to full size reactors
  - Modeling consistent with lumped parameter code framework (simplified vs. complex)
- Targeted Applications
  - Perform plant specific integrated analysis under postulated beyond DBA events and application to probabilistic risk assessment (PRA)
  - Perform containment response analysis under postulated DBA/beyond DBA events
  - Perform accident analysis of non-reactor systems (e.g., spent fuel pool)
- Success Criteria
  - Prediction of phenomena in qualitative agreement with current understanding of physics and uncertainties are in quantitative agreement with experiments
  - Focus on mechanistic models where feasible with adequate flexibility for parametric models
  - Code is portable, robust and relatively fast running and the code maintenance follows established Software Quality Assurance (SQA) standards
  - Availability of detailed code documentation (including user guide, model reference, and assessment)

MELCOR Development History (1)

- MELCOR 1.8.2 (1993)
  - One of the earliest versions for widespread release
  - Not recommended for use
- MELCOR 1.8.3 (1994)
  - BH Package (no longer used)
  - CORCON-MOD3
  - Not recommended for use
- MELCOR 1.8.4 (1997)
  - Retention of molten metals behind oxide shells
  - Vessel creep rupture model
  - Flow blockage model
  - Radiant heat transfer between Heat Structure (HS) surfaces
  - Hygroscopic aerosols
  - chemisorption on surfaces
  - SPARC 90 (pool scrubbing of fission products)
- MELCOR **1.8.5** (2000)
  - Control function (CF) arguments could be added to plot file
  - Consistency checks on COR/CVH volumes
  - Iterative flow solver added
  - Diffusion flame model
  - Supporting structure (SS) & non-supporting structure (NS) components added for structural modeling
  - Upward & downward convective & radiative heat transfer from plates
  - Particulate debris in bypass introduced
  - Improvements to candling, debris slumping, and conductive, radiative, and candling heat transfer
  - Passive Autocatalytic Recombiner (PAR) model was added
  - CsI added as a default class
  - Improvements to hygroscopic model
  - Iodine pool modeling
  - Carbon steel was added to MP package

MELCOR Development History (2)

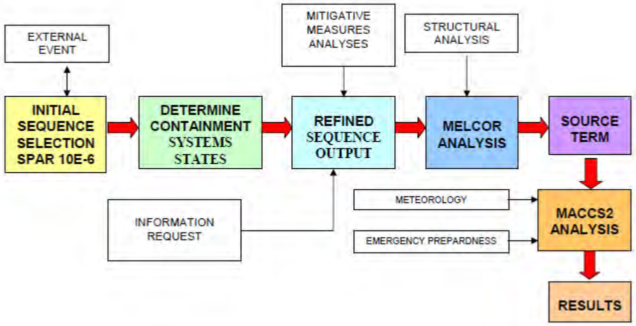
- MELCOR **1.8.6** (2005)
  - An option was added to generate input for the MACCS consequences model.
  - Input was added to simplify conformance with the latest best practices (now defaults in 2.x)
  - New control functions (LM-CREEP & PIP-STR) for modeling pipe rupture
  - Modeling of the lower plenum was revised to account for curvature of the lower head
  - Formation and convection of stratified molten pools
  - Core periphery model for PWRs to model core baffle/formers and the bypass region
  - Reflood quench model
  - Oxidation of B4C poison
  - Release of Ag-In-Cd control poison
  - Column support structures was added
  - Interacting materials added to allow modifying enthalpy tables
  - Spent Fuel Pool modeling
  - Flashing model
  - Modified CORSOR Booth release model added
  - Jet impaction model
  - Hydrogen chemistry models

- MELCOR **2.1** (Beta release in 2006)
  - Code internal structure greatly modified
  - Dynamic memory allocation
  - New input format
  - Formula type control functions
  - New HTGR modeling (PBR, PMR)
  - Counter-current flow model
  - Point kinetics model
  - Smart restart
  - Simplified accumulator model
  - Ability to track radionuclide activities
  - Turbulent deposition model & bend impaction
  - Control function for deposition mass for each deposition mechanism.
  - MELCOR/SNAP interaction in real-time
  - Full report to user of sensitivity values
  - Cell-based porosity
  - Spent fuel pool models
  - Intermediate heat exchanger /machinery models
  - Hydrogen chemistry models

SAC Applications

- Forensic analysis of accidents – Fukushima, TMI, PAKS
- SOARCA
- Risk informed regulation
- Design Certification
- Preliminary Analysis of new designs
- Support of International Code Users
- Non-reactor applications
  - Leak Path Factor Analysis
  - Transport of radiological releases, toxins, and biohazards in buildings, building complexes
    - DOE Safety Software "Toolbox" code

SOARCA PROCESS

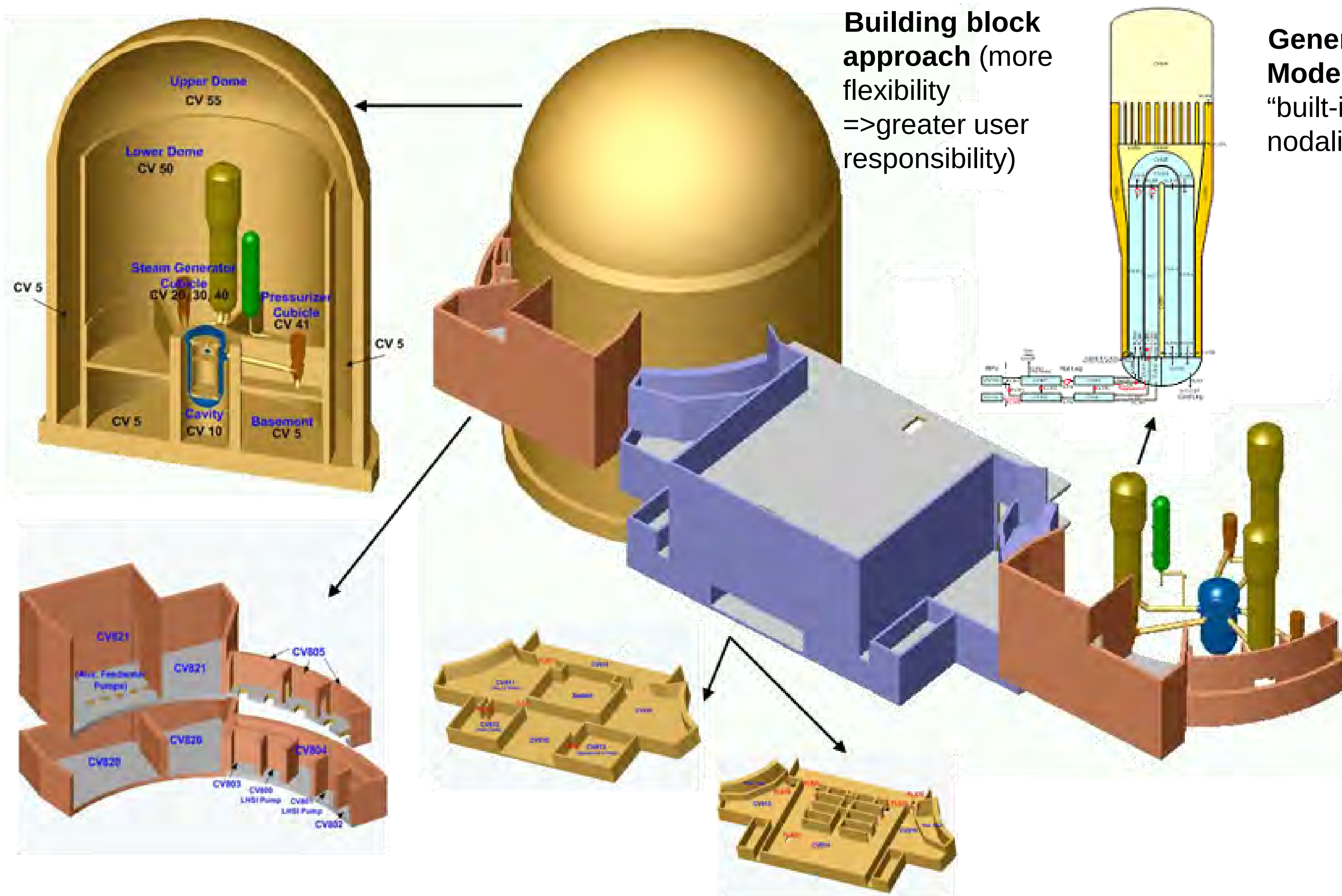


MELCOR's Task:

Simulate under severe accident conditions all of the important components and physical processes in a massive, complex industrial nuclear facility

Building block approach (more flexibility =>greater user responsibility)

Generic Models (no "built-in" nodalization)



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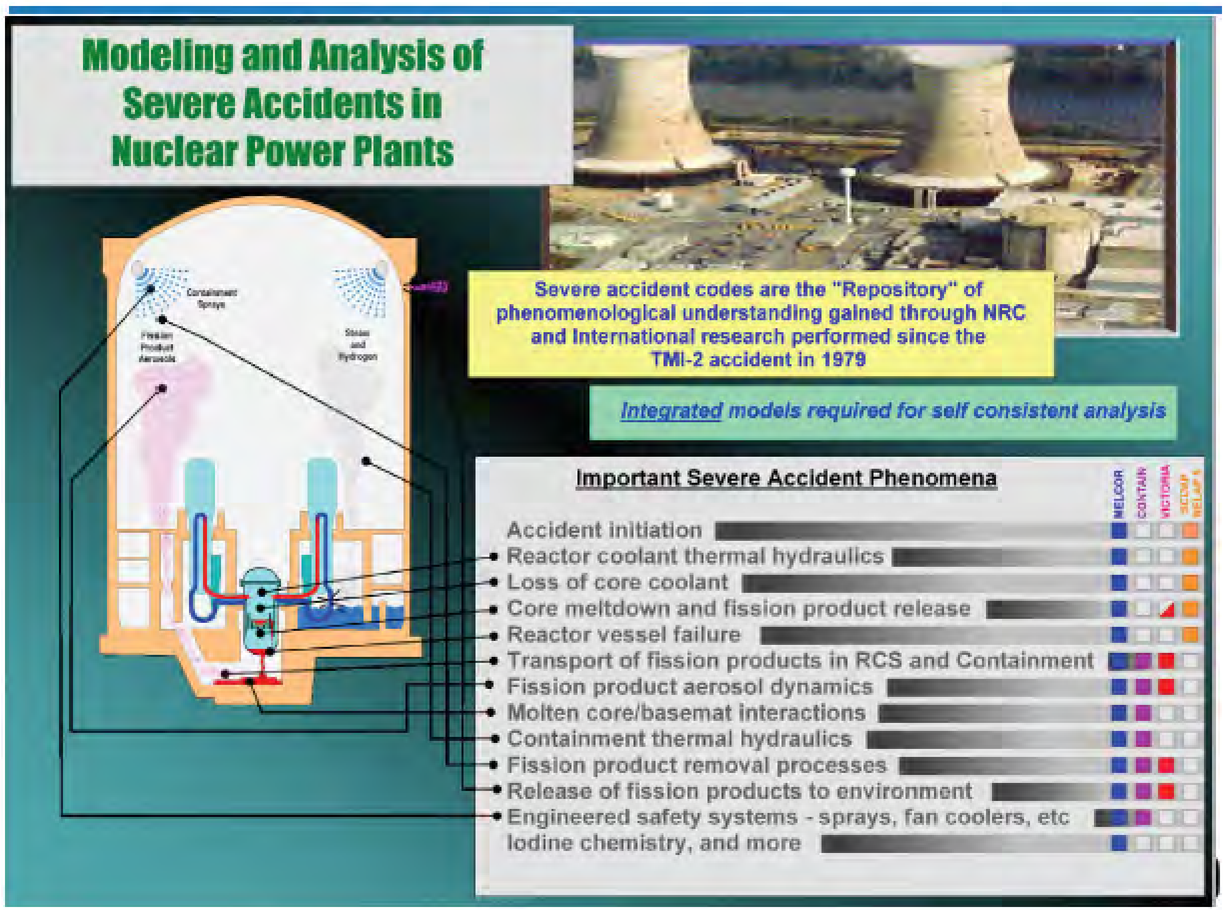
MELCOR Equation set represents models for a host of Severe Accident Phenomena



MELCOR CVH Equations

Mass Conservation

$$M_{i,m}^{n} = M_{i,m}^{o} + \sum_{j} \sigma_{ij} \alpha_{j,\varphi}^{n} \rho_{j,m}^{d} v_{j,\varphi}^{n} F_{j} A_{j} \Delta t + \delta M_{i,m}$$

Energy Conservation

$$E_{i,\varphi}^{n} = E_{i,\varphi}^{o} + \sum_{j} \sigma_{ij} \alpha_{j,\varphi}^{n} \left(\sum_{m} \rho_{j,m}^{d} h_{j,m}^{d} \right) v_{j,\varphi}^{n} F_{j} A_{j} \Delta t + \delta H_{i,\varphi}$$

Velocity model Equation

$$v_{j,\varphi}^{n} = v_{j,\varphi}^{o+} + \frac{\Delta t}{\rho_{j,\varphi} L_{j}} \left(P_{i}^{\tilde{n}} + \Delta P_{j} - P_{k}^{\tilde{n}} + (\rho\, g \Delta z)_{j,\varphi}^{\tilde{n}} + v_{j,\varphi}^{o} (\rho\, \Delta v)_{j,\varphi}^{o} \right)$$

$$- \frac{K_{j,\varphi}^{*} \Delta t}{2 L_{j}} \left(\left| v_{j,\varphi}^{n-} + v'_{j,\varphi} \right| v_{j,\varphi}^{n} - \left| v'_{j,\varphi} \right| v_{j,\varphi}^{n-} \right) - \frac{\alpha_{j,-\varphi} f_{2,j} L_{2,j} \Delta t}{\rho_{j,\varphi} L_{j}} \left(v_{j,\varphi}^{n} - v_{j,-\varphi}^{n} \right)$$

Linearized EOS for Pressure

$$P_{i}^{\tilde{n}} = P_{i}^{*} + \sum_{m} \frac{\partial P_{i}^{*}}{\partial M_{i,m}} \left(M_{i,m}^{n} - M_{i,m}^{*} \right)$$

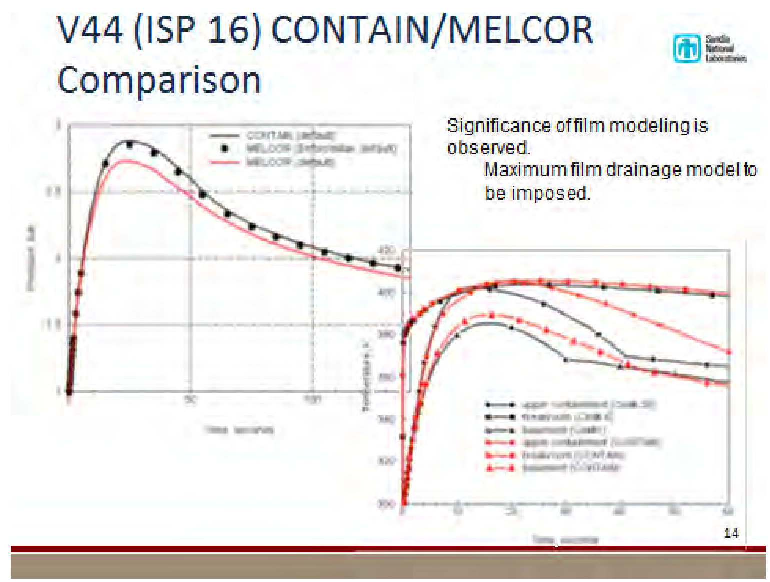
$$+ \frac{\partial P_{i}^{*}}{\partial E_{i,P}} \left(E_{i,P}^{n} - E_{i,P}^{*} \right) + \frac{\partial P_{i}^{*}}{\partial E_{i,A}} \left(E_{i,A}^{n} - E_{i,A}^{*} \right)$$

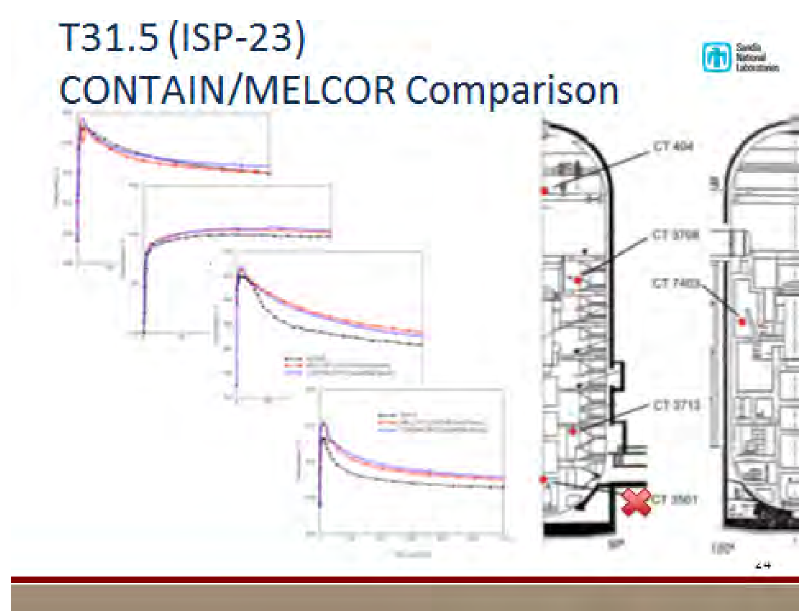
Comparison with Other Codes

MELCOR	RELAP5	TRACE
Back solve mass and energy equations for density and energy	Back solve energy and momentum equations for energy and velocity	Back solve energy and momentum equations for energy and velocity
Conservation of Mass	Conservation of Momentum	Conservation of Momentum
$P = EOS(\rho, e)$	$\rho = EOS(P,e)$	$\rho = EOS(P,e)$
No Flow regime map Momentum exchange between pool and atm to reproduce Wallis flooding curve	Flow regime map	Flow regime map

MELCOR Containment Thermal Hydraulics

- Test provides an indication of the effect of forced convective condensation during a blowdown event.
- Significance of film modeling is observed.
  - Code enhancement to permit a maximum film drainage model to be imposed (like CONTAIN).
  - New model permits investigation of the relevance of film depth, the corresponding heat transfer, and impact to peak pressure

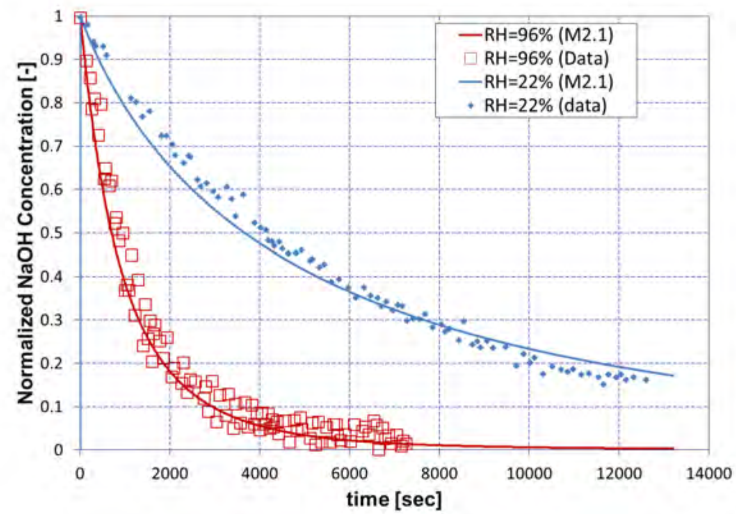




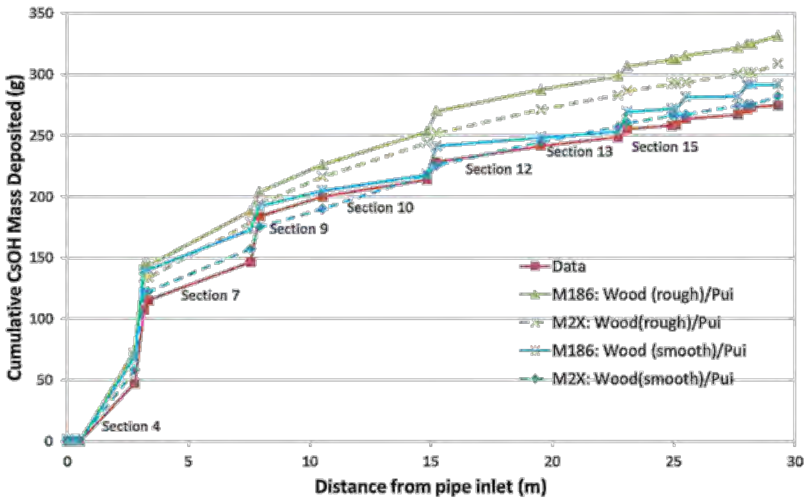
Radionuclide Package

- Tracks the release and transport of
  - Fission product vapors & aerosols
  - Non-radioactive masses such as water, concrete, etc.
  - Traces hosted by other materials
    - Negligible volume and heat capacity
- Aerosol physics
  - MAEROS
- Agglomeration of aerosols
  - Several mechanisms cause collisions and sticking to produce larger particles
    - Brownian diffusion
    - Differential gravitational settling
    - Turbulent agglomerating by shear and inertial forces
- Hygroscopic effects
- Condensation & evaporation
  - TRAP-MELT
- Deposition on surfaces
  - Modeled as always sticking to surfaces contacted
  - Several mechanisms drive aerosols to surfaces
    - Gravity
    - Brownian diffusion
    - Thermophoresis
    - Diffusiophoresis
    - Turbulent deposition
- Pool Scrubbing
  - SPARC
- Validation
  - ABCOVE, ACE, AHMED, DEMONA, LACE, LOFT, PHEBUS, POSEIDON, STORM, …

AHMED – Hygroscopic Effects



LA3 – Turbulent Deposition



Oxidation
Additional Considerations

- Refrozen conglomerate (candled) material blocks intact surface (including PD) from oxidation
- Surface areas must be defined consistently with component mass since they are used in calculating thickness.
- Two-sided components residing in channel with a surface in contact with bypass can oxidize
  - Volume expansion accommodated through borrowing virtual volume from bypass
- Zirconium emissivity is calculated as a function of oxide thickness
- Oxidation calculated for submerged surfaces
  - Gas film between unquenched surfaces and pool
- Debris surface area is partitioned between Zr, SS, and other materials
  - Surface area for Zr oxidation from volume fraction of Zr + ZrO_2
    - Modeled as layers with ZrO_2 outer layer
  - Surface area for SS oxidation from volume fraction of SS + SSOX
    - Modeled as layers with SSOX outer layer

Conglomerate On Components

- Each component has an intact mass field
  - User typically defines intact masses only (before onset of core degradation)
  - User also defines surface areas of intact components
  - Intact material has never melted (though it may have resulted from failure of intact component, i.e., intact particulate debris)
- Each component has a conglomerate mass field
  - Material has melted but may have refrozen on surfaces
    - Can be molten in molten pool component
  - Can fill interstitials in particulate debris
  - Different Composition
    - Can have materials that are not available in the intact field
  - Intact and conglomerate mass in thermal equilibrium (same temperature)
  - Affects surface area exposed to fluid convection, oxidation, radiation, and further refreezing
  - Affects thermal conductivity of particulate debris

Special Components Created During Core Degradation

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Particulate Debris (PD, PB)

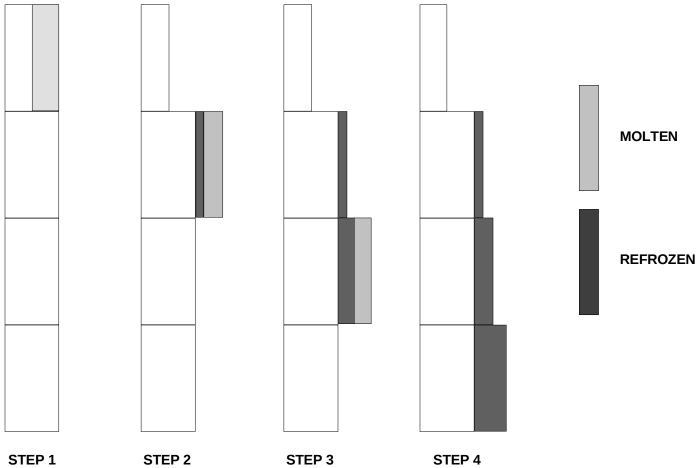
- Formed when an intact component fails or when molten pool freezes
- Has both intact & conglomerate fields
  - Unique composition but same temperature
- "Intact" mass
  - Porosity assumed from user input & conglomerate mass
  - Has never melted
- Conglomerate mass
  - Fills interstitials first
    - Affects effective thermal conductivity, heat surfaces for oxidation and radiation, and fluid flow
  - Excess assumed above

Molten Pool (MP1, MP2, MB1, MB2)

- Formed when other components melt
  - molten material blocked during candling
  - Melting PD
- All mass resides in the conglomerate field.
- Freezing MP is moved to the PD component and equilibrated
- Can form contiguous molten pool
  - Special routines for convection and freezing (Stefan model)
- Non-contiguous cells
  - Does not participate in convecting molten pool calculation (more later)
  - Heat transfer similar to PD

Downward Relocation of Molten Material

- Candling - Downward flow of molten core materials
  - Subsequent refreezing (creation of ‘conglomerate’)
  - Blockage (creation of molten pool)
  - Solid material transport of secondary materials
    - Thin oxide shells or dissolution of UO_2 by molten Zr
- Semi-mechanistic
  - Based on fundamental heat transfer principles
  - Assumptions
    - Steady generation and flow of molten material
      - Does not solve a momentum equation for velocity
      - All material generated in a time step reaches its final destination in that step
        - » There is no separate field for conglomerate and must equilibrate with a component
      - relatively independent of time step history
    - Molten material is held up behind oxide shell or retained behind blockage.
      - For breakaway melt, assumption of steady generation no longer valid
    - Freezes on originating component or alternate component

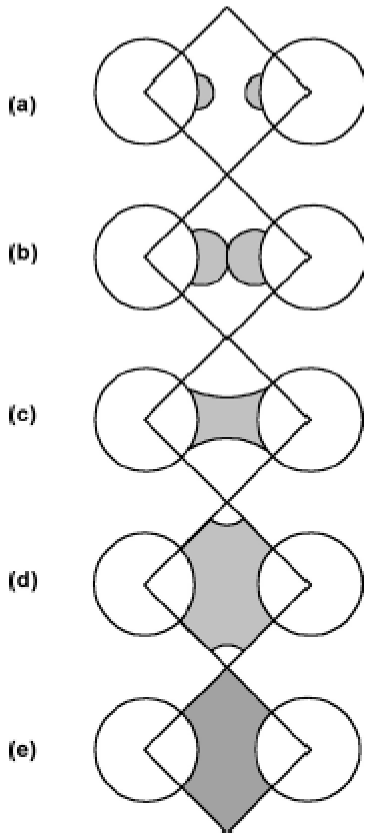


Evolving Surface Areas During Core Degradation

- Particulate debris surface areas

$$A_{s,pd} = \frac{6\ V_{px}}{D_{px}}$$

- Surface area changes from freezing conglomerate
  - Assumption of rivulets freezing in rod lattice
    - During the first stage, the surface area of the conglomerate debris grows as the square root of its volume up to some critical volume.
    - During the third stage, beyond some critical volume, the surface area of the conglomerate debris decreases as the square root of the empty volume
    - During the second stage, the surface area of the conglomerate debris is interpolated linearly with volume between A^{c1} and A^{c2}.
  - Applied to particulate debris geometry
    - Alternate model developed but not validated or implemented by default



Gravitational Settling of PD and MP components

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- Gravitational settling occurs at constant velocity (VFALL) for both particulate debris and molten pool
  - PD displaces MP
- Each ring is calculated separately, starting at the center (radial spreading occurs later)
  - Distinction between channel and bypass
    - PD stays in channel & PB stays in bypass
    - PD & PB mixed where canister has failed
    - PD & PB split based on cross-sectional area when relocating to unfailed cell
- Radial relocation models intended to simulate the gravitational leveling between adjacent core rings
  - Tends to equalize the hydrostatic head in a fluid medium.
  - PD & MP spread radially at different rates
    - Radial displacement of molten pool by spreading PD

Molten Pool Convective Heat Transfer

Energy Balance on MP1:

$$MC_{p,MP1}\frac{T^{n}_{MP1}-T^{o}_{MP1}}{\Delta t}=\dot{Q}_{MP1,decay}$$

$$-\sum_{s\in seg} h_{MP1\to s}A_s\left(T^{n}_{MP1}-T_s\right)-h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right)$$

$$-\left\langle h_{MP1-fluid}A_f\left(T_{MP1}-T_{fluid}\right)-\sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP1}-T^{4}_{ambient}\right)\right\rangle .$$

Energy Balance on MP2:

$$MC_{p,MP2}\frac{dT^{n}_{MP2}}{\Delta t}=\dot{Q}_{MP2,decay}$$

$$-\sum_{s\in seg} h_{MP2\to s}A_s\left(T^{n}_{MP2}-T_s\right)+h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right)$$

$$-h_{MP2-fluid}A_f\left(T^{n}_{MP2}-T_{fluid}\right)-\sigma\varepsilon_{eff}A_{up}\left(T^{4}_{MP2}-T^{4}_{ambient}\right)$$

- Heat Transfer coefficients from empirical Rayleigh coefficients obtained for steady state conditions correlating Ra number with internal heat generation rate
- Correlations adapted to transient conditions based on the average of the decay heat and the boundary heat losses
  - Solved recursively
  - Approaches steady state in limit
- Time constant for establishing convective currents
  - Arbitrarily set to 1 sec to smooth transition but not based on any physical significance

Lower Head Failure Mechanisms

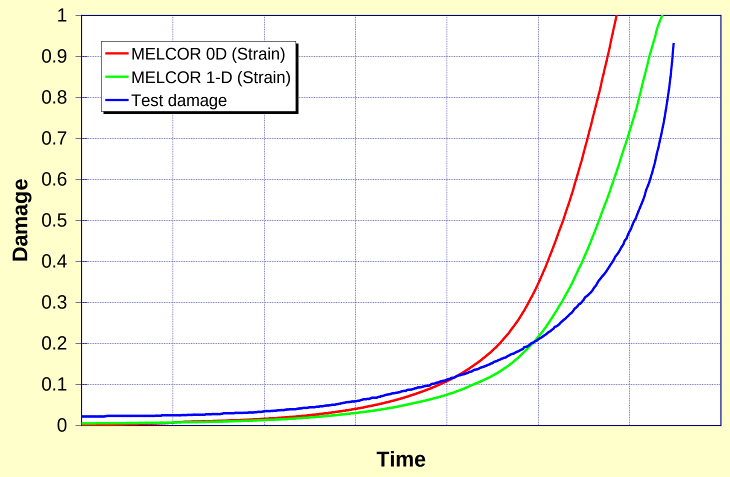
- Creep-rupture failure of a lower head ring occurs

$$t_R = 10^{\left(\frac{P_{LM}}{T} - c\right)} \qquad P_{LM} = \min\left[a_1 \log_{10}(\sigma_e) + b_1, a_2 \log_{10}(\sigma_e) + b_2\right]$$

  - 2-D internal model to account for stress and temperature distribrution through the vessel
    - Load redistributed to cooler nodes
  - Failure occurs when damage = 1.0
    - Strain at failure is defined as 18%
- Penetration failure
  - Failure Temperature, TPFAIL, or
  - Control function for penetration failure
    - OLHF and LHF tests suggest strain-based failure criteria
- Overpressure from the falling-debris quench model
  - Default failure criterion is 20 MPa
    - Redefine on record COR_LP, but not greater than P_{crit}
- Load on vessel includes weight of debris and structures in ring above supported by vessel in addition to hydrodynamic pressure.

MELCOR Lower Head Failure Models

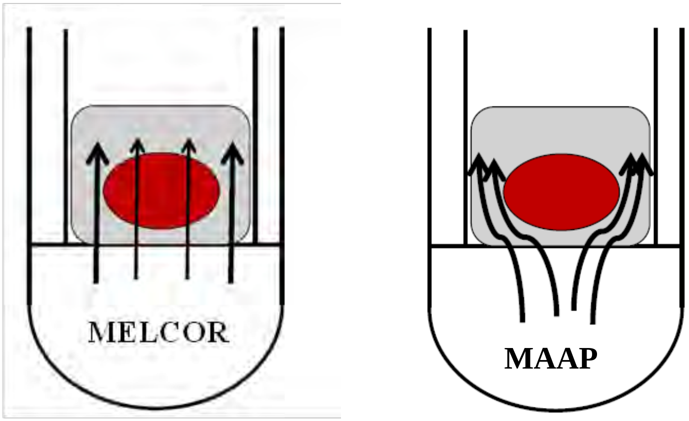
- Failure based on Robinson's Rule, i.e., lifetime rule from Larson-Miller parameter
- Two models are available in MELCOR:
  - Zero-Dimensional Model
    - Default Model
  - One-Dimensional Model
    - Selected by setting sensitivity coefficient SC1600(1) = 1
    - Recommended Model
  - Part of thickness can be non-load-bearing (e.g., insulation)
    - `NINSLH` (from record `COR00000`) outer meshes, with default 0, will be excluded from the calculation

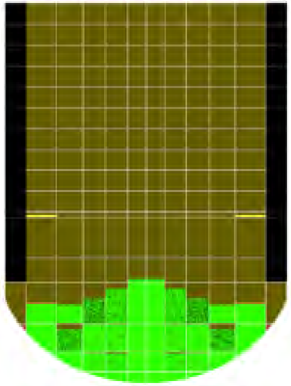


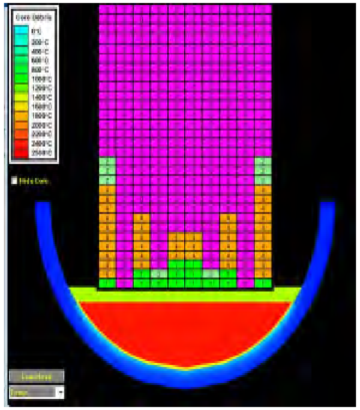
Assessment of models with LHF and OLHF test results

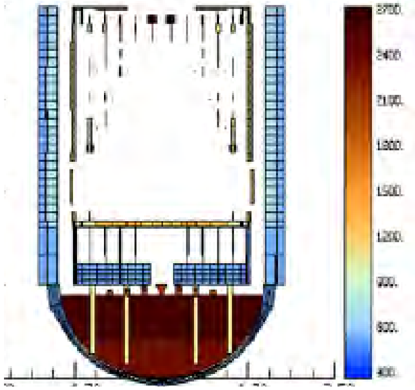
Core Degradation Modeling – Cross walk comparisons

- Differences in assumption of permeability of debris crust
  - MELCOR – flow blockage model with permeable crust
  - MAAP – impermeable crust
- Fuel rod collapse modeling
  - MELCOR/MAAP – fuel rod collapse model
  - ASTEC – Rods melt to form magma but no collapse









Experimental Validation

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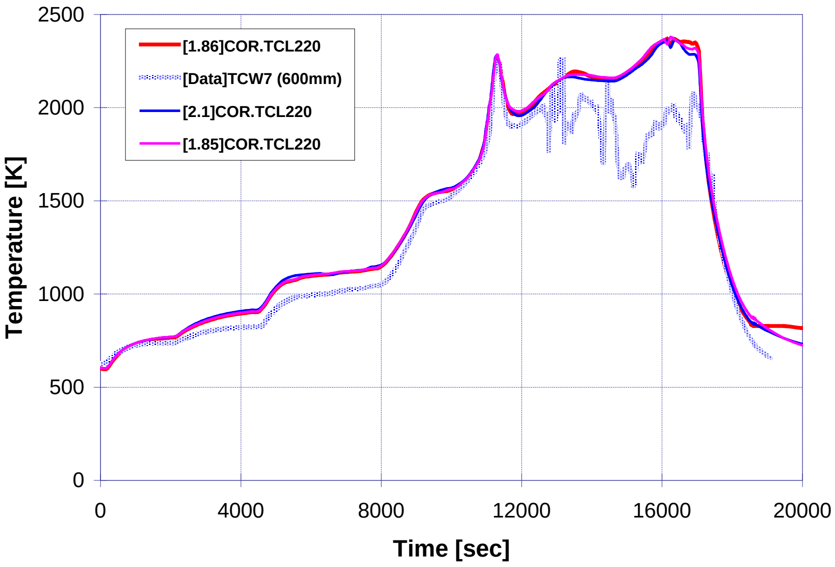
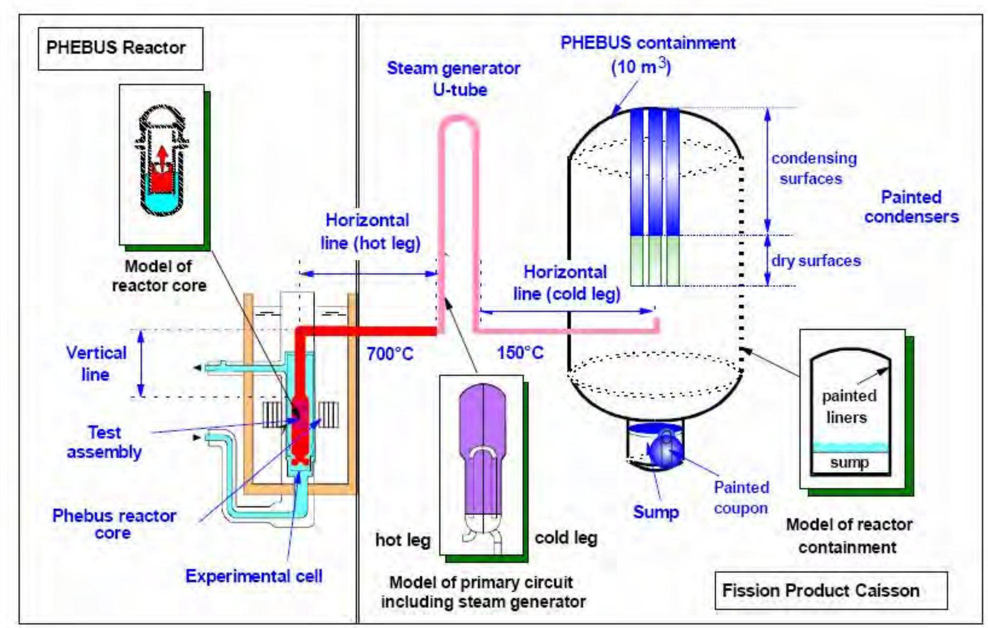
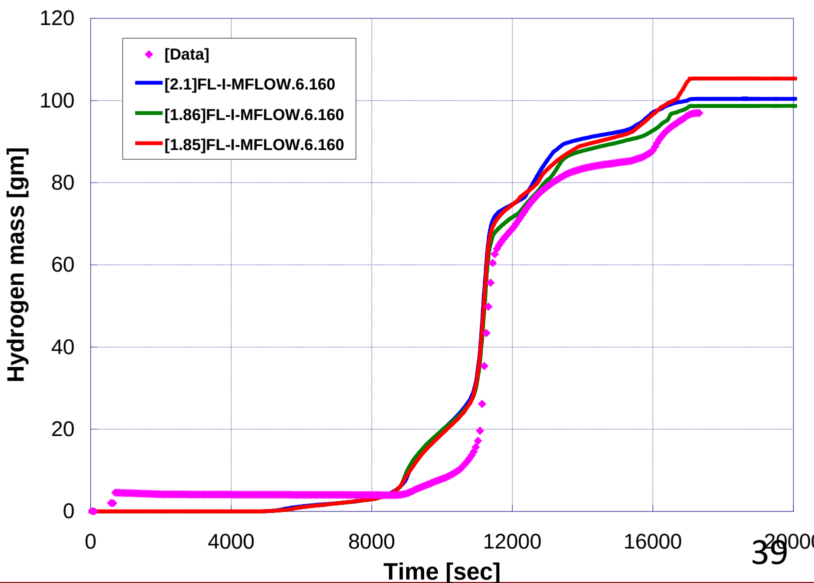
- Importance of validation
  - Provide necessary guidance in developing and improving models
  - Desirable to have validation test at time of model implementation
  - Increased confidence in applying code to real-world application
  - Improved understanding of modeling uncertainties
- Separate Effects Tests
  - Designed to focus on an individual physical process
  - Eliminates complications from combined effects
  - May be difficult or impossible to design a single test to isolate a single process
  - Sometimes geometry or boundary conditions for SETs are difficult to model within an integral code
- Integral Tests
  - Examines relationships between coupled processes
  - Tests should be selected that are applicable to the calculation domain of the code
- Actual Plant Accidents
  - TMI, Fukushima, etc.
  - Captures all relevant physics
  - Poorly 'instrumented'
- International Standard Problems (ISPs)
  - Well documented
  - Often there are code-to-code comparisons to compare modeling approaches

FPT-1 (ISP-46)

- ***General Description***
  - FPT-1 experiment was an in-pile, irradiated fuel experiment conducted in the PHEBUS Fission Product Facility by the Nuclear Safety and Protection Institute (IPSN) at Cadarache, France, on July 26, 1996. The objective of the fuel bundle assembly was to assess fuel degradation and fission product release
- ***Important Physics***
  - Oxidation
  - Material relocation
  - Fission product release, transport, and deposition

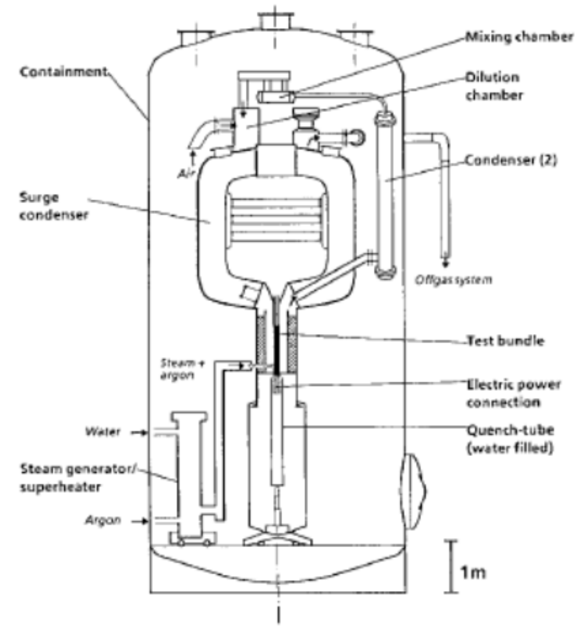




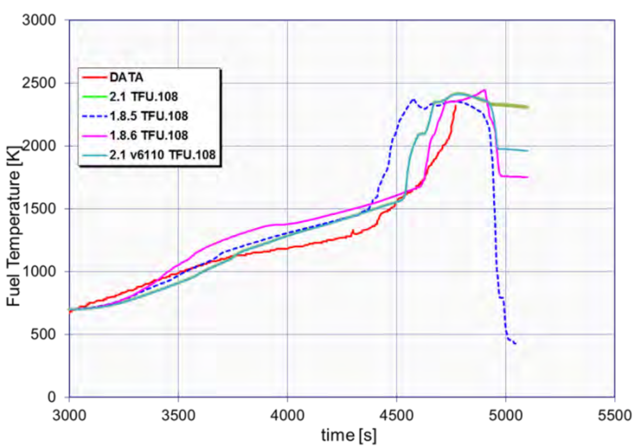


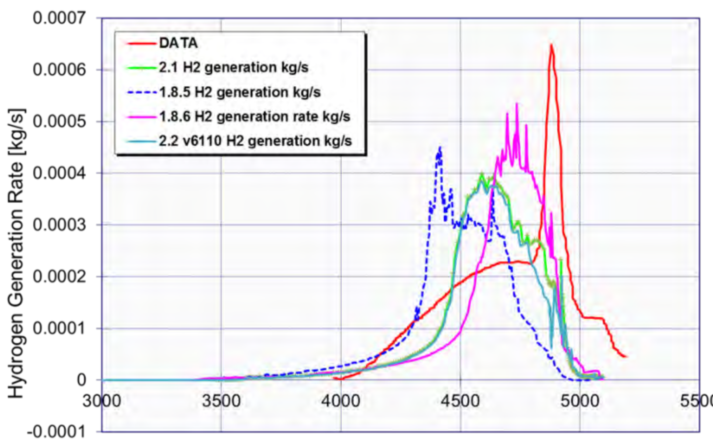
CORA-13 (ISP-31)

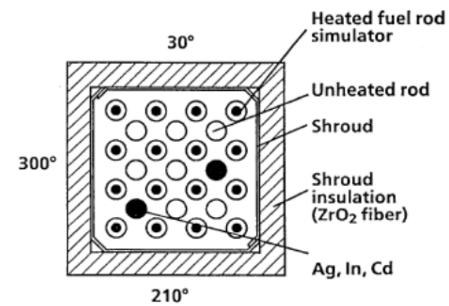
- ***General Description***
  - Analysis of the heat-up and meltdown phases of a PWR type fuel element in the CORA test facility. The CORA facility consists of a fuel rod bundle with heated and unheated rods under controlled thermal-hydraulic boundary conditions with a steam supply to provide superheated steam and a quench capability
- ***Important Physics***
  - Oxidation/hydrogen generation, fragmentation of rods, relocation of core materials, formation of blockages, forced convection, conduction, radiation, and fluid-structure heat transfer



CORA Facility







Cross section of test bundle

time [s]

Alternative TMI-2 (ATMI)

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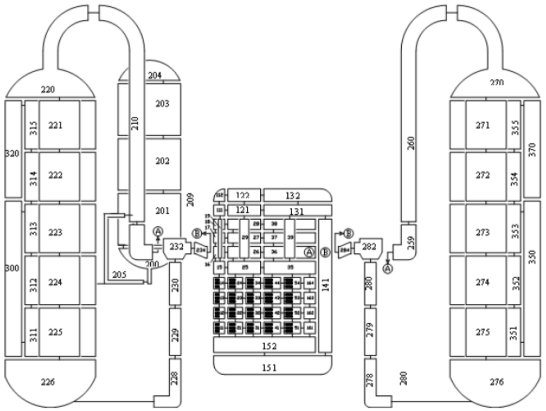
ABILITY OF CURRENT ADVANCED CODES TO PREDICT CORE DEGRADATION, MELT PROGRESSION AND REFLOODING

NEA/CSNI/R(2009)3

Benchmark Exercise on an Alternative TMI-2 Accident Scenario

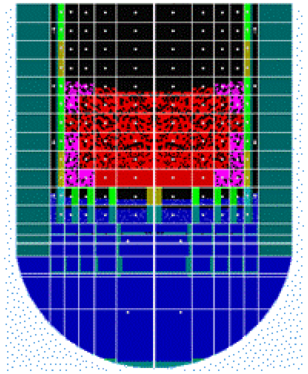
Computer Code	Organization	Country
ASTEC V1.3	ENEA	Italy
ASTEC V1.3	IVS	Slovakia
MELCOR 1.8.5	Univ. Pisa	Italy
ATHLET-CD	GRS	Germany
ATHLET-CD / WABE / MEWA	IKE	Germany
ICARE/CATHARE V2	IRSN	France
MELCOR 1.8.6	NRC/SNL	U.S.A
MAAP4 / RELAP5	Seoul Nat. Univ.	S. Korea



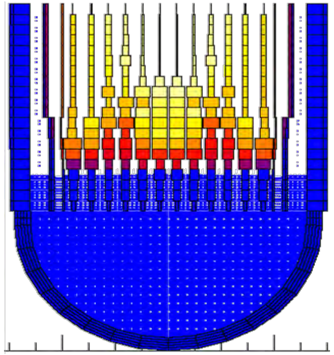
- Initial event:
  - Loss of main feedwater
  - Opening of a small break in hot leg A
    - size: 0.001 m^2
- Assumptions
  - No PORV failure
  - HPI
    - Begins 5000 sec after pump trip
    - 30 kg/s, per loop (60 kg/s total).
  - Primary pumps stop when primary mass < 85,000 kg
- Boundary Conditions
  - Make-up flow = 3.0 kg/s
  - Steam generator secondary side pressure and water level

Alternative TMI-2 (ATMI)

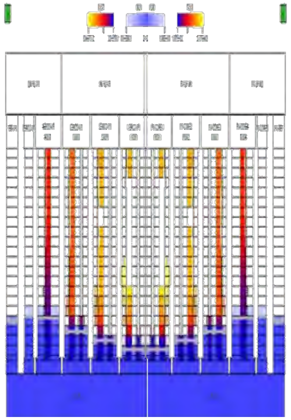
Start of Reflood



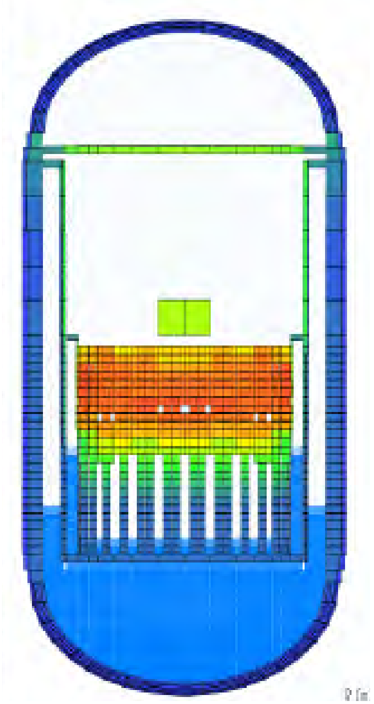
SNL MELCOR
(1.8.6 YR)



ENEA (ASTEC V1.3)



GRS
ATHLET-CD



IRSN
ICARE/CATHARE V2

Alternative TMI-2 (ATMI)

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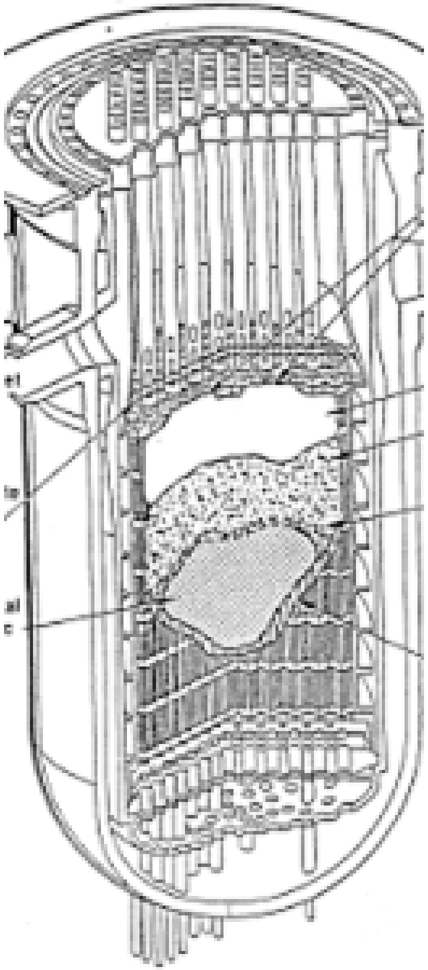
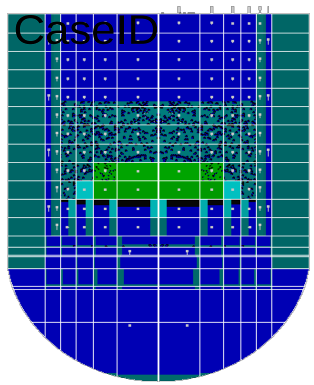
End of Reflood/Calculation



TMI



SNL MELCOR
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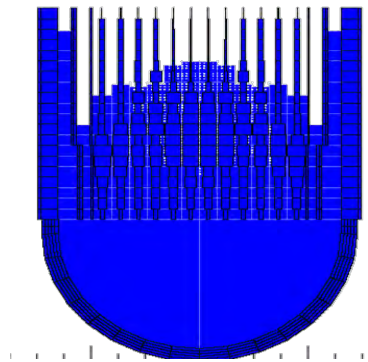
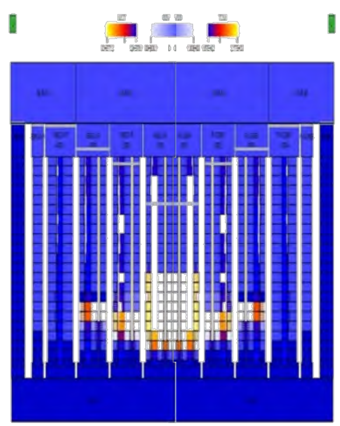


ENEA
(ASTEC V1.3)



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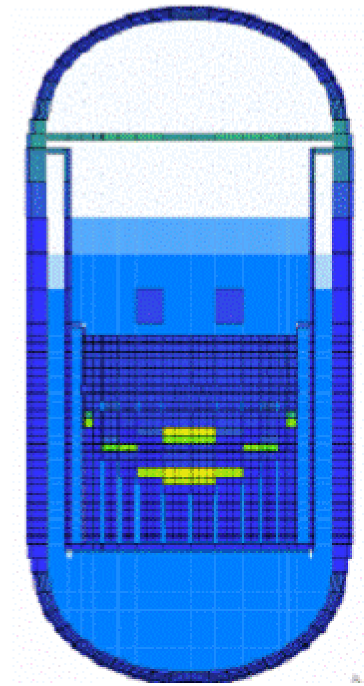
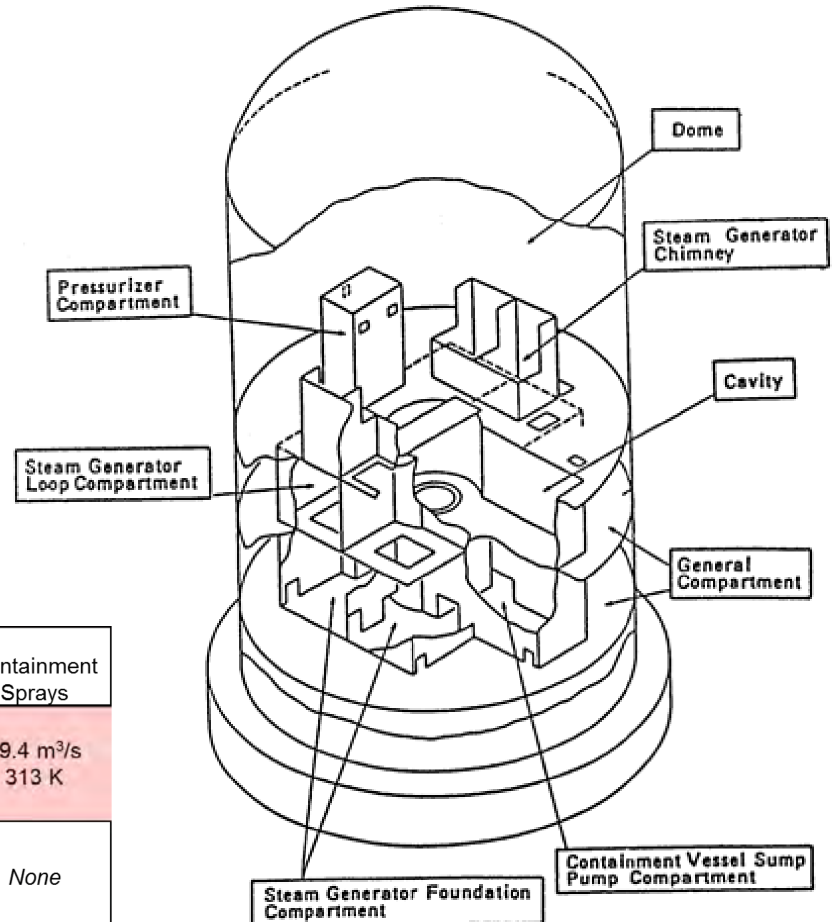


IRSN
ICARE/CATHARE V2

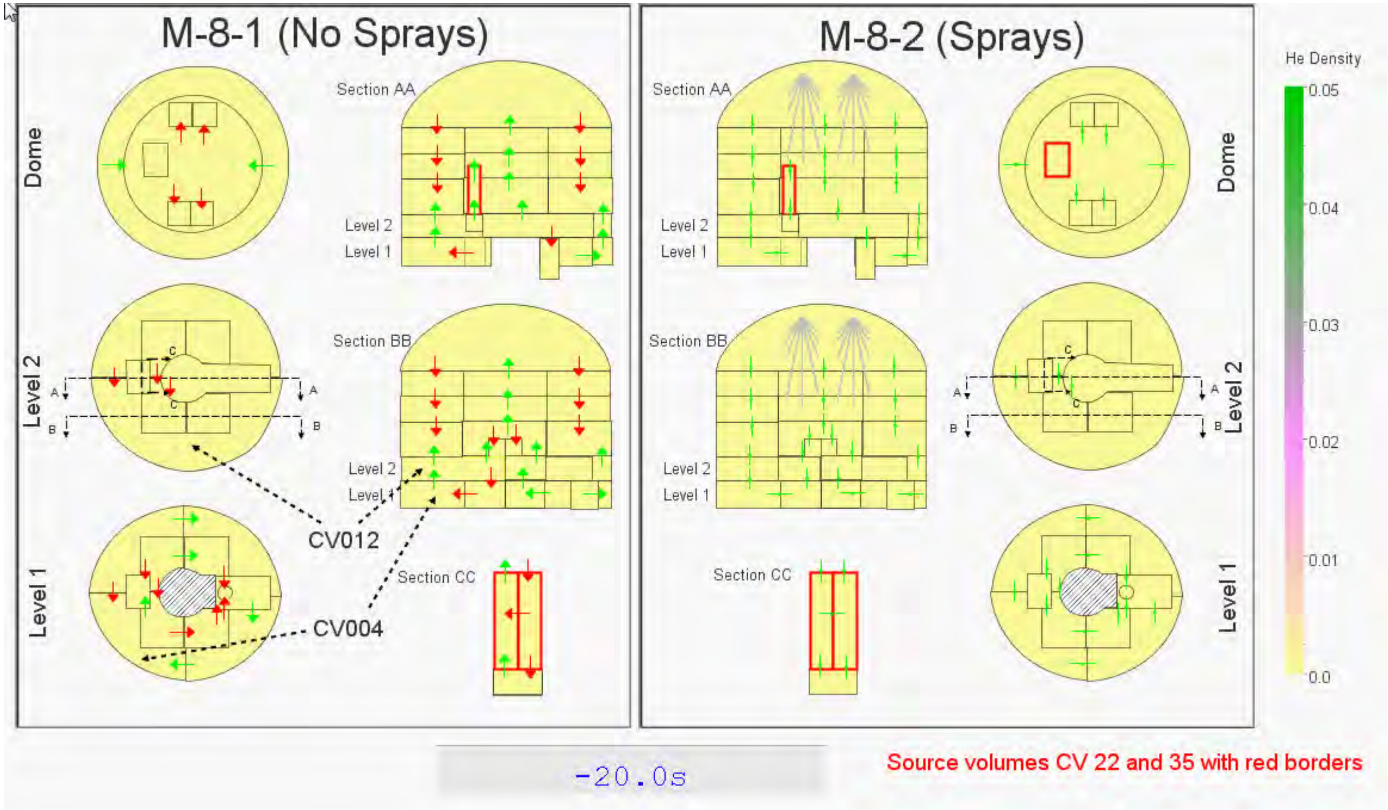
NUPEC M-7-1, M-8-1, and M-8-2

- Validation objectives
  - Pressure response;
  - Temperature distribution and stratification
  - Hydrogen mixing
  - Spray modeling
  - Film Tracking Model
- ¼ Scale Containment
  - 10.8 m OD domed cylinder,
  - 17.4 m high
  - 25 interconnected compartments (28 total)

Test	Injection Location	Initial Conditions	Relative Humidity	Helium Source	Steam Source	Containment Sprays
M-7-1	Bottom of SG Comp D (8)	343 K, 146 kPa	0.95	0→0.03 kg/s→0 283 K	0.08 kg/s→0.03 kg/s 383 K	19.4 m^3/s 313 K
M-8-1	Upper Pressurizer Comp (22)	303 K, 101 kPa	0.7	0.027 kg/s 283 K	0.33 kg/s, 388 K	*None*
M-8-2	Upper Pressurizer Comp (22)	343 K, 146 kPa	0.95	0→0.03 kg/s→0 283 K	0.08 kg/s→0.03 kg/s 363 K	19.4 m^3/s 313 K



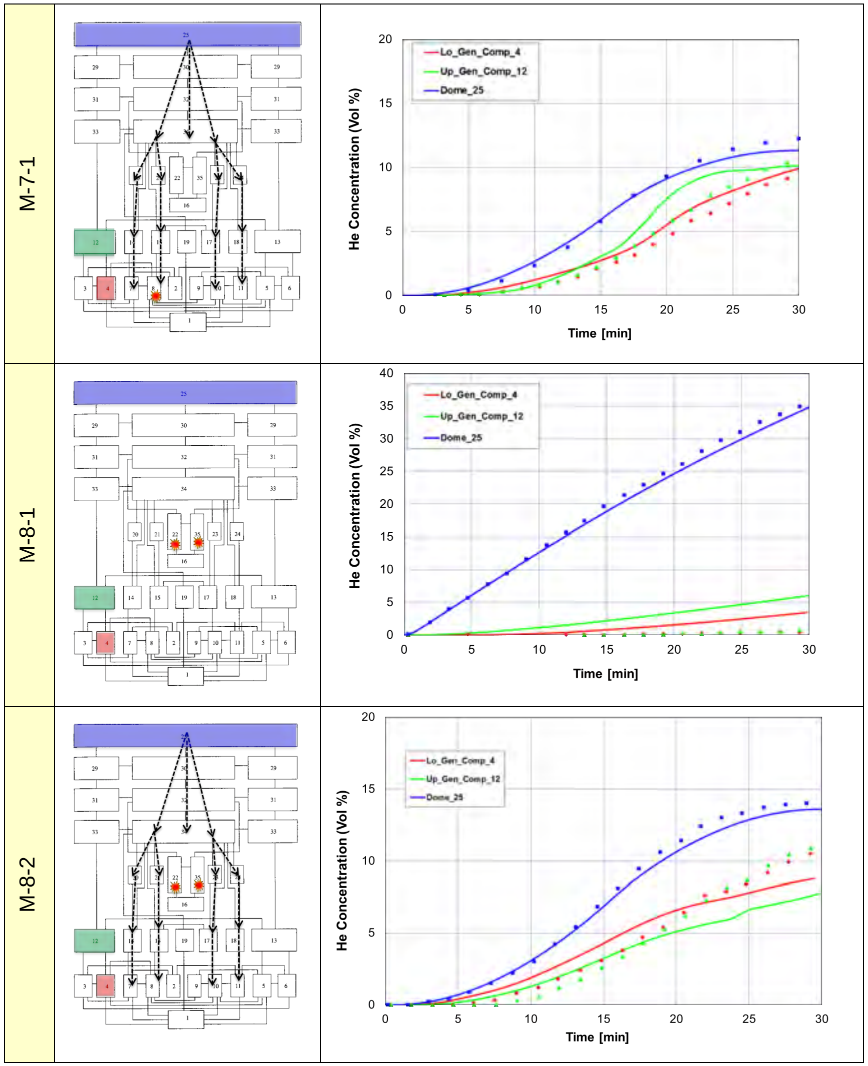
He Concentration Distributions

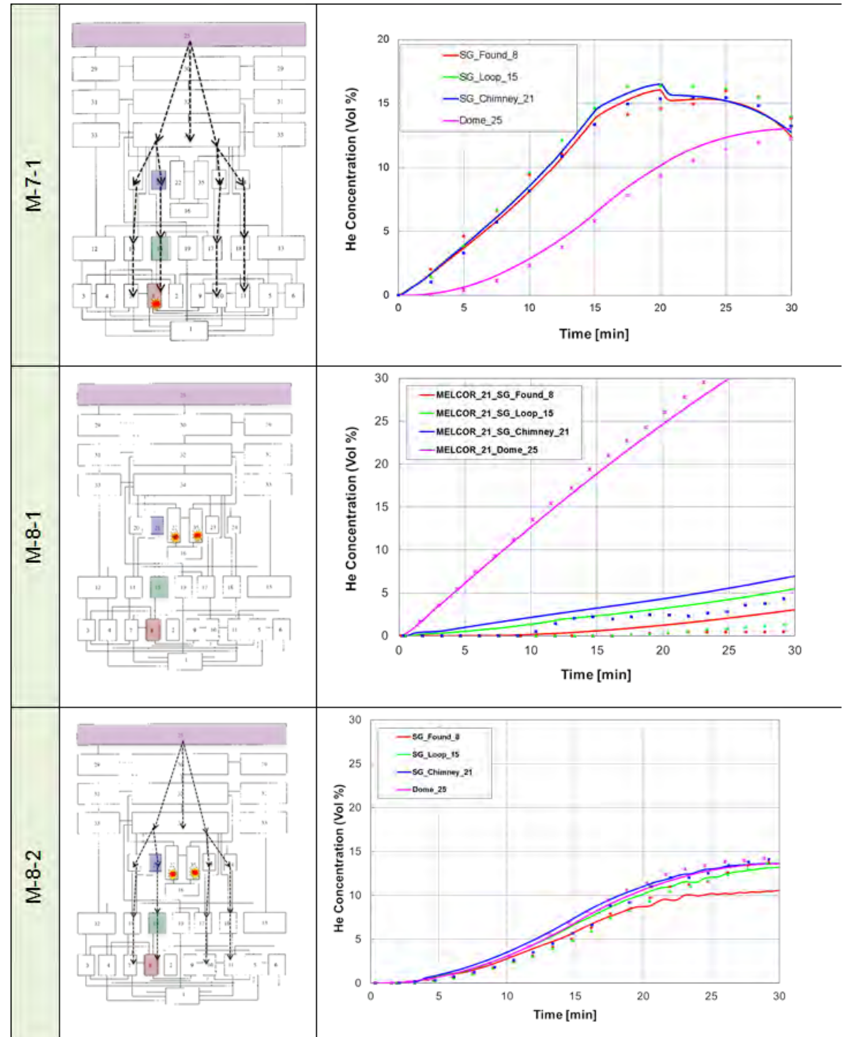


- Similarly, stratification of helium in the upper dome is much more significant for M-8-1 than M-8-2
- Stratification by floor in outer, lower compartments

He Concentrations for vertical distribution volumes

SG loop D





Color indicates CV

Exceptional service in the national interest

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MELCOR
- New Modeling
- SQA
- Utilities

Recent Code Improvements and Impact on SOARCA

ACRS Briefing on MELCOR Modeling

April 18, 2017

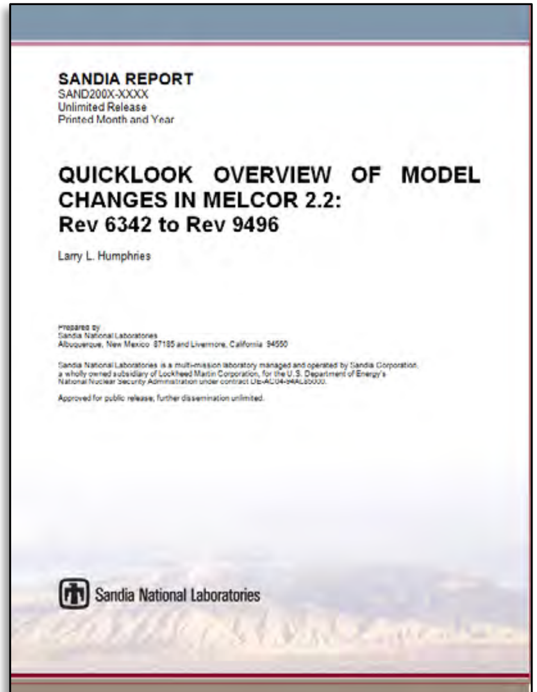
Presented by Larry Humphries

llhumph@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

MELCOR 2.2 Code Release

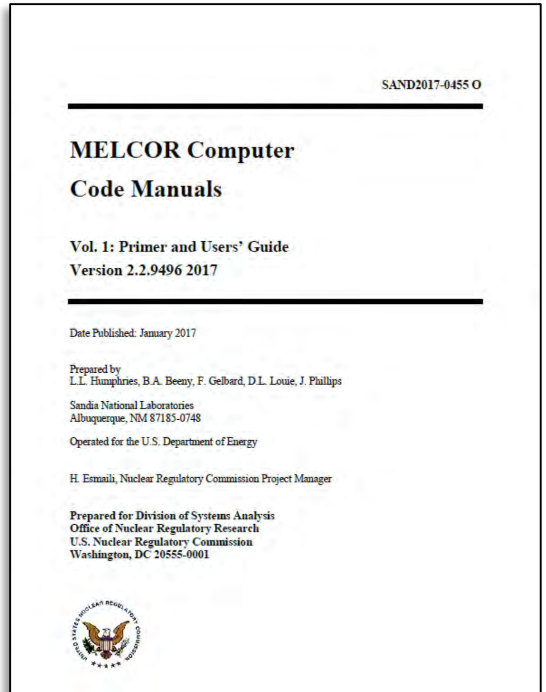

SANDIA REPORT
SAND200X-XXXX
Unlimited Release
Printed Month and Year

QUICKLOOK OVERVIEW OF MODEL CHANGES IN MELCOR 2.2:
Rev 6342 to Rev 9496

Larry L. Humphries

Sandia National Laboratories

MELCOR 2.2 Quicklook Overview of Model Changes in MELCOR 2.2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Version 2.2.9496 2017

Date Published: January 2017

Prepared by
L.L. Humphries, B.A. Beeny, F. Gelbard, D.L. Louie, J. Phillips

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Operated for the U.S. Department of Energy

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Prepared for Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Volume I: User Guide

R&A Complete
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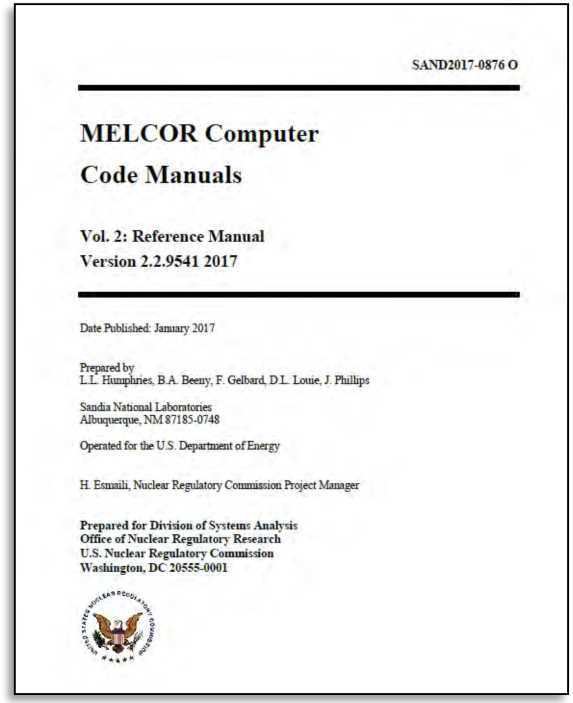
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MELCOR Computer Code Manuals

Vol. 2: Reference Manual
Version 2.2.9541 2017

Date Published: January 2017

Prepared by
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Operated for the U.S. Department of Energy

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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Volume II: Reference Manual

R&A Complete
SAND2017- 0876 O

Significant Code Changes

- New Defaults
  - Fuel Rod Collapse Model
  - Melt Spreading Model
- Code Corrections
  - Mass error with flashing model when hygroscopic model is enabled [r8612]
  - Revised candling model for canisters [r7864 but not active until 9387]
  - Corrections to reflood quench model [multiple revisions]
  - Lipinski dryout model not used above the core support plate [r7874]
  - Decay heat transfer to small fluid volumes [r8274]
  - Correction to fuel rod collapse modeling (temperature failure criteria) [r8574]

Changes in H2 Generation from Oxidation

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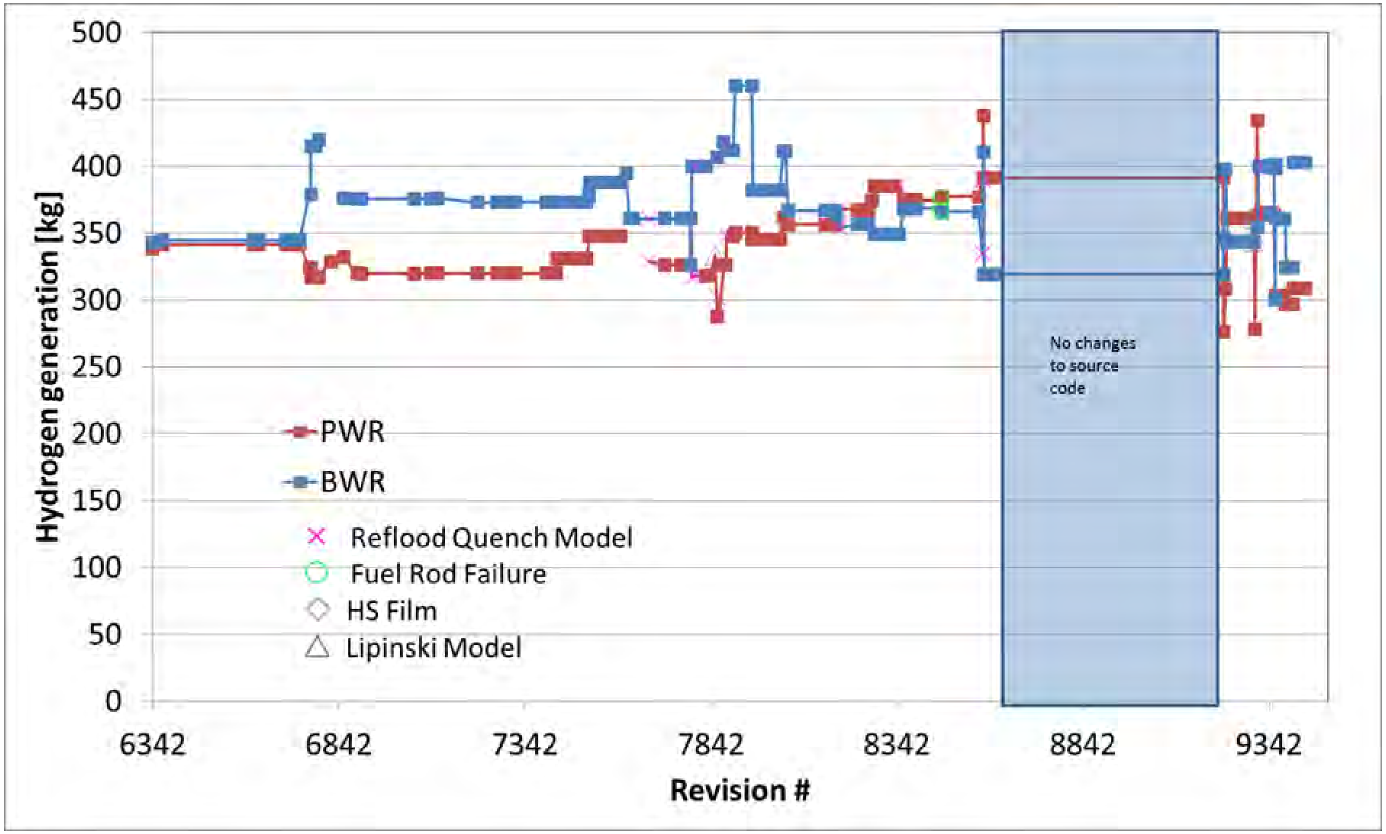
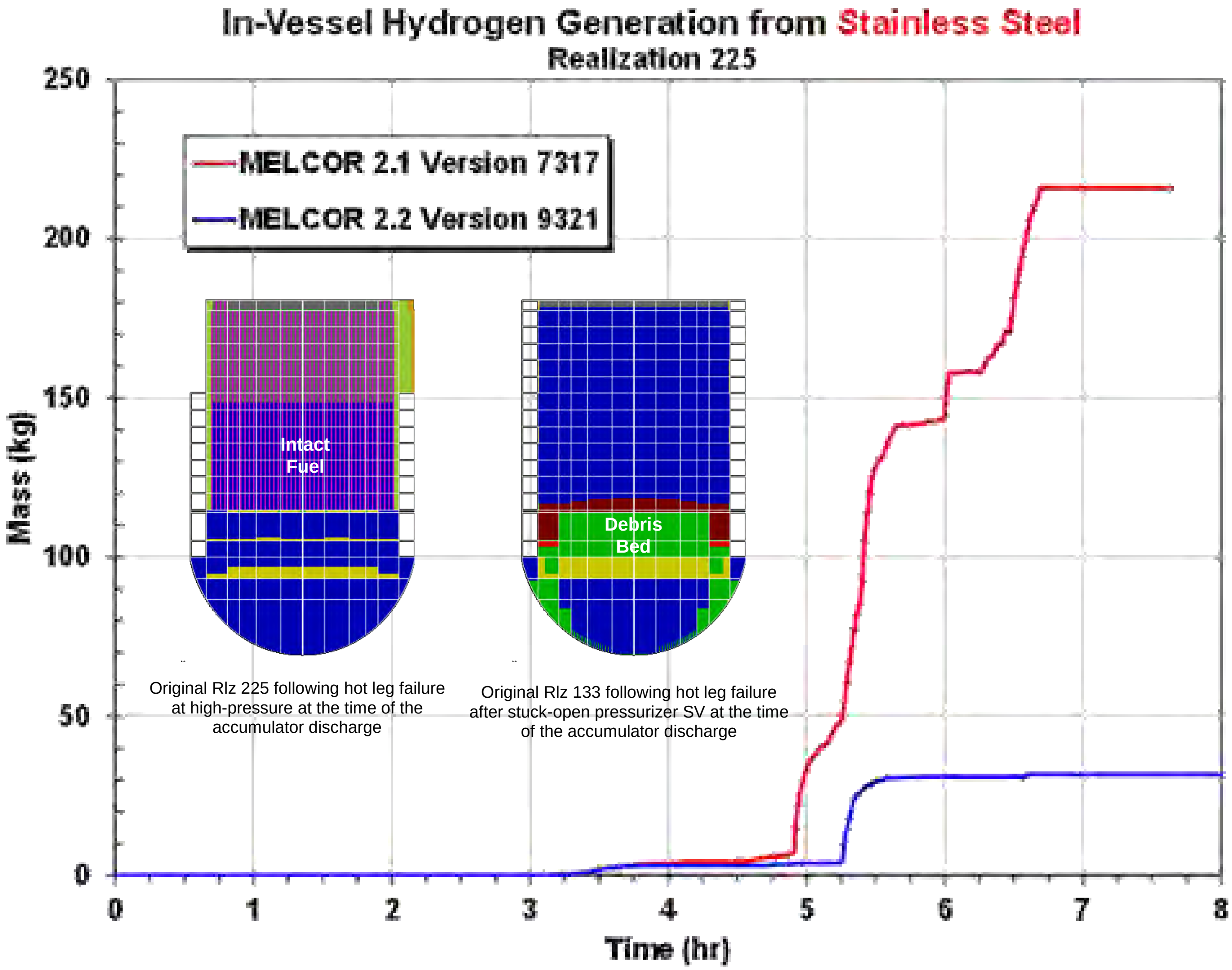


Impact of Code Changes on H2 Generation – Sequoyah UA



Impact of Model Changes on H2 in Containment - Sequoyah UA

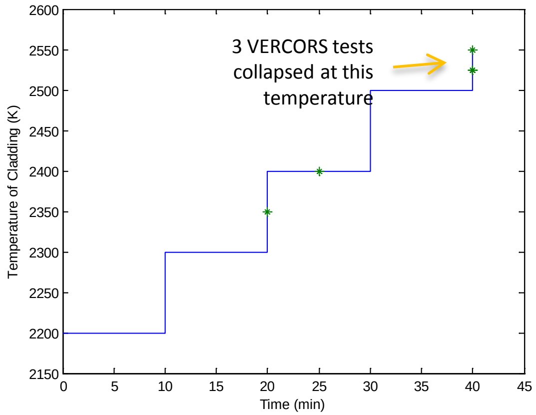
- Requirements for early containment failure
  - >150 kg hydrogen in containment dome
    - ~375 kg in-vessel hydrogen production
    - A pressurizer safety relief valve needs to fail to close to vent hydrogen
    - The lower flammability limit for hydrogen needs to be > 5%
- Small number of early failures in recent calculations is due to smaller likelihood of safety valve failing to close.
  - Reduction in hydrogen generated in-vessel due to code changes not as important as model changes.

Fuel Rod Collapse Model

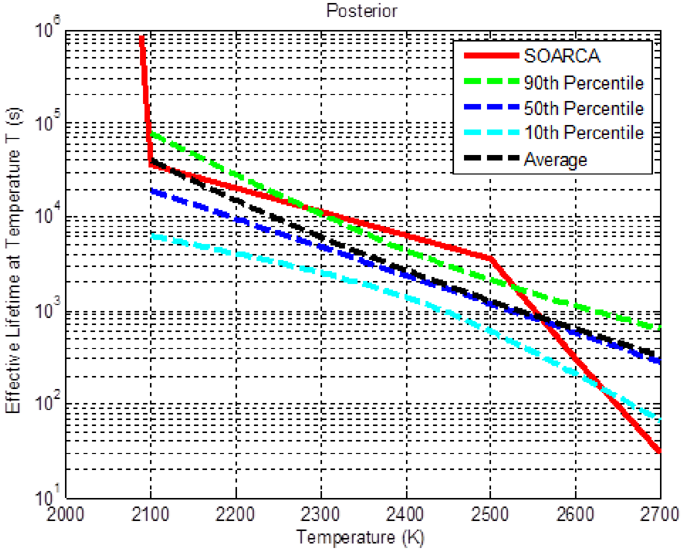
- Time-at-temperature model
  - Available in M186 but not default until now
  - Characteristics had to be provided by user
  - Eliminates temperature threshold effect from failure temperature model
- Updated based on VERCORS experiments and original SOARCA models
  - Damage function used in original SOARCA analyses

$$\frac{1}{L(T)} = A\,exp(BT)\ ,DF(t) = \sum\left(\frac{1}{L(T)} * \Delta t\right)$$

  - Coefficients A & B fit using Bayesian statistical analysis of VERCORS fuel collapse data
    - 6 Data points
- Sequoyah UA samples collapse temperature from fit to VERCORS data
  - Same database as default model
  - Convenience in sampling rod collapse
  - No impact on study

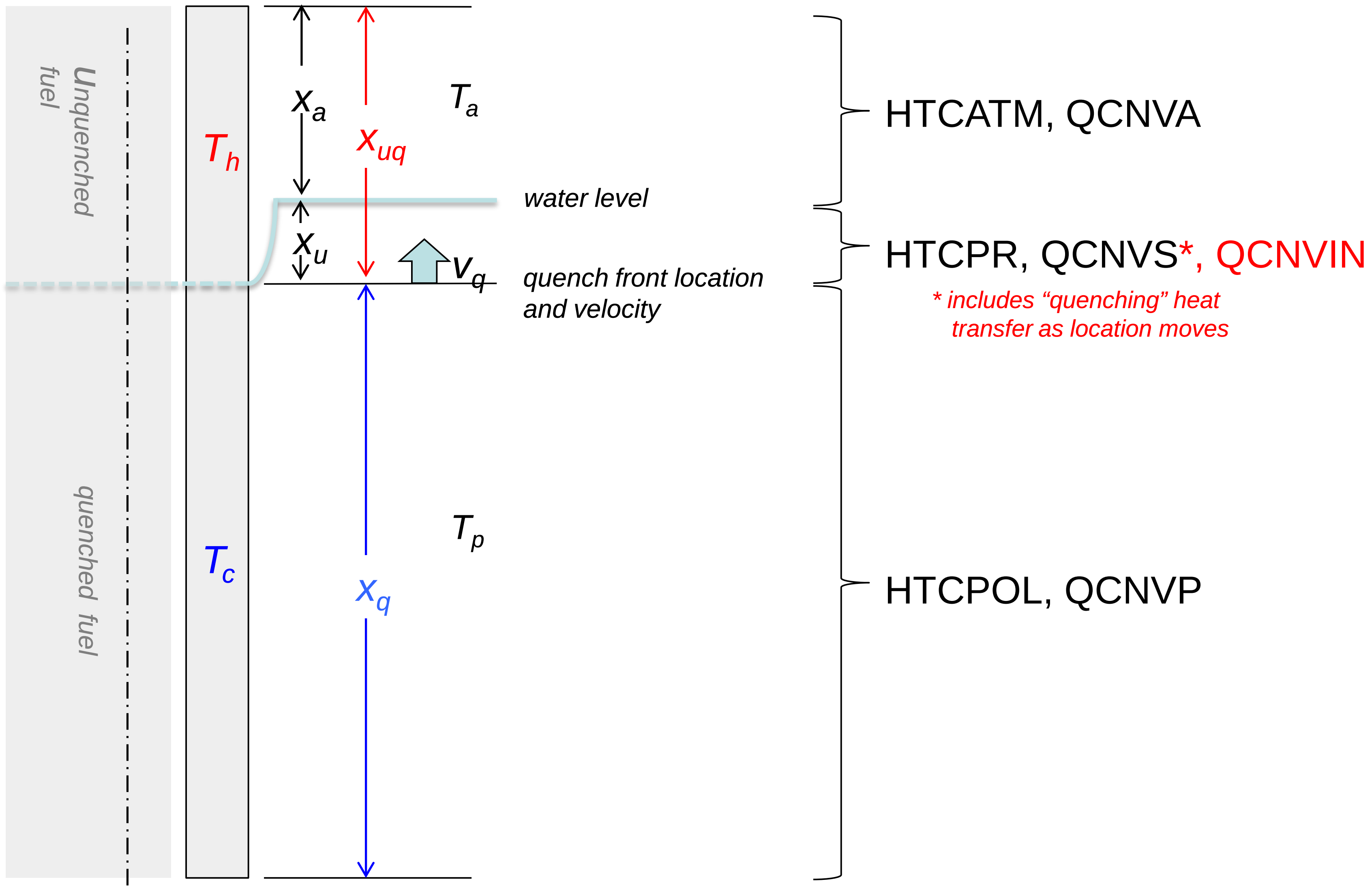


Time at Temperature Histories from the VERCORS Experiments . All tests underwent identical temperature ramps, stars indicate fuel collapse times.



"Development of the SharkFin Distribution for Fuel Lifetime Estimates in Severe Accident Codes", 2016 ANS Winter Meeting**.**
M. R. Denman

Illustration for Reflood Quench Model



Reflood Quench Model

- MELCOR computes a quench velocity, distinct from pool water level
  - The quench velocity correlation implemented is that of Dua and Tien[1]

$$Pe = \left[\bar{B}(1 + 0.4\bar{B})\right]^{1/2}$$

    - Where
      – Pe is the dimensionless quench velocity or Peclet number

$$Pe = u^* = \frac{u\delta}{\alpha}$$

      – $\bar{B}$ is a dimensionless Biot number

$$\bar{B} = Bi(1-\Theta)^2 / \Theta \qquad Bi = \frac{h^*\delta}{k} \qquad \Theta = \frac{T_h - T_{sat}}{T_{max} - T_{sat}}$$

  - May be thought of as an interpolation between a result based on one-dimensional conduction in thin surfaces (small Bi), and one based on two-dimensional conduction in thick surfaces (large Bi).
    - For small $\bar{B}$, $Pe = \sqrt{\bar{B}}$
    - For large $\bar{B}$, $Pe = 0.63\bar{B}$

[1]*S. S. Dua and C. L. Tien, Intl. J. Heat and Mass Transfer 20, pp.174-176 (1977).*

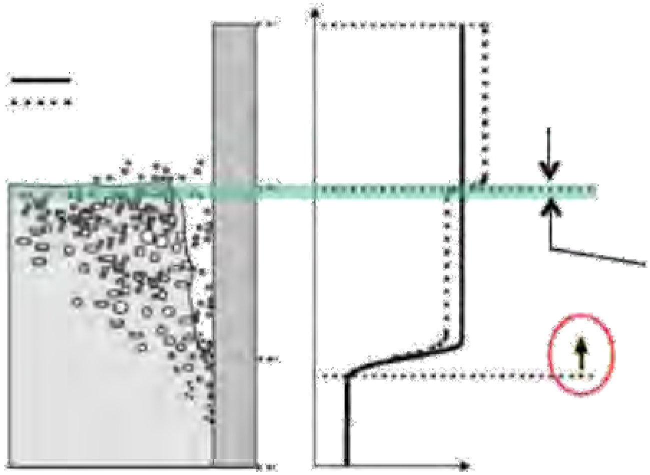
Observations on Model Implementation

1. All of the thermal energy associated with the change in temperature across the quench front is transferred into a direct vaporization of liquid water into steam.
2. The thermal capacitance of the COR components relative to that of the surrounding coolant is typically quite large.
3. Because the quench velocity model is based on “steady” (i.e. non time-varying”) conditions, when conditions change, no matter how quickly, the computed quench velocity will also change instantaneously.

Revised Quench Front Velocity

This revision prevents the code from producing unphysical pressure oscillations by enabling the quench front velocity to

(1) Have its rate-of-change temporally relaxed, and
(2) be smoothly driven to zero within a small user-specified distance of the pool level (C1260(5), DXQNCH).



Example specification of DXQNCH:

```
COR_SC   1 ! n nnnn   value   index
           1  1260    0.02     5
```

DXQNCH: fractional width of quench vel. Reduction zone near pool level (default is 0.02)

Temporal relaxation is not applied to receding quench fronts

The reduction in velocity near the surface is computed using a simple cubic polynomial-based multiplier that drives the value to zero.

ISP-45 Quench06 Experiment

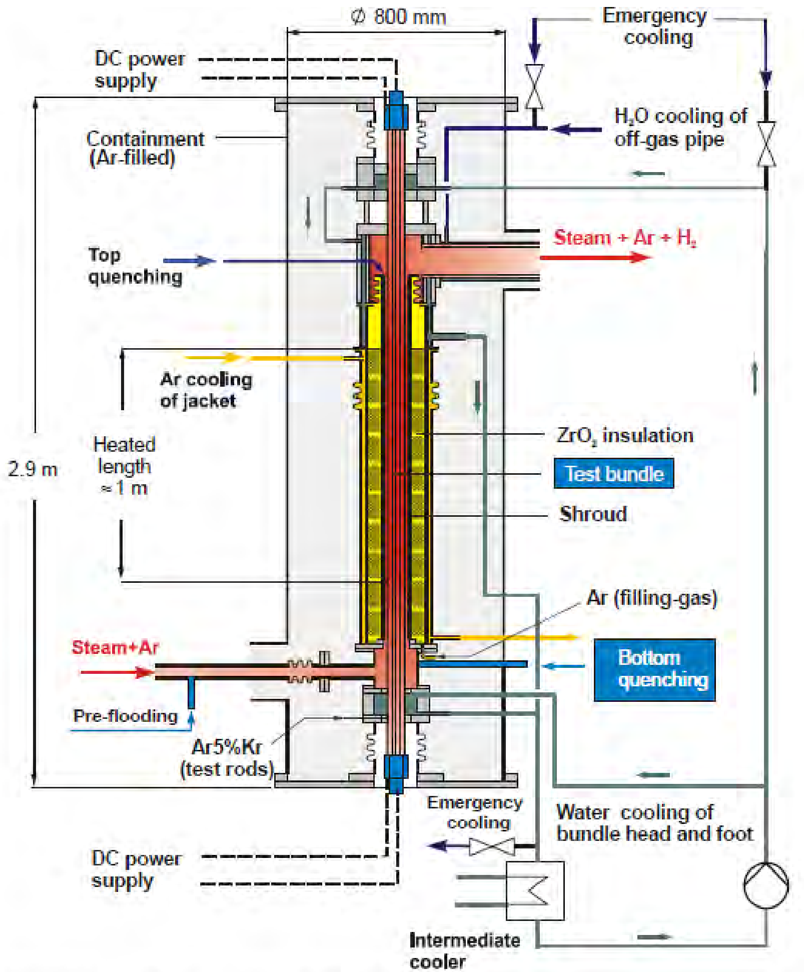
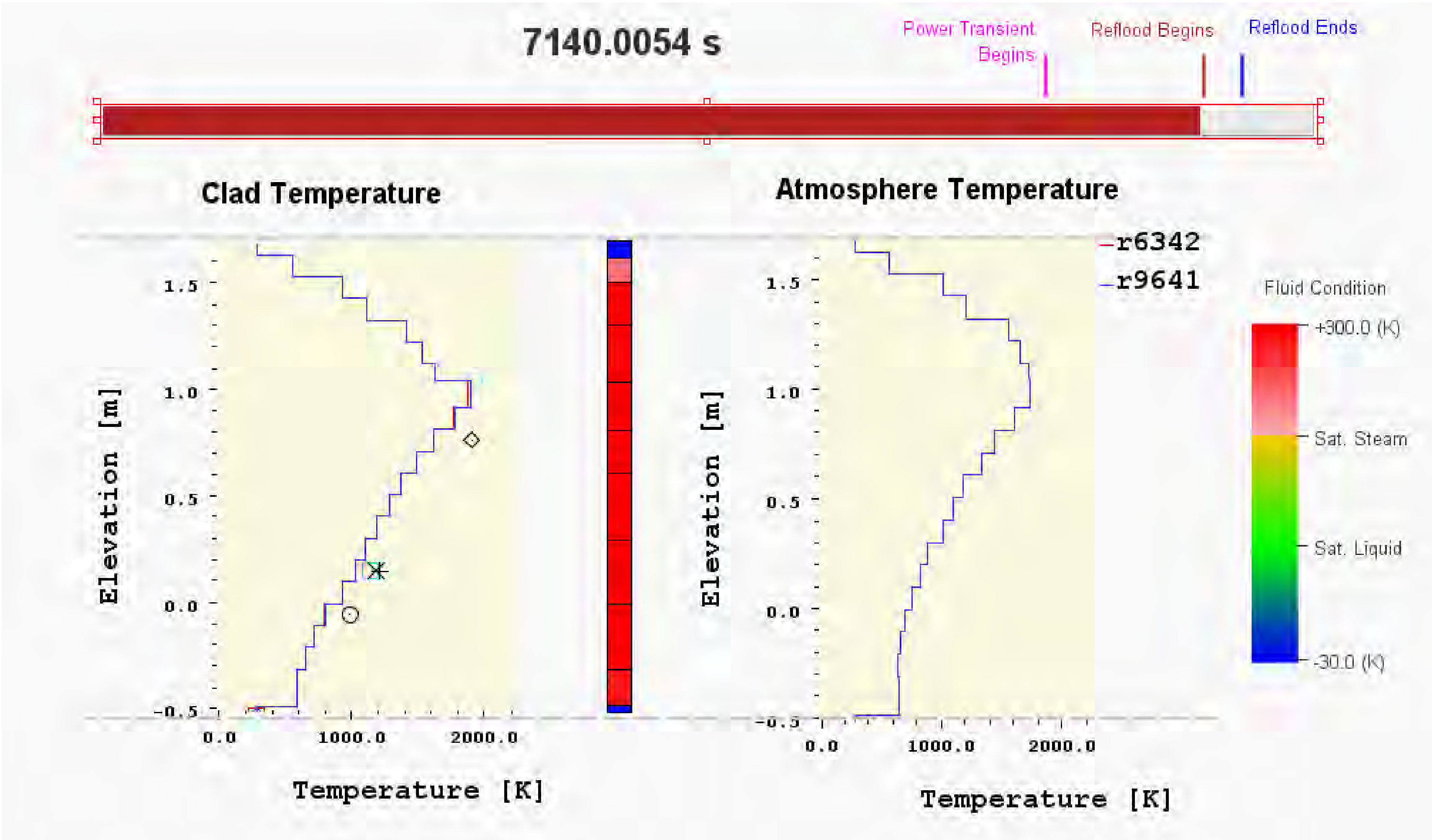


Figure 2.1 Main flow paths in the QUENCH facility.

Table 3.1 Events and phases of QUENCH-06

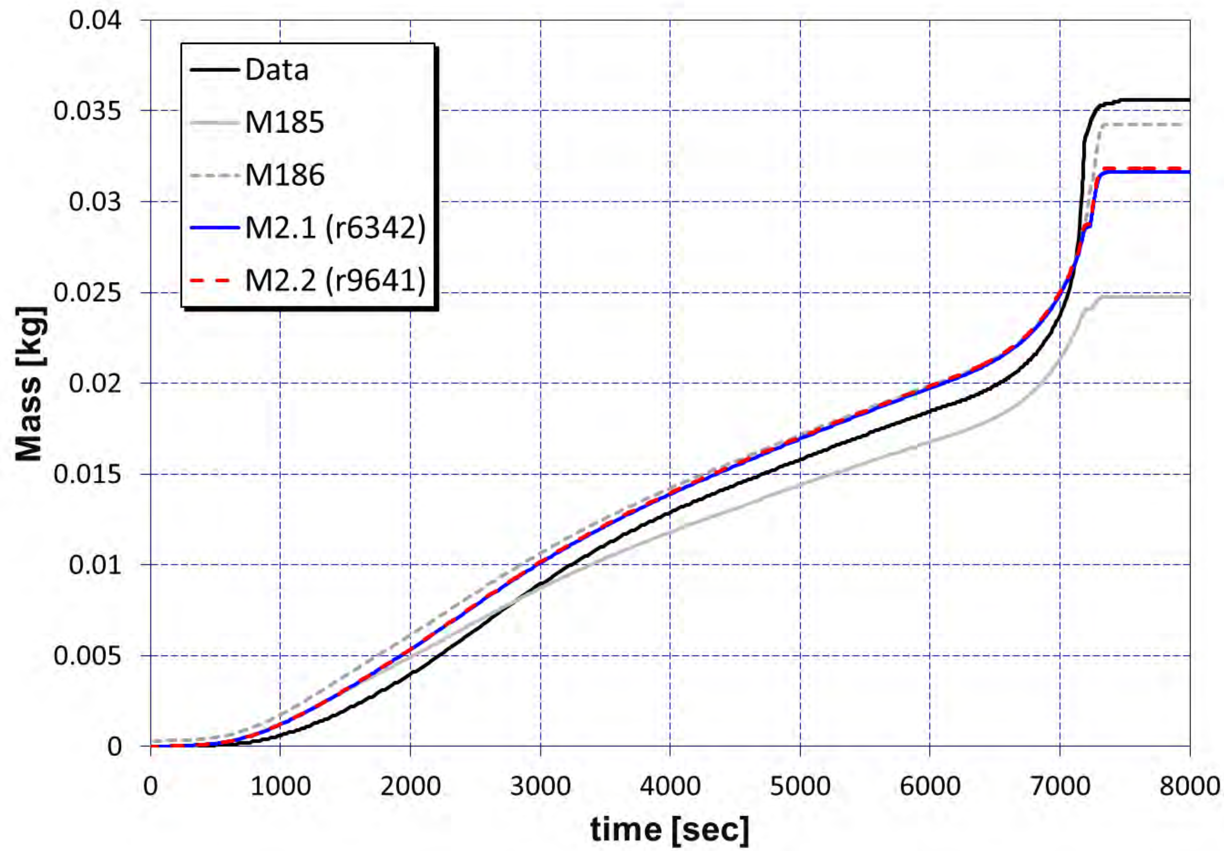
Time	Event	Phase
0	Start of data acquisition	
30	Heat up to about 1500 K	Pre-oxidation
1965	Pre-oxidation at about 1500 K	
6010	Initiation of power transient	Power transient
6620	Initiation of pull-out of corner rod (B)	
7179	Quench phase initiation	Reflood
	Shut down of steam supply	
	Onset of fast water injection	
	Start of quench water pump	
	Detection of clad failure	
	First temperature drop at TFS 2/1	
7181	Steam mass flow rate zero	Quench
7205	Onset of electric power reduction	
7221	Decay heat level reached	
7430	Onset of final power reduction	
7431	Shut down of quench water injection	Post-reflood
7431	Electric power < 0.5 kW	
7435	Quench water mass flow zero	
11420	End of data acquisition	

Visualization of Quench Phenomenon

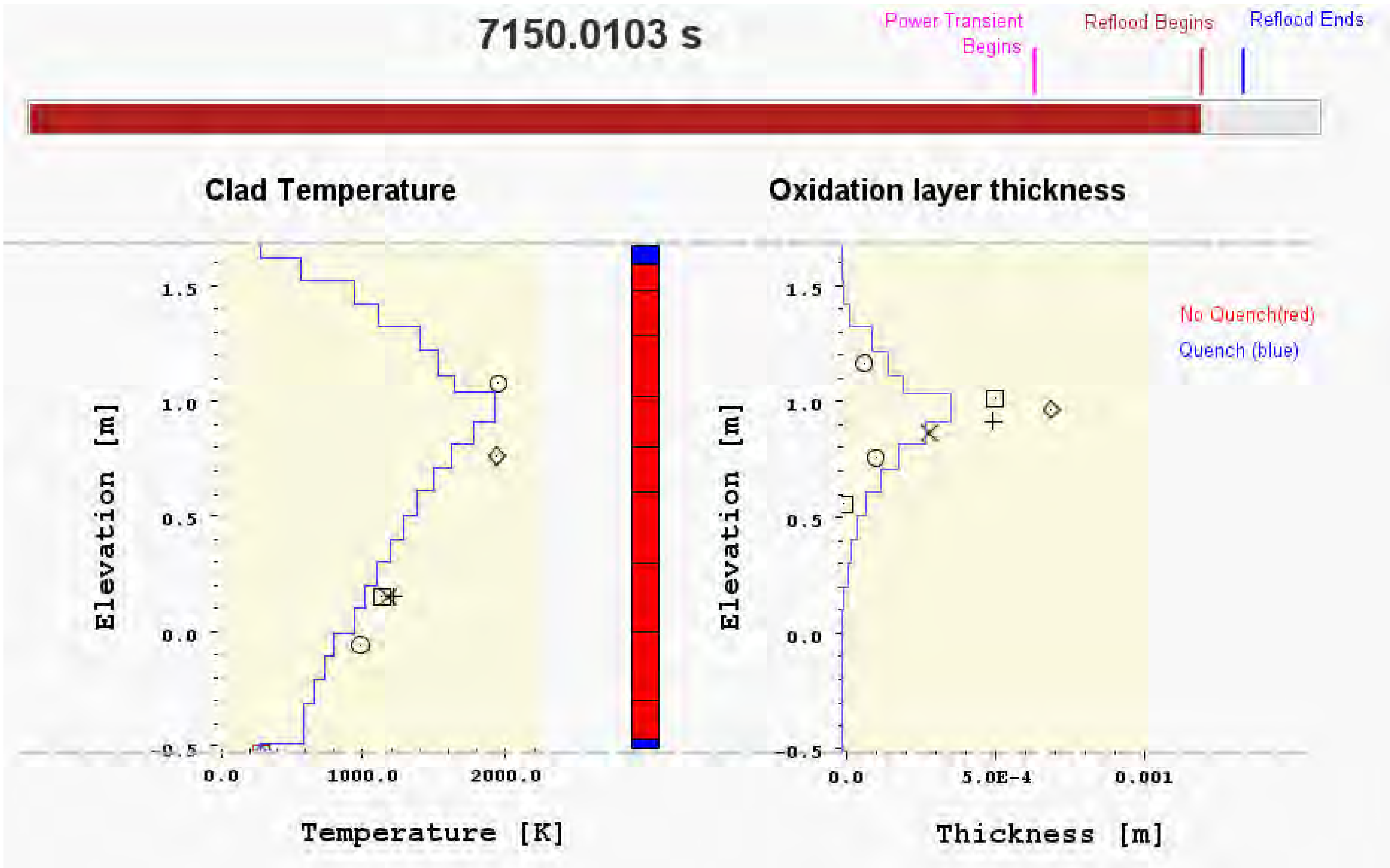


ISP-45 Quench 6 Oxidation

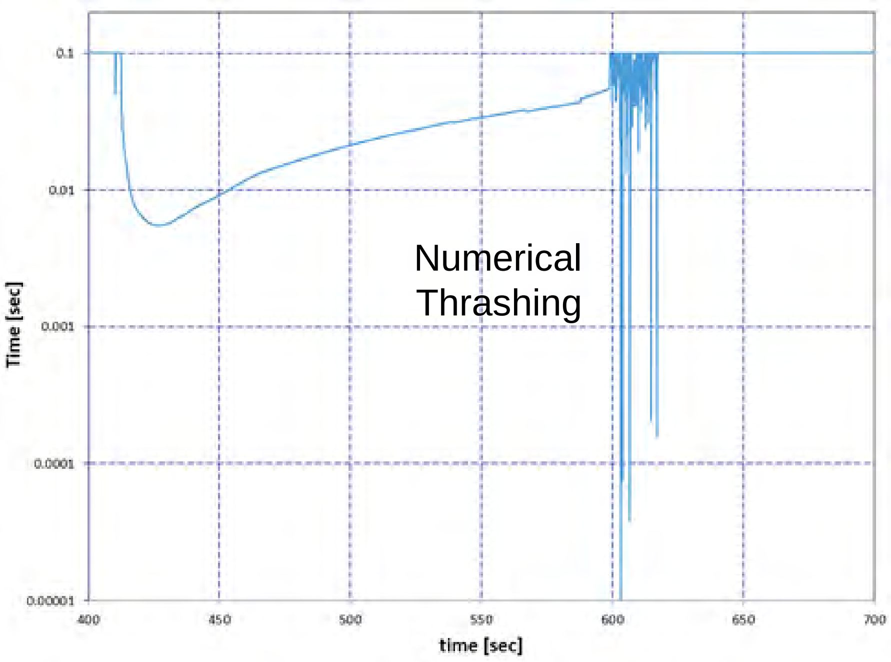
- Little change between revision M186, 6342, and 9641
- M185 differences largely due to mass of heater rods



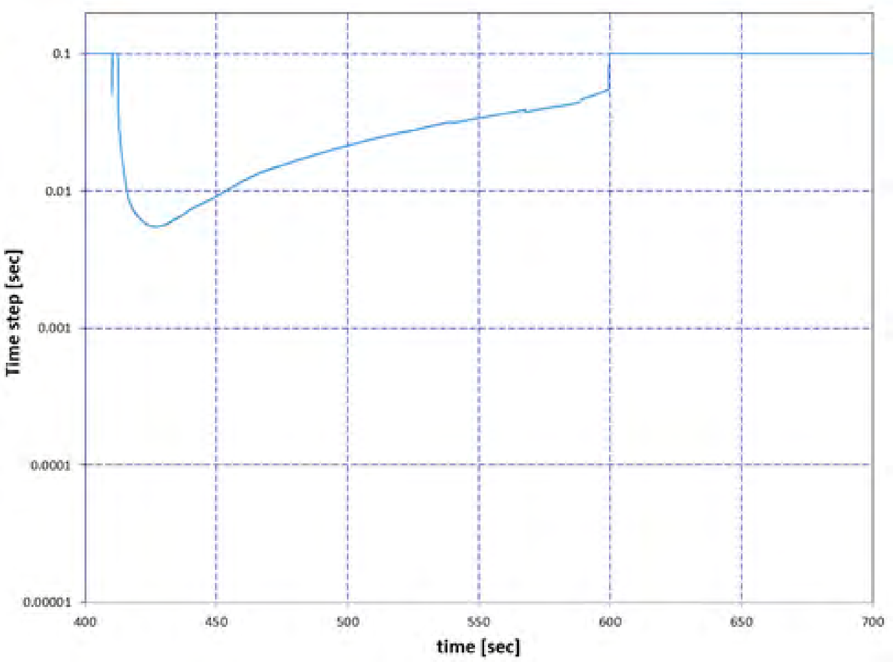
Axial Oxidation Profile



Temporal Relaxation of Quench Velocity
Time-step size vs. simulation time



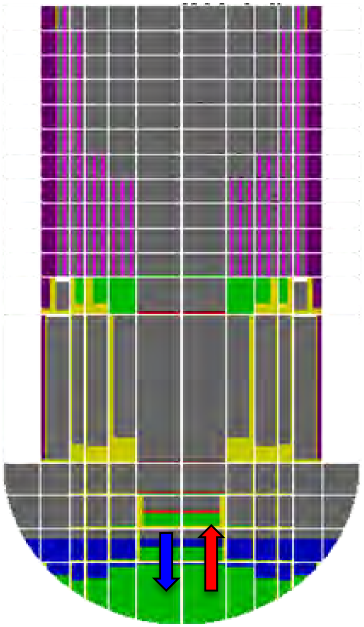
Modeling changes inactive



Modeling changes active

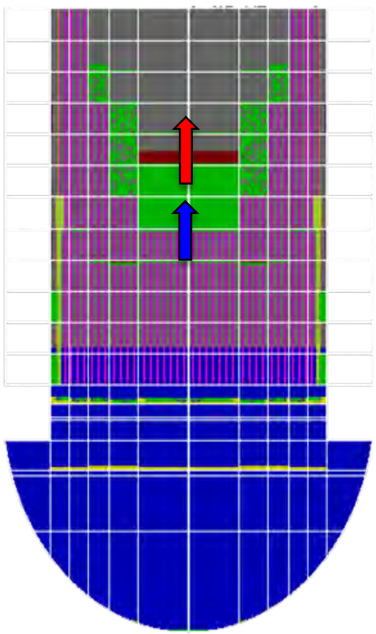
Lipinski Dryout Model

Debris in Lower Plenum

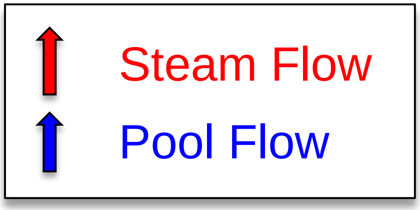


- Same geometry assumed for Lipinski 0-D model/experiments
- Counter-current flow of water and steam.
  - Potential for dryout

Debris in Upper Core



- Geometry not valid for Lipinski 0-D model
- Steam flow in same direction as pool flow.

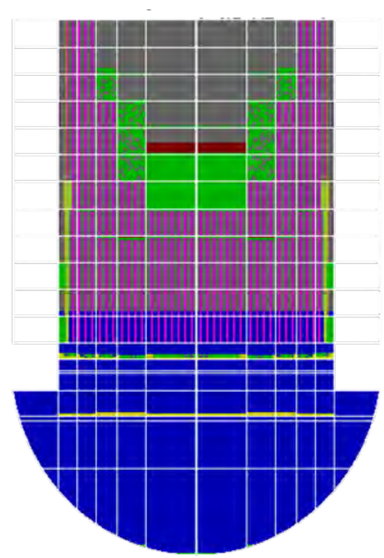


Corrections to Implementation of Lipinski 0-D Model

- Model only applied in lower plenum
  - Removes criteria for disabling heat removal from intact components when critical heat flux observed.
- Lipinski model is disabled as debris bed thickness approaches particulate characteristic dimension.
- TMI-2 shows simulation shows promise for improvement when Lipinski 0-D model disabled in upper core.

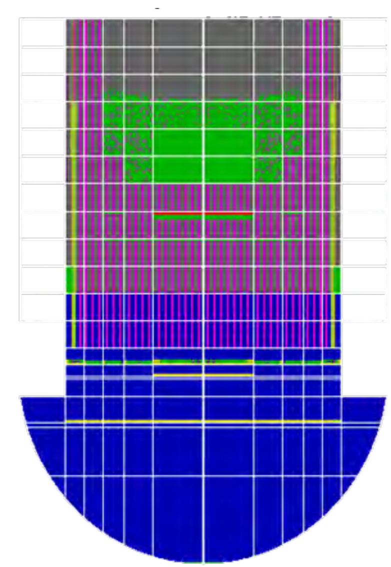
Comparison of Core Degradation for TMI-2

Lipinski 0-D **Off** in Upper Core



10430 (sec)

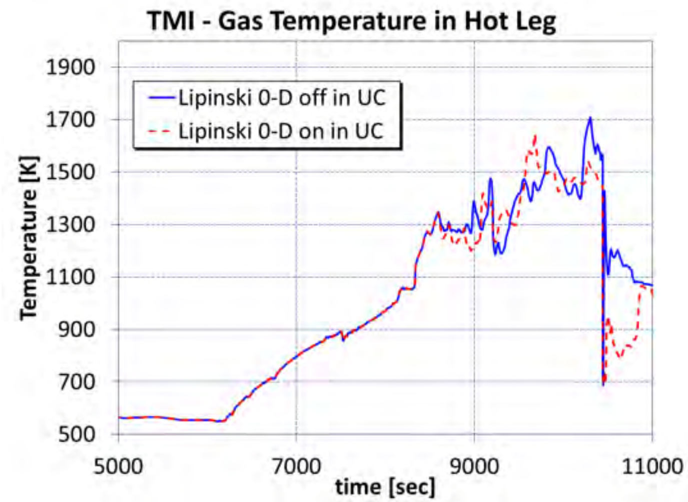
Lipinski 0-D **On** in Upper Core

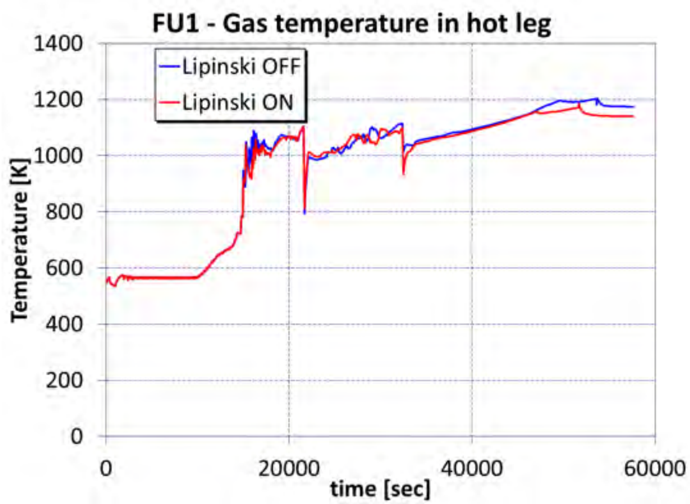


10430 (sec)

Corrections to Implementation of Lipinski 0-D Model
Effect on Gases in Hot Leg (TMI)

- Potential for impact on gas temperatures in hot leg
  - When Lipinski 0-D model was on:
    - No convective heat transfer to the pool is calculated for other components in cells quenching at the dryout heat flux.
    - No heat transfer is calculated for particulate debris or other intact structures below dryout level
- Debris dryout in upper core is an infrequent event
  - Water level typically below PD bed
  - Small impact on gas temperatures
  - May have impact on core degradation



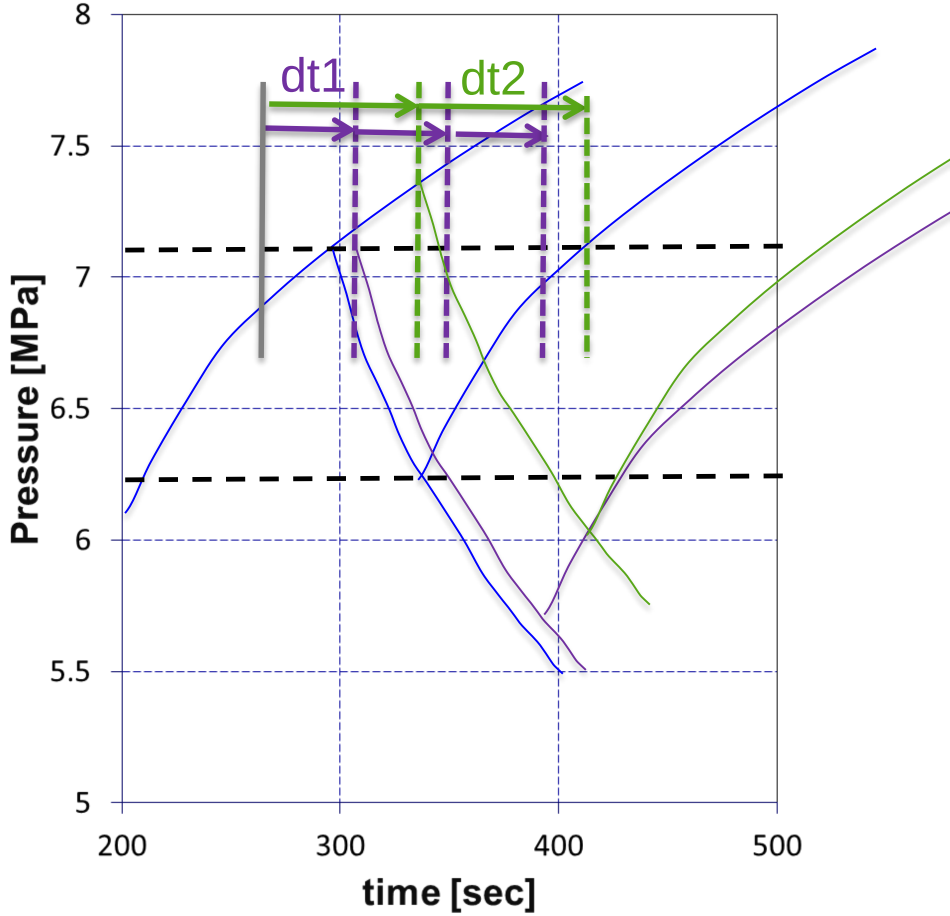


Numerical Variance

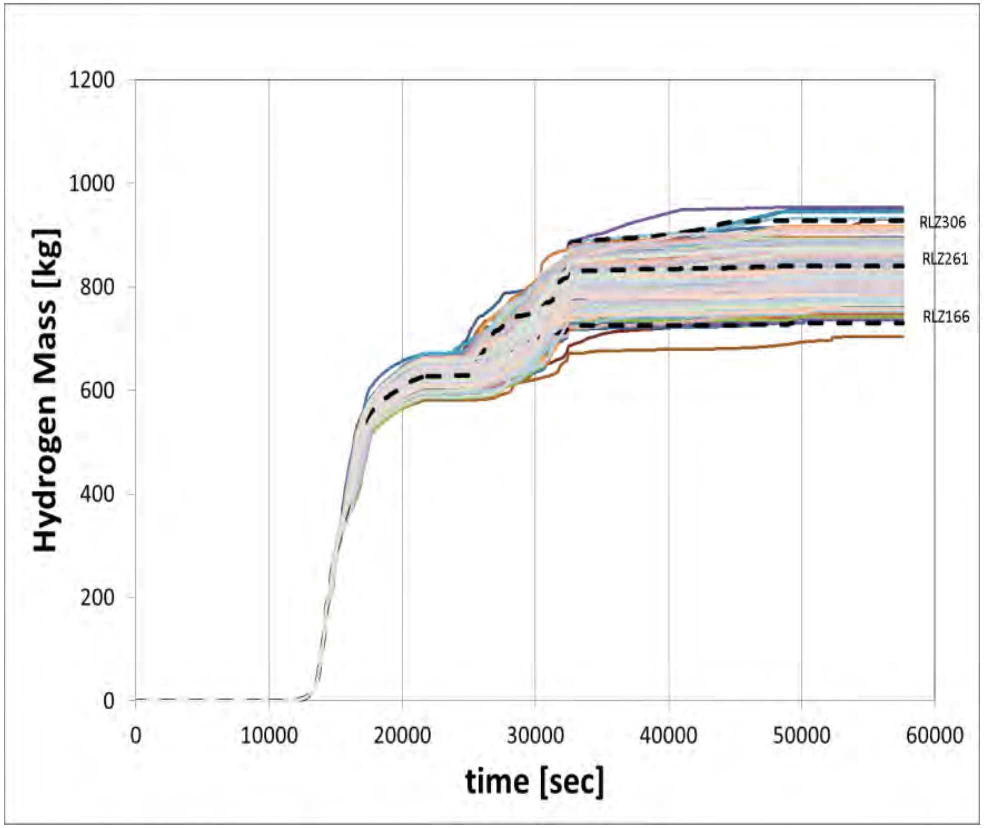
- Characterization of Numerical Variance
  - Background code variance
    - Sources of variance – tolerances, hysteresis effects, others
    - Amplifiers – cliff-edge effects such as collapse of fuel rods in a ring
  - Assess the sensitivity of the variance to COR degradation models
    - <u>Variance is extremely small prior to COR degradation</u>
    - Effect of COR Nodalization on Numerical Variance
      - COR cell nodalization
      - CVH nodalization
  - Time step variations & time step convergence
  - Application to UA variations
    - Discriminating parameter variance from background variance
      - Signal to noise ratio
- Reduction of Numerical Variance
  - Reduction of tolerances
  - Smart relief valves
  - Time-at-temperature rod failure
  - Multi-rod model
  - Others

Numerical variance from hysteresis function for SRV valve model

- Pressure rise in SBO calculation as system heats up.
  - Pressure rise limited by upper setpoint in SRV model (valve opens)
  - De-pressurization limited by lower setpoint in SRV (valve closes)
  - Small overshoot in pressure predicted for dt1
  - For larger time step, dt2, pressure overshoot leads to much larger pressure variation
- Flow of steam (valve open) leads to oxidation and heat removal during depressurization
- 'Smart' hysteresis model added to drop timestep to minimize overshoot.



Identical Input Definition but Input Record Ordering is Randomized



- Each realization is essentially equivalent descriptions of problem
- Order of input definition randomly varied
- Representative extremes examined separately by Monte Carlo sampling over state of knowledge uncertain parameters
- Do different but equivalent flow path descriptions produce different distributions in UA ?

Representative Extremes of “shuffle” used as seed for 10% UA variations

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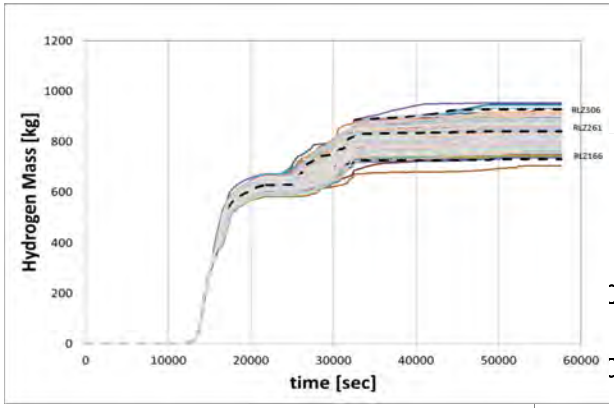
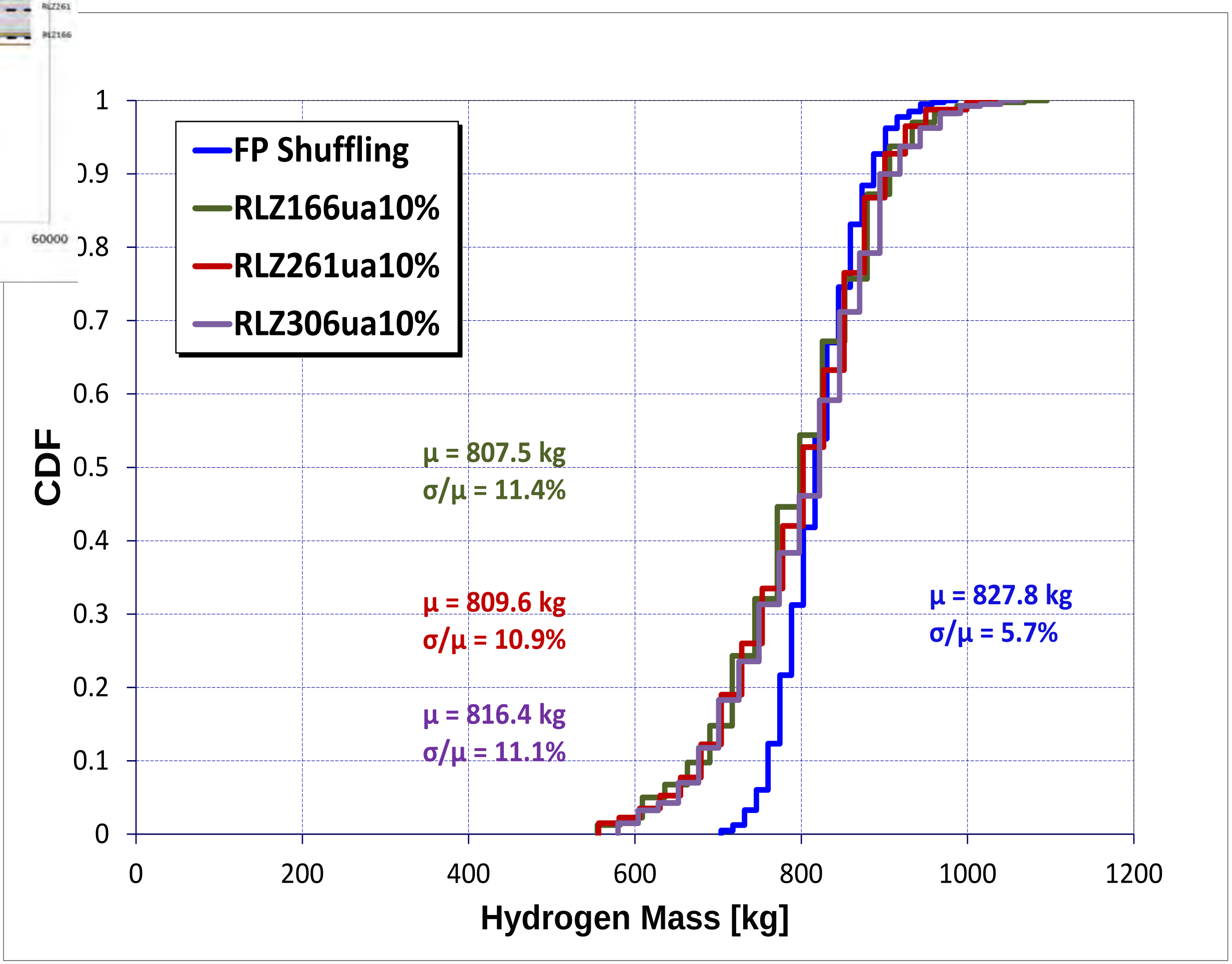


Each representative member of the “shuffle” ensemble returns the same resultant distribution when UA parameters are varied



Representative members of "shuffle" used as seed for 20% UA variations

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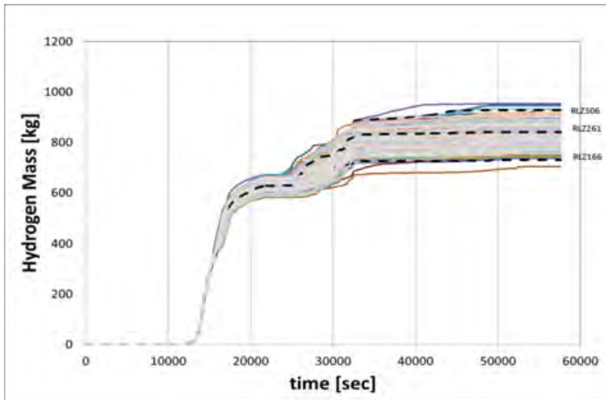
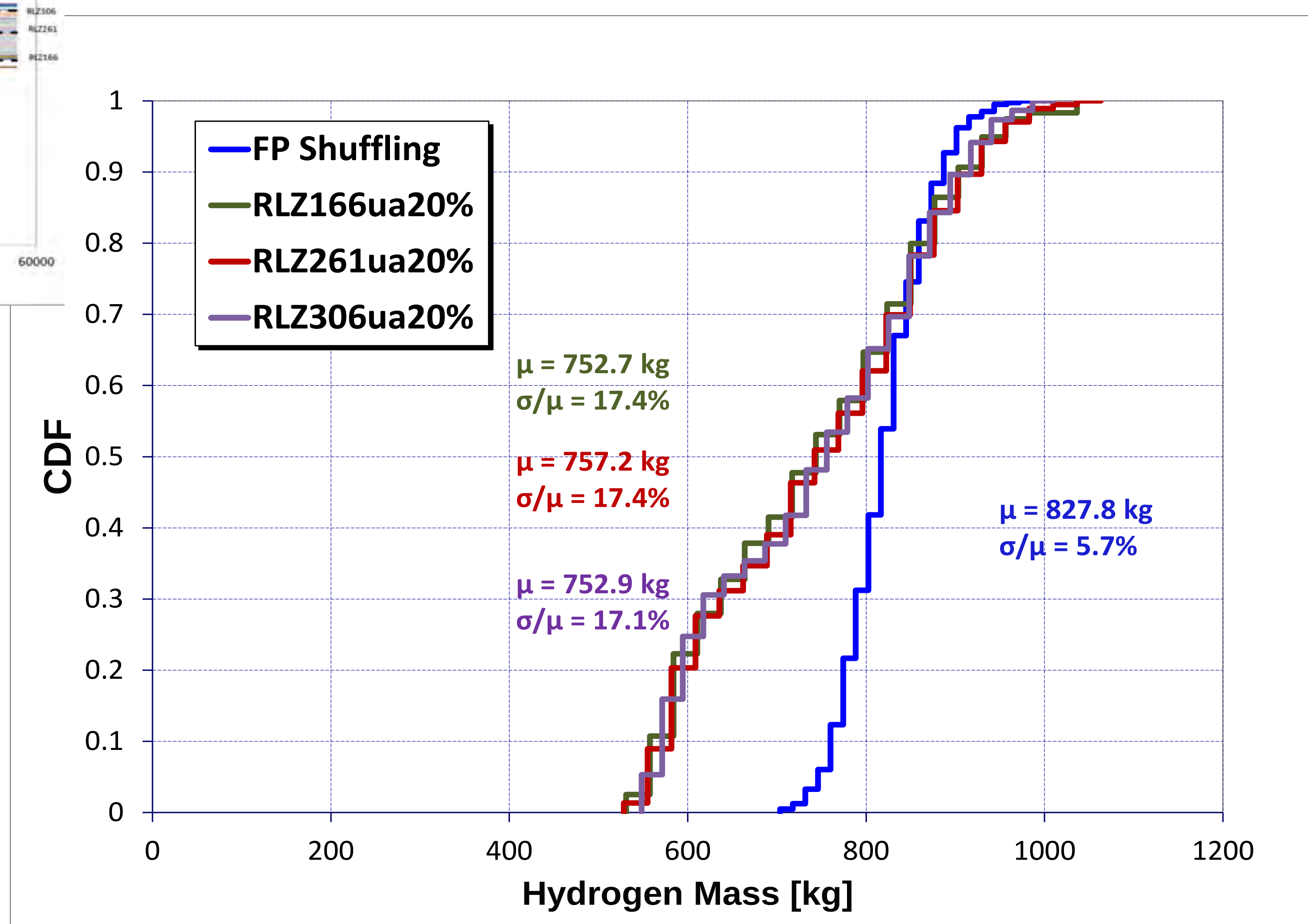


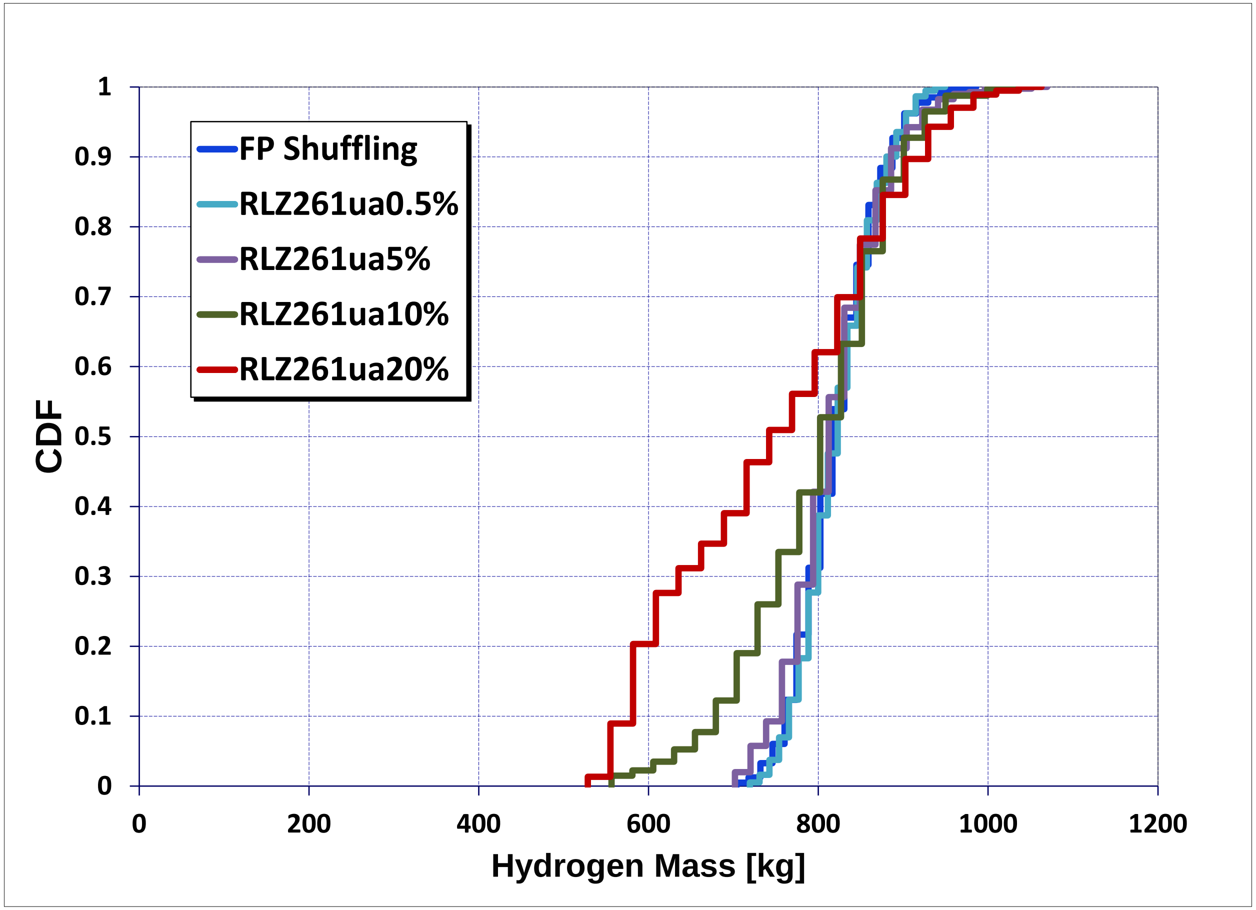


Same result for 20% UA Variation

Note: that mean is shifting down,

Upper H2 limited by core degradation

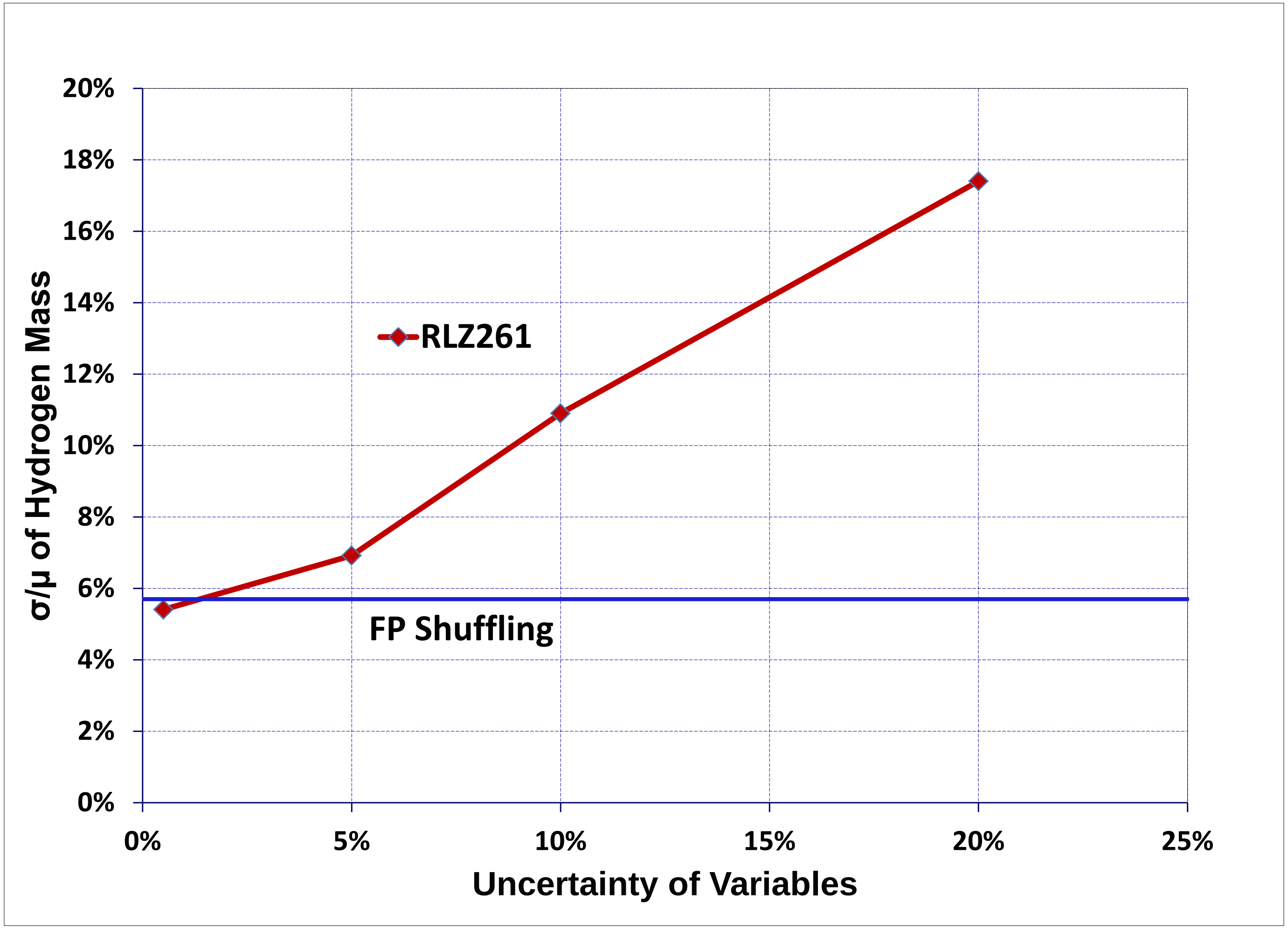
UA Variation Explored to Characterize Signal to Noise Ratio



0.5% and 5% UA variations nearly same as background numerical noise

10% and higher variation clearly distinguishable from background noise

Signal to Noise versus % Variation for Hydrogen




why
who
where
when
QUESTIONS
why
who
where
how
who
what
how
when

Backup Slides

New Model Development Tasks (2014-2016)

- Completed
  - Fuel Rod Collapse Model
  - Homologous pump model
  - Multi-HS radiation enclosure model
  - Aerosol re-suspension model
  - Zukauskas heat transfer coefficient (external cross-flow across a tube bundle)
  - Core Catcher (multiple containment vessels)
  - Multiple fuel rod types in a COR cell
  - Generalized Fission Product Release Model
  - New debris cooling models added to CAV package
    - Water-ingression
    - Melt eruption through crust
  - Spreading model implemented into CAV package
  - Miscellaneous models and code improvements
    - COR_HTR extended to heat structures
    - LAG CF
    - MACCS Multi-Ring Release
    - Valve Flow Coefficient
    - MACCS release types
- In Progress
  - Vectorized Control Functions
  - CONTAIN/LMR models for liquid metal reactors
  - CVH/FL Numerics

Revised Candling Model from PD to Cell below with intact Rods

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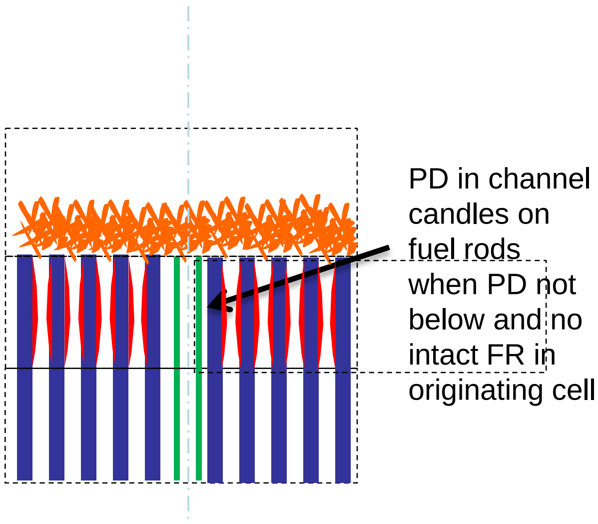
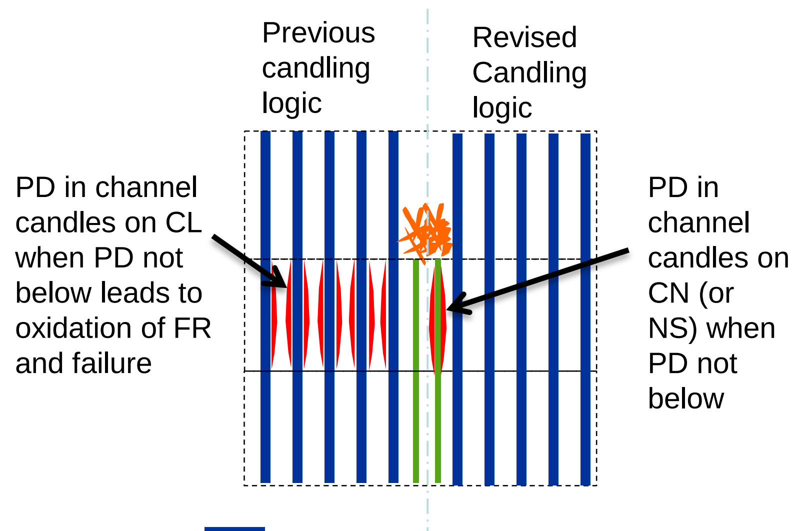
PD from cell with no intact FR

No Change



PD from cell with intact FR

Candles on NS, CN, or CB



- Fuel Rods (FU+CL)
- Canister (CN+CB)
- Conglomerate (candling)
- Particulate Debris (PD+PB)

CORCNV basically has four key parts

1. If quenching, compute new quench location and region fractions (lines 177-210)
   - Call function XUQNew

2. Compute heat (and mass) transfer coeficients for different regions based on various Nusselt number correlations for different component types (lines 211-533)
   - Section 2.3 of COR Reference Manual

3. If quenching, solve for new “hot” and “cold” region temperatures (lines 534-552)
   - Call either COR_CORCLL2 or COR_CORCLL4

4. Compute convective heat transfer
   - Included in CORCLL2 and CORCLL4, or
   - Lines 554-674
   - Basic equation has form:

$$Q_{cnv,r} = h_r (x_r A_s)\left(T_s - T_f\right)$$

MELCOR Equations for simple-case two-temperature model

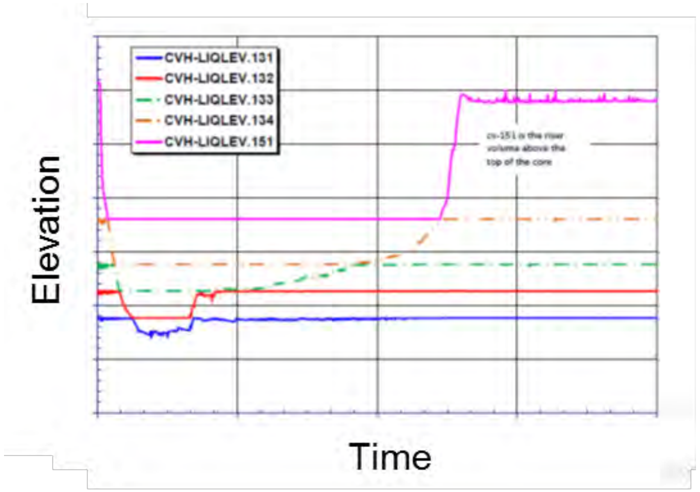
$$\frac{C}{\Delta t}\left(x_h^n T_h^n + x_c^n T_c^n\right) = \frac{C}{\Delta t}\bar{T}^o - h_h x_h^n A\left(T_h^n - T_a\right) - h_c x_c^n A\left(T_c^n - T_p\right) + \dot{Q}$$
$$- K(T_h^n - T_c^n)$$

$$\frac{C}{\Delta t} x_c^o T_c^n = \frac{C}{\Delta t} x_c^o T_c^o - h_c x_c^n A\left(T_c^n - T_p\right) + x_c^n \dot{Q}$$

Certain double-sided components require that conduction heat be calculated from one surface and added as an explicit source to the other surface. A future modification is anticipated to allow both surfaces to be calculated simultaneously.

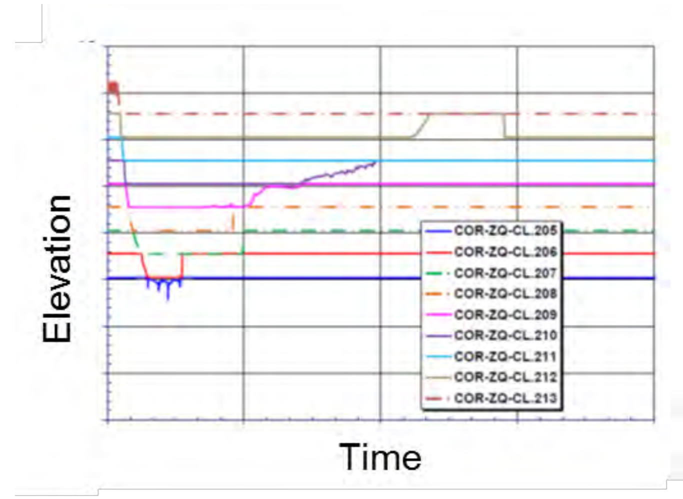
Error Correction to Quench Model Implementation

Water Level

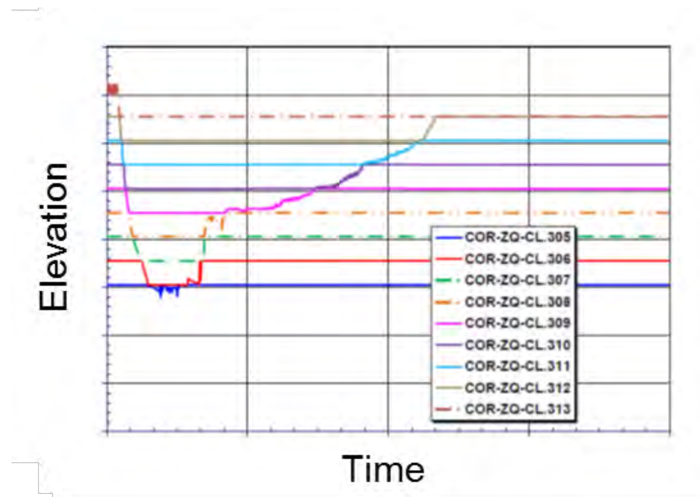


Quench Level

Before correction



After correction



- Quench location on reflood would not cross a cell boundary, but was ‘stuck’, even though the liquid pool had risen much higher.
  - Quench would not advance if the “hot” temperature in the cell below was above a prescribed threshold.
  - Changed the temperature criteria to a test of the quench fraction in the cell below.

Lipinski Dryout Model

- Dryout heat flux based on steady state experiments on uniform particle beds with water pool above.
- No heat transfer is calculated for particulate debris or other intact structures below dryout level.
- No convective heat transfer to the pool is calculated for other components in cells quenching at the dryout heat flux.

$$q_d = 0.756\ h_{lv} \left[\frac{\rho_v\ (\rho_l - \rho_v)\ g\ d\,\varepsilon^3\ (1 + \lambda_c / L)}{(1-\varepsilon)\ \left[1 + (\rho_v / \rho_l)^{1/4}\right]^4} \right]^{1/2}$$

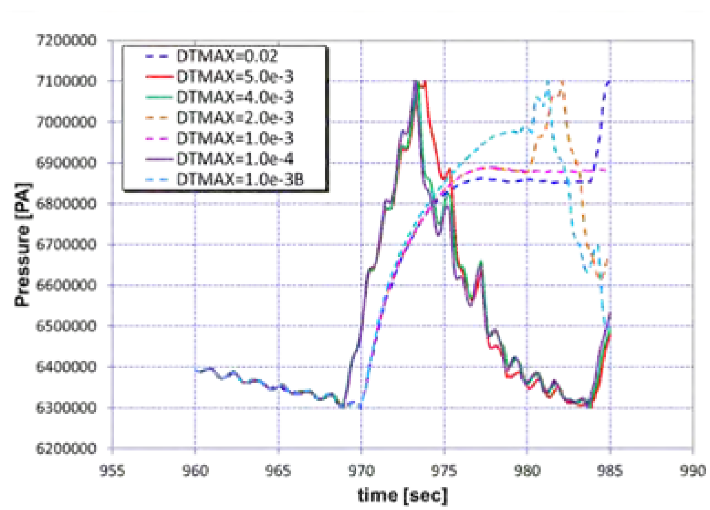
In this equation, h_{lv}, ρ_l, and ρ_v are the latent heat ,liquid, and vapor densities of water, respectively; g is the gravitational acceleration; d is the debris particle diameter; ε is the bed porosity; L is the total bed depth; and λ_c is the liquid capillary head in the debris bed,

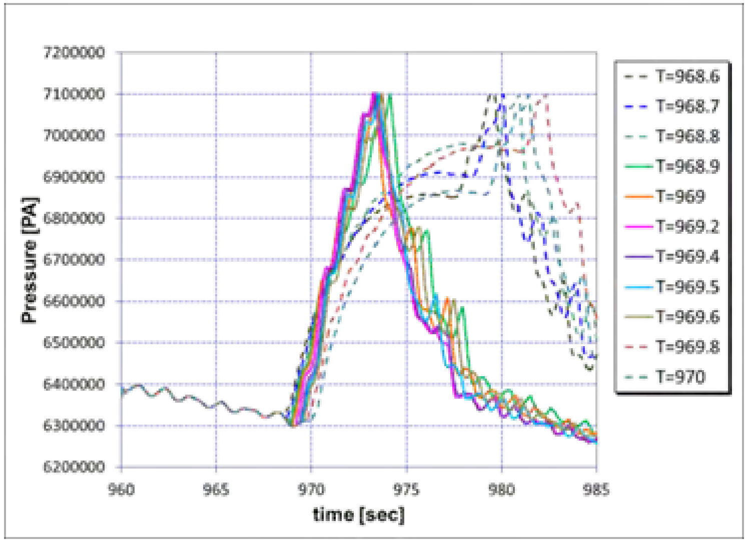
$$\lambda_c = \frac{6\ \sigma\ \cos\theta\ (1-\varepsilon)}{\varepsilon\ d\ (\rho_l - \rho_v)\ g}$$

where σ is the water surface tension and is wetting angle. The leading constant, the nominal capillary head for 0.5 mm particles in approximately 0.089 m of water, and the minimum bed porosity allowed in the correlation are accessible to the user as sensitivity coefficient array C1244. A default minimum porosity of 0.15 was selected to ensure that some heat transfer occurs from molten debris pools. The actual capillary head is adjusted for particle diameter size within the model

Inherent Variance in User Model

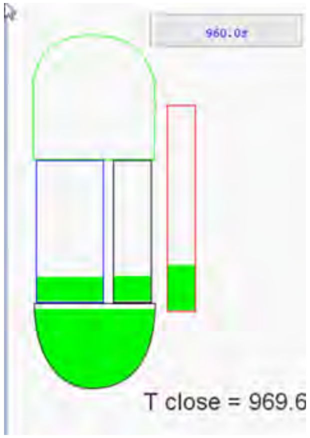
- A number of calculations were performed with the simple BWR test deck each starting with the same restart dump
  - History up to that point was identical
  - Time step was varied for each subsequent run
  - Results highly dependent on time step
  - Bimodal response dependent on time step
    - Does not appear to be convergent with time step size
  - Bimodal response dependent on valve closing time.





Variance due to interaction of time step and model.

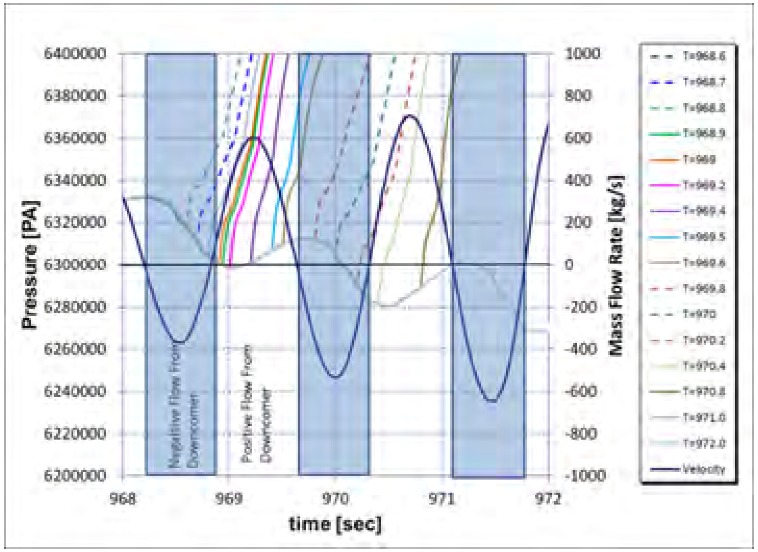
- Variance results from the modeling of the trapped gas in the dead-end volume
  - Interaction of time step with harmonic from sloshing of water in lower plenum
- Momentum of flow at time of valve opening or closure is important.
  - If the water is moving away from the valve at valve opening, it will slow down the depressurization due to interfacial friction and inertia.
  - If the water is moving towards the valve, the inertia will accelerate depressurization.



$$f = \frac{1}{2\pi}\sqrt{\frac{k}{Mass}}$$

$$k = -\frac{F}{x} = \frac{-\Delta P \cdot Area^2}{dVolume}$$

F=~ 2 sec



Future MELCOR Manual Updates

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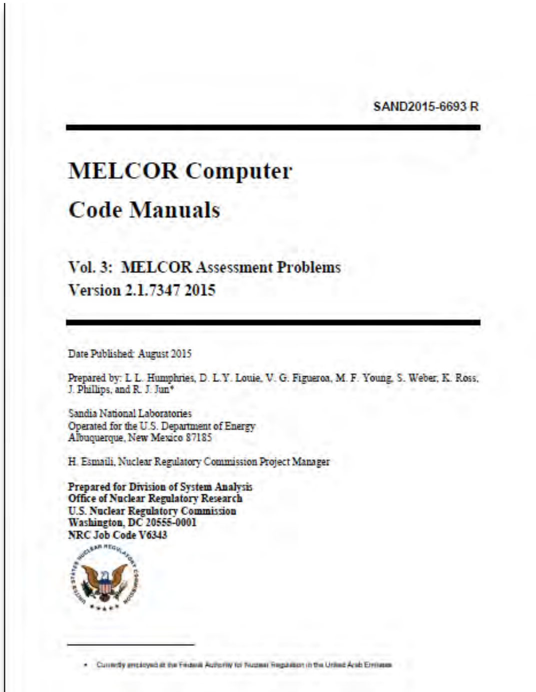
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MELCOR Computer Code Manuals

Vol. 3: MELCOR Assessment Problems
Version 2.1.7347 2015

Date Published: August 2015

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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code V6343

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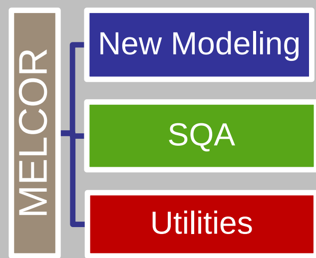
By December 2017
- Demo PWR plant deck
- Demo BWR plant deck
- COR/CVH Nodalization
- Containment DBA
- Numerical Variance
- Steady State Initialization

By December 2018
- FL/CVH Modeling
- Uncertainty Analysis
- Spent Fuel Pool Modeling
- Radionuclide Class Modeling
- MELCOR/MACCS Integration
- Troubleshooting MELCOR runtime issues
- Lower Head Modeling
- Heat Structure Modeling
- Cavity Related Modeling

Volume III: Assessments

Volume IV: Modeling Guide

R&A Complete
SAND2015-6693 R



IV Recent Applications of MELCOR

3 week MELCOR source term calculations FU3

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Presented by Larry Humphries

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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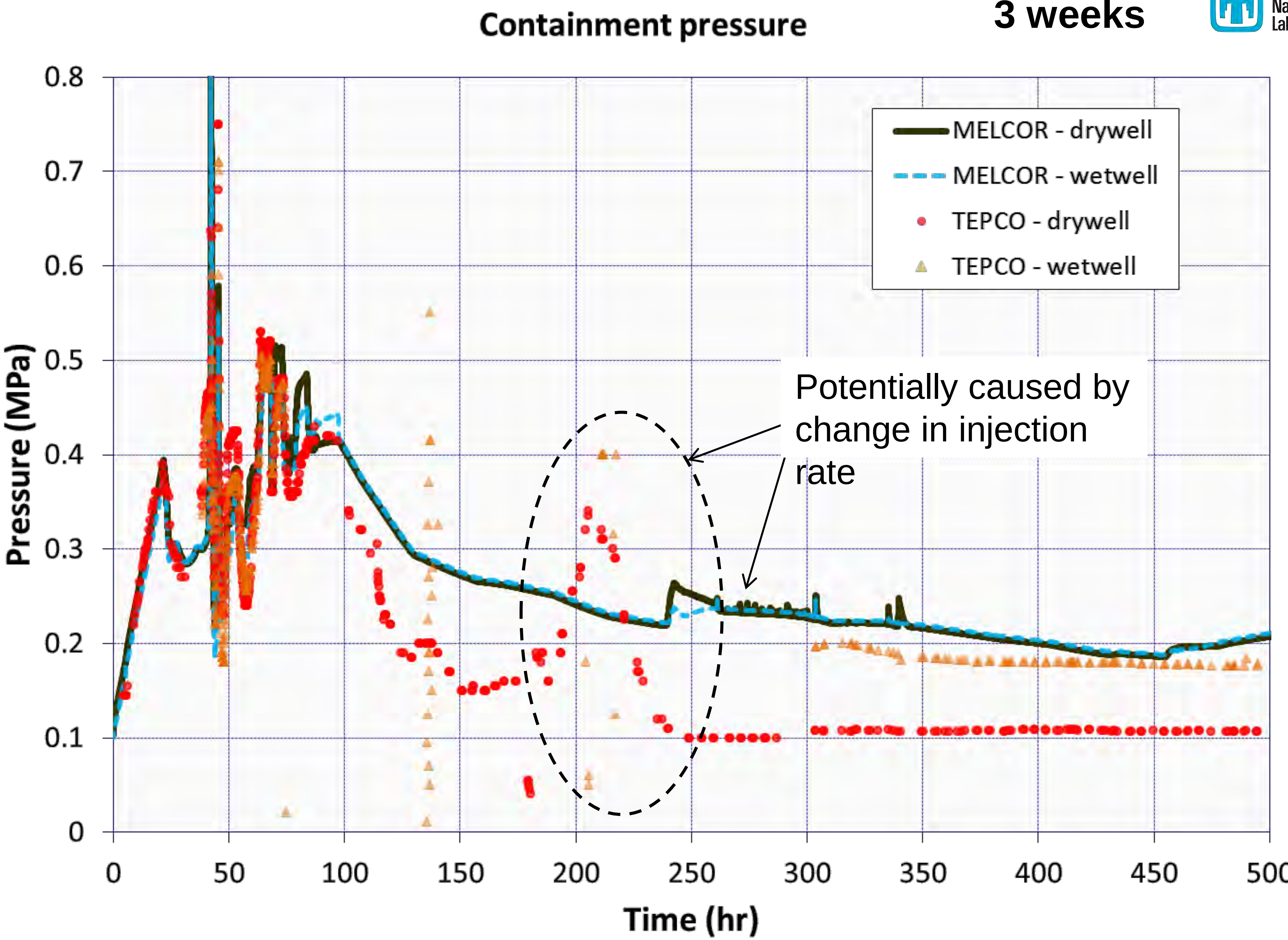
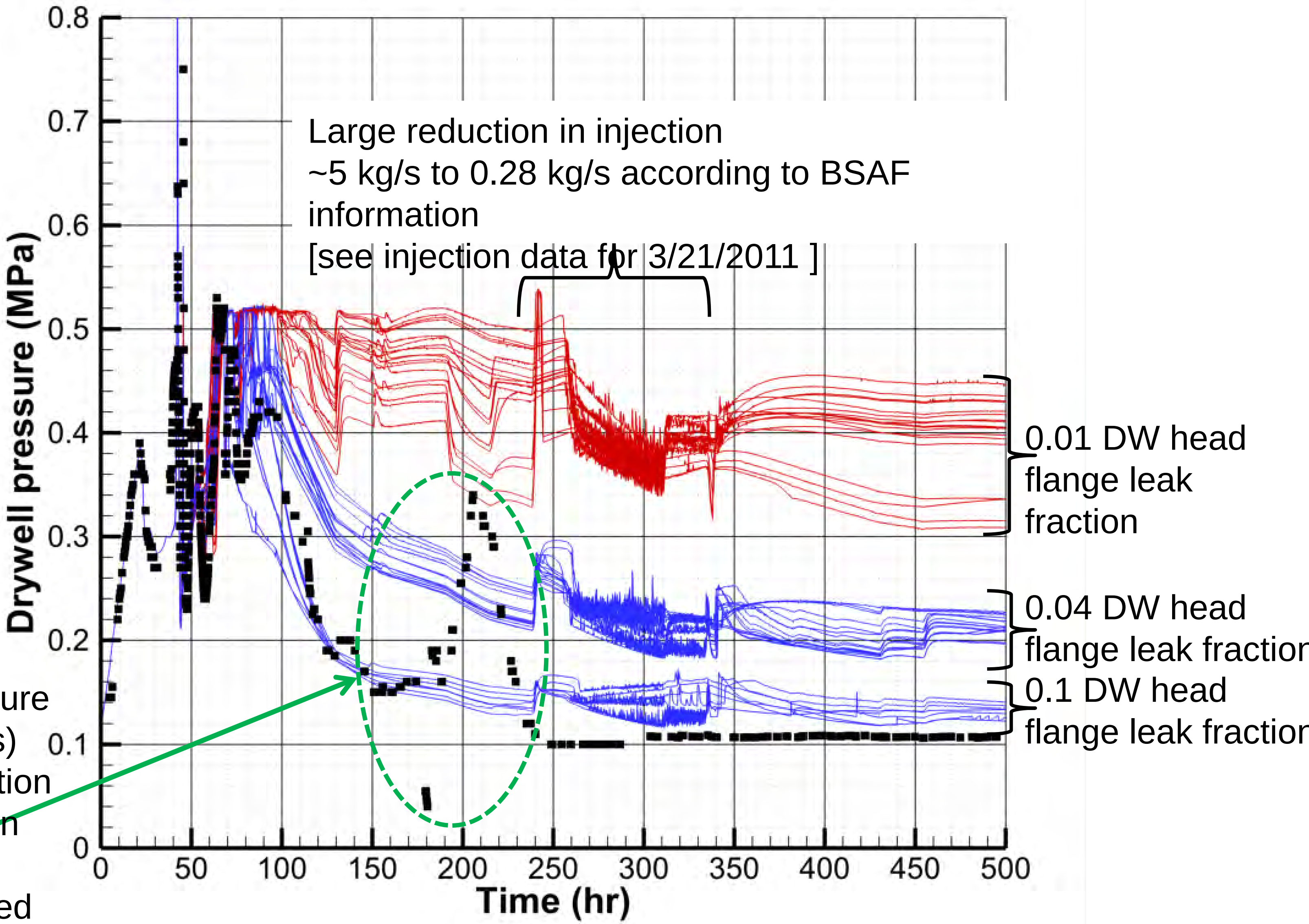
3 weeks

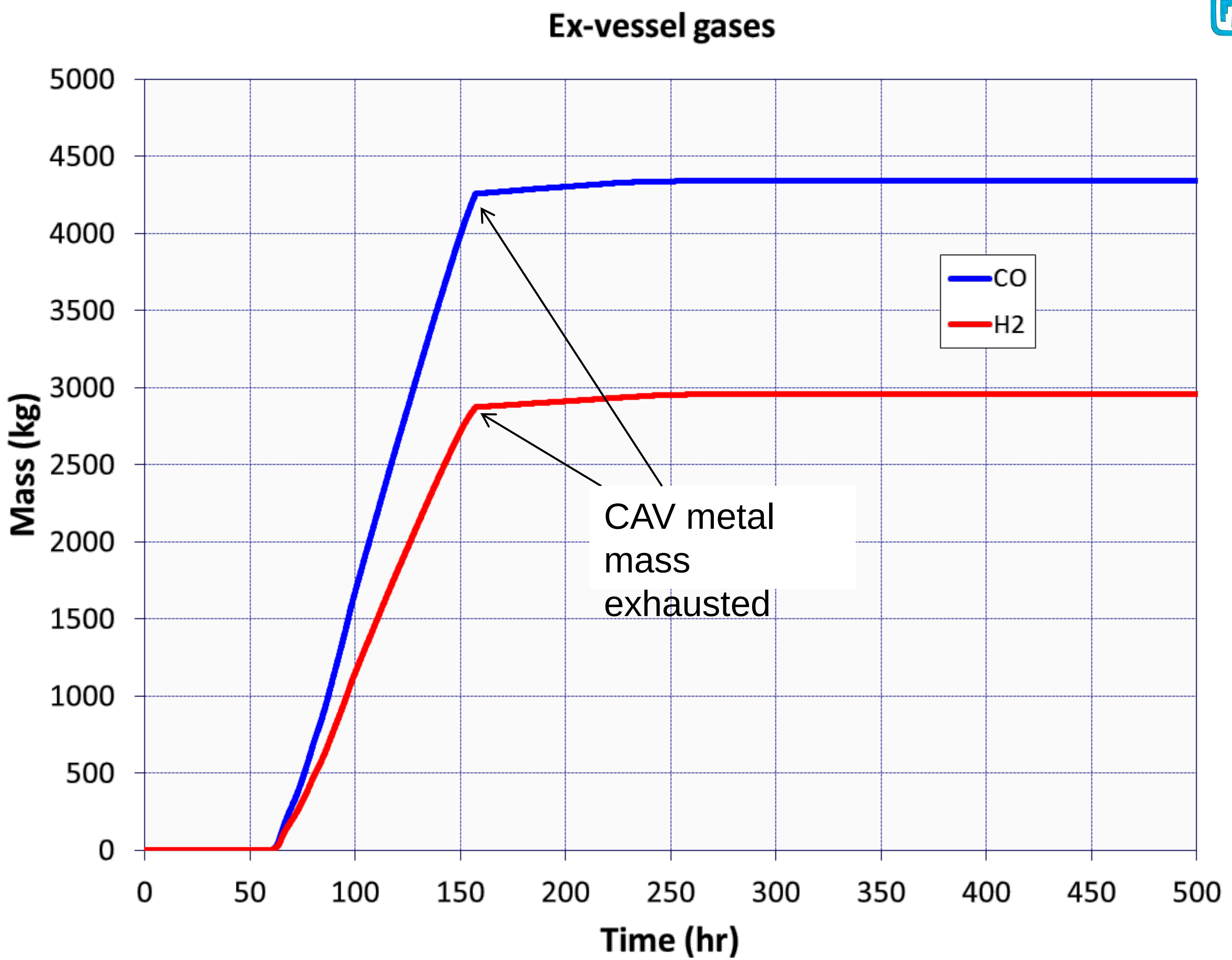


Containment pressure
Pressure (MPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400
450
500
Time (hr)
MELCOR - drywell
MELCOR - wetwell
TEPCO - drywell
TEPCO - wetwell
Potentially caused by change in injection rate

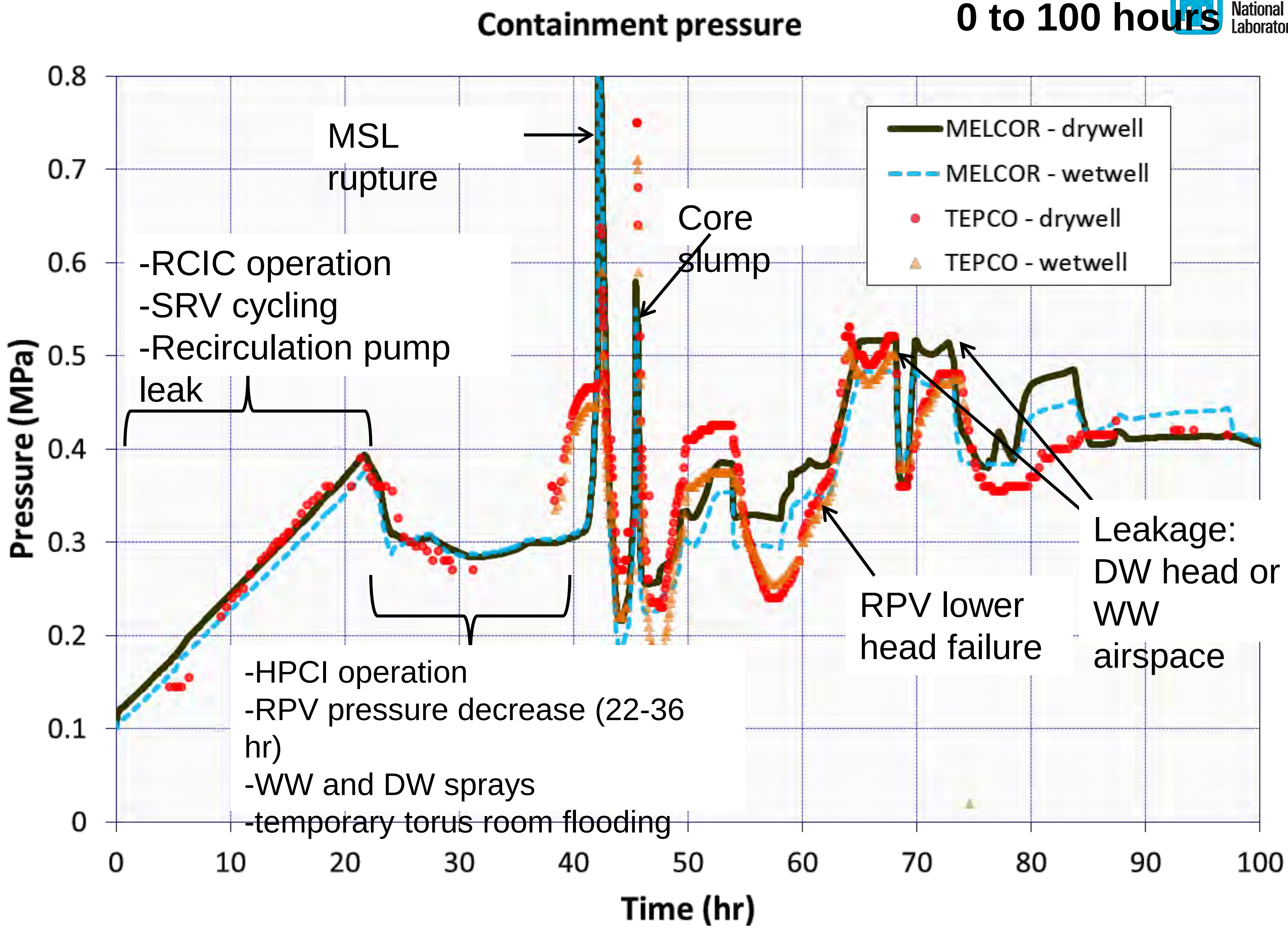
Containment (drywell) pressure

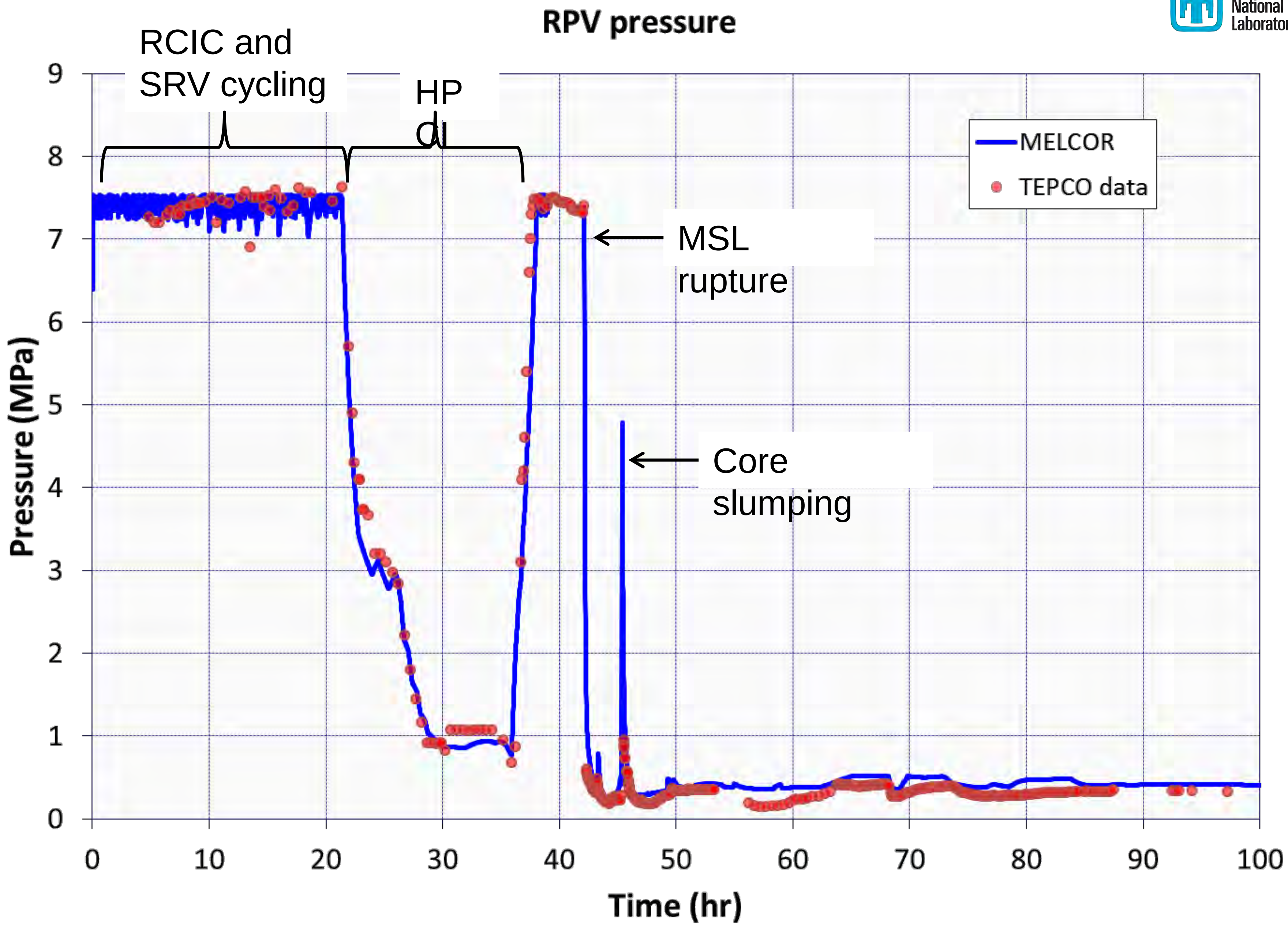


However, pressure data (black dots) suggests reduction in water injection might have actually occurred earlier

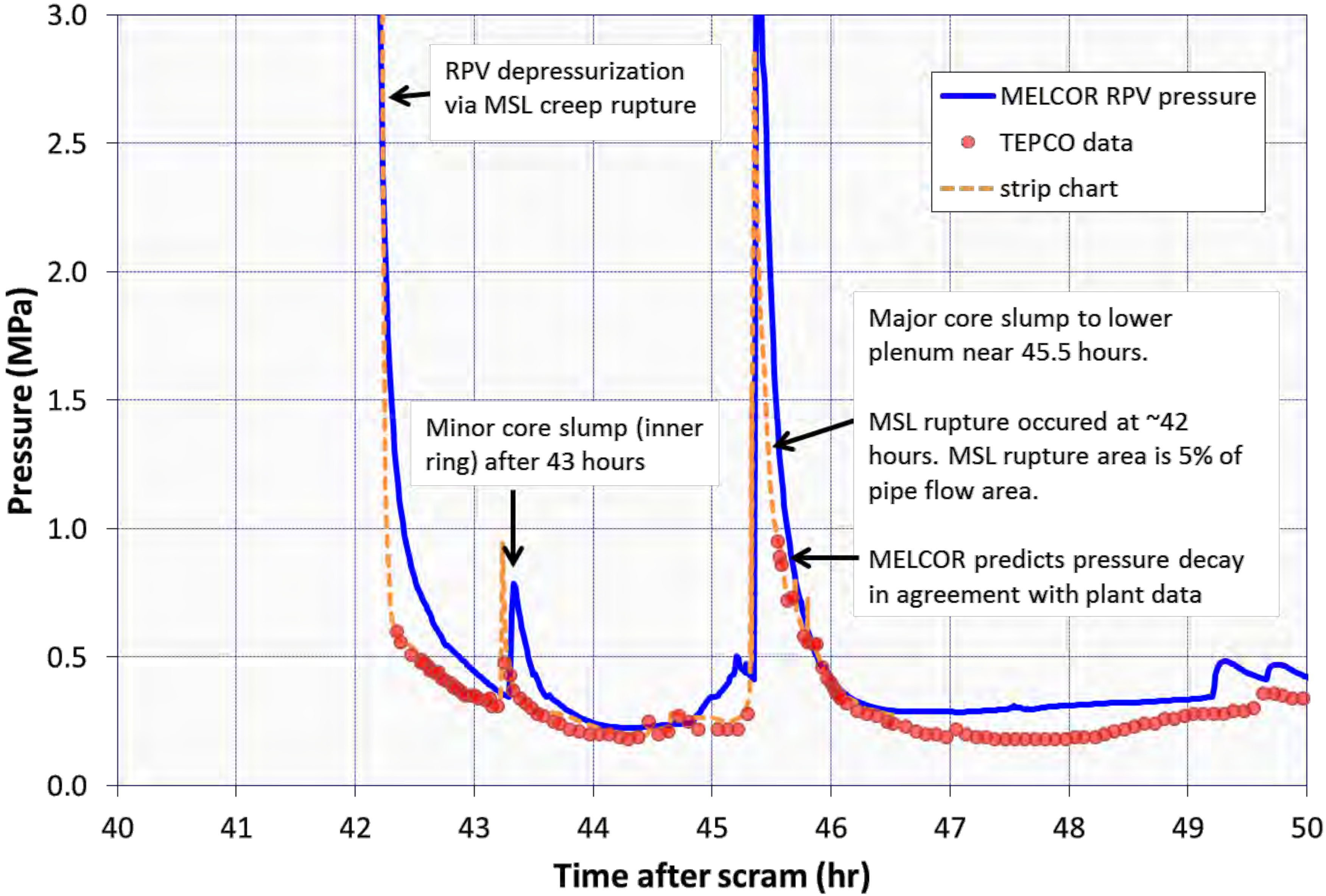

Ex-vessel gases
Mass (kg)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
400
450
500
Time (hr)
CO
H2
CAV metal mass exhausted

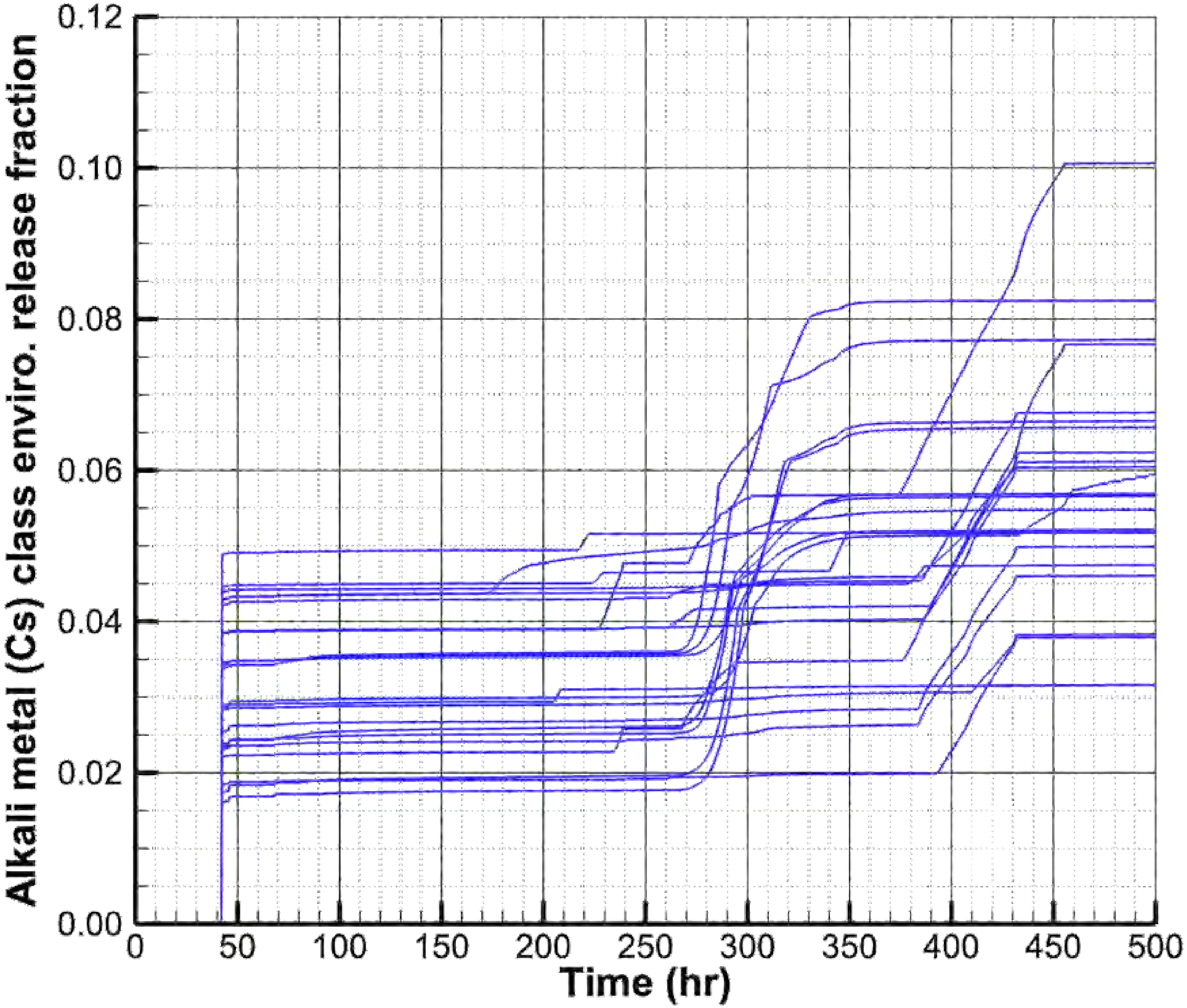
0 to 100 hours




RPV pressure
RCIC and SRV cycling
HP CI
MSL rupture
Core slumping
MELCOR
TEPCO data
Pressure (MPa)
Time (hr)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100

RPV pressure response after depressurization




Alkali metal (Cs) class enviro. release fraction
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0
50
100
150
200
250
300
350
400
450
500
Time (hr)

extra

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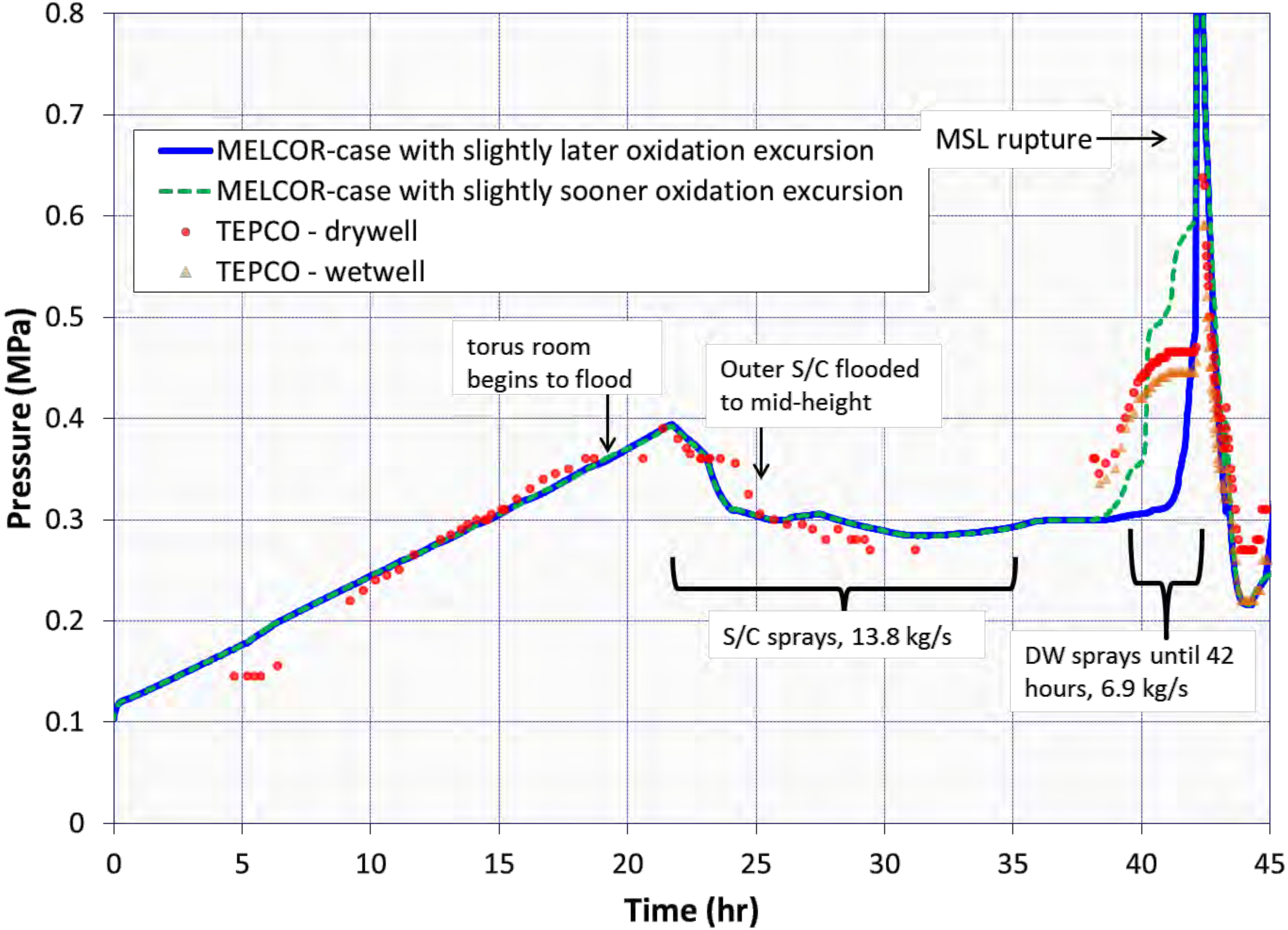
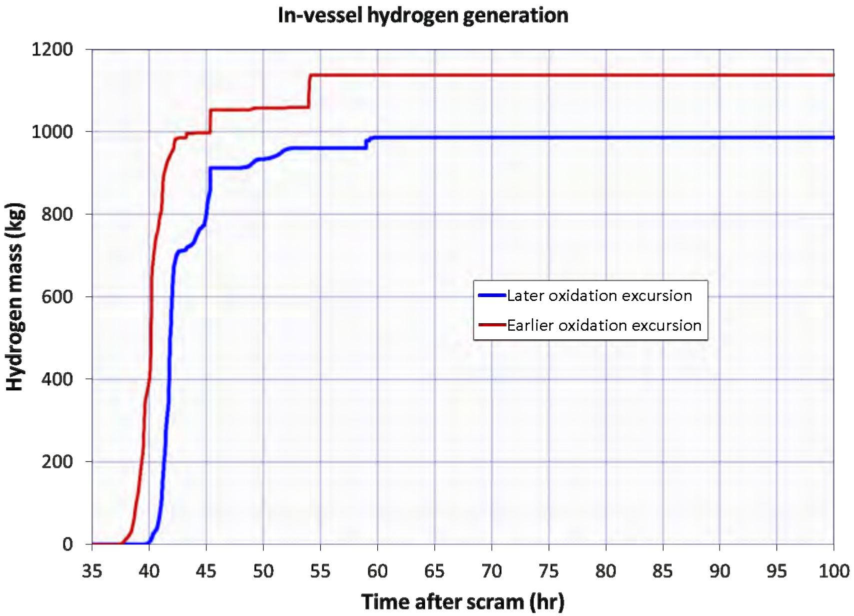
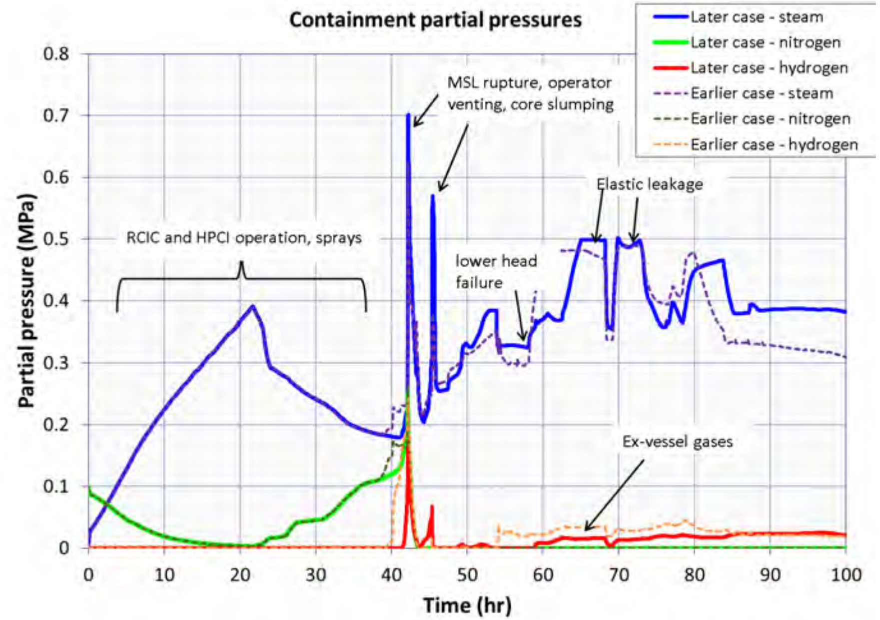
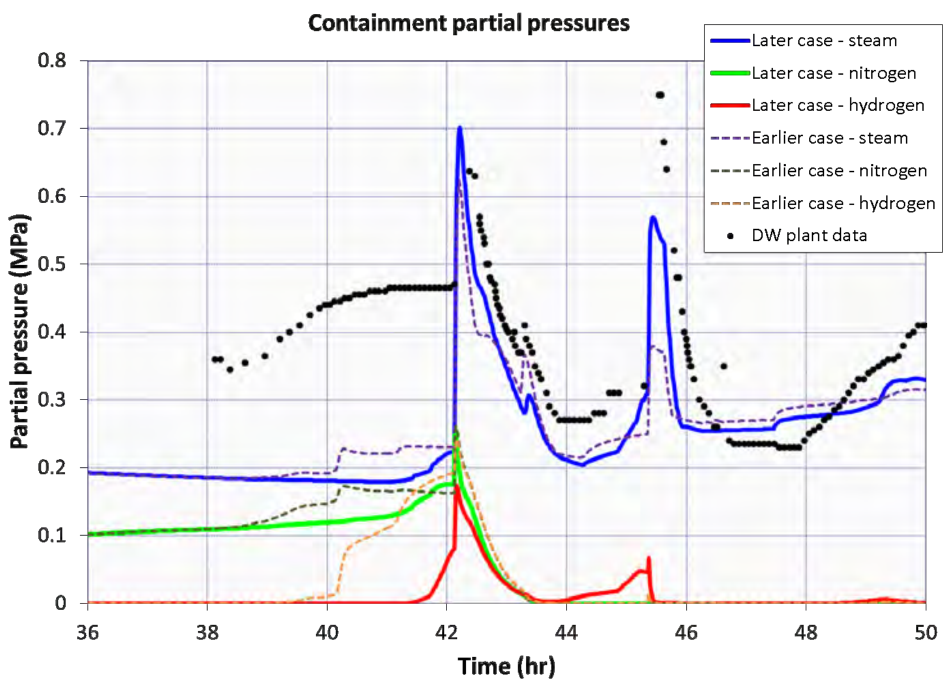
0 to 45 hours



Pressure (MPa)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
Time (hr)
MELCOR-case with slightly later oxidation excursion
MELCOR-case with slightly sooner oxidation excursion
TEPCO - drywell
TEPCO - wetwell
MSL rupture
torus room begins to flood
Outer S/C flooded to mid-height
S/C sprays, 13.8 kg/s
DW sprays until 42 hours, 6.9 kg/s


In-vessel hydrogen generation
Hydrogen mass (kg)
Time after scram (hr)
Later oxidation excursion
Earlier oxidation excursion
0
200
400
600
800
1000
1200
35
40
45
50
55
60
65
70
75
80
85
90
95
100


Containment partial pressures
Partial pressure (MPa)
Time (hr)
Later case - steam
Later case - nitrogen
Later case - hydrogen
Earlier case - steam
Earlier case - nitrogen
Earlier case - hydrogen
MSL rupture, operator venting, core slumping
RCIC and HPCI operation, sprays
lower head failure
Elastic leakage
Ex-vessel gases
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80
90
100


Containment partial pressures
Partial pressure (MPa)
Time (hr)
Later case - steam
Later case - nitrogen
Later case - hydrogen
Earlier case - steam
Earlier case - nitrogen
Earlier case - hydrogen
DW plant data
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
36
38
40
42
44
46
48
50

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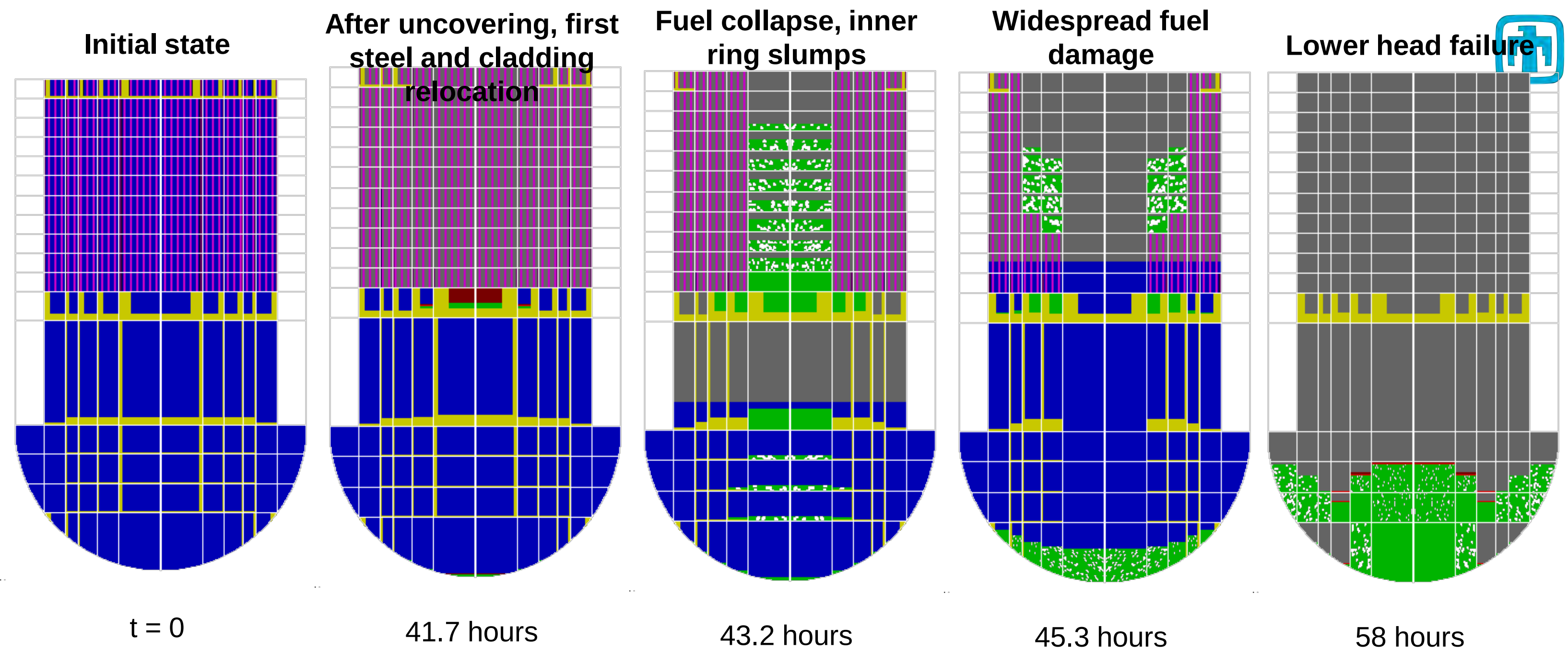
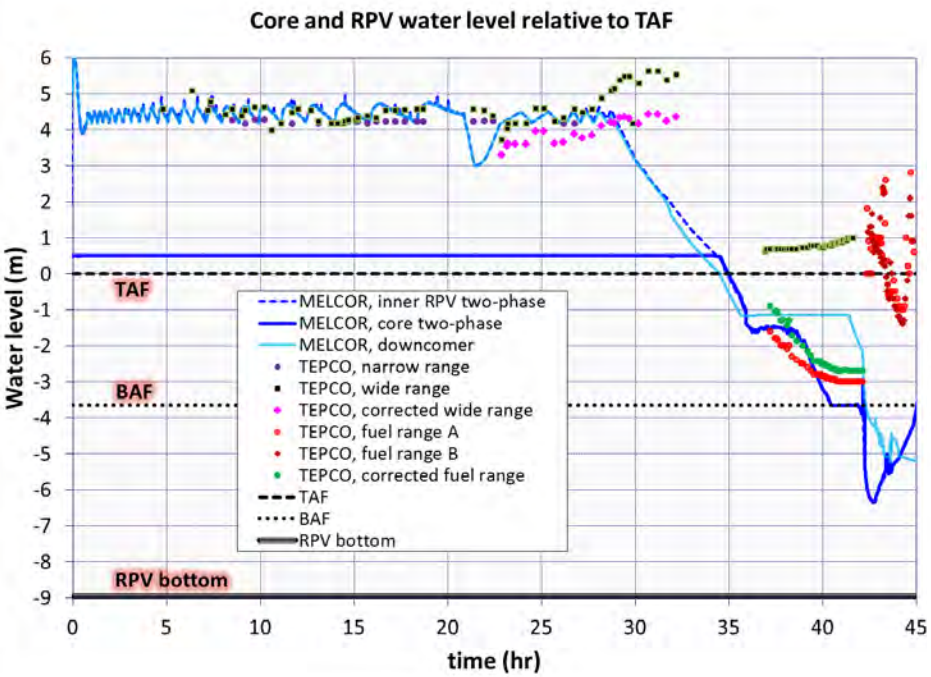
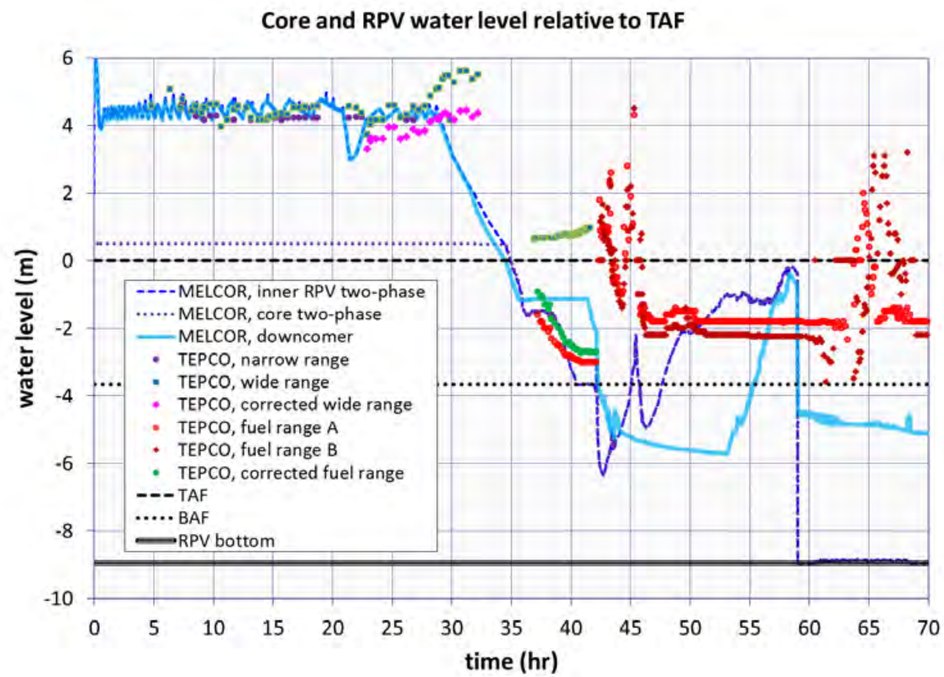
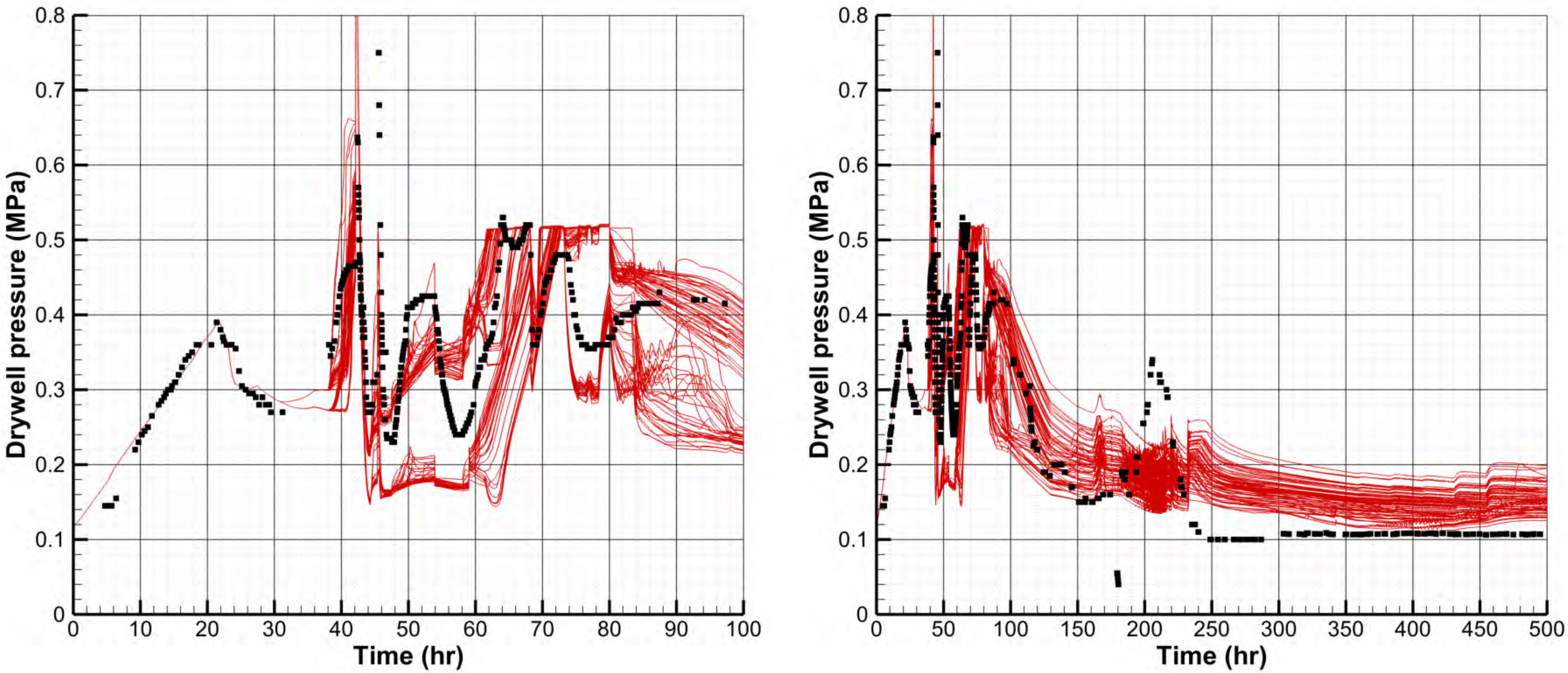




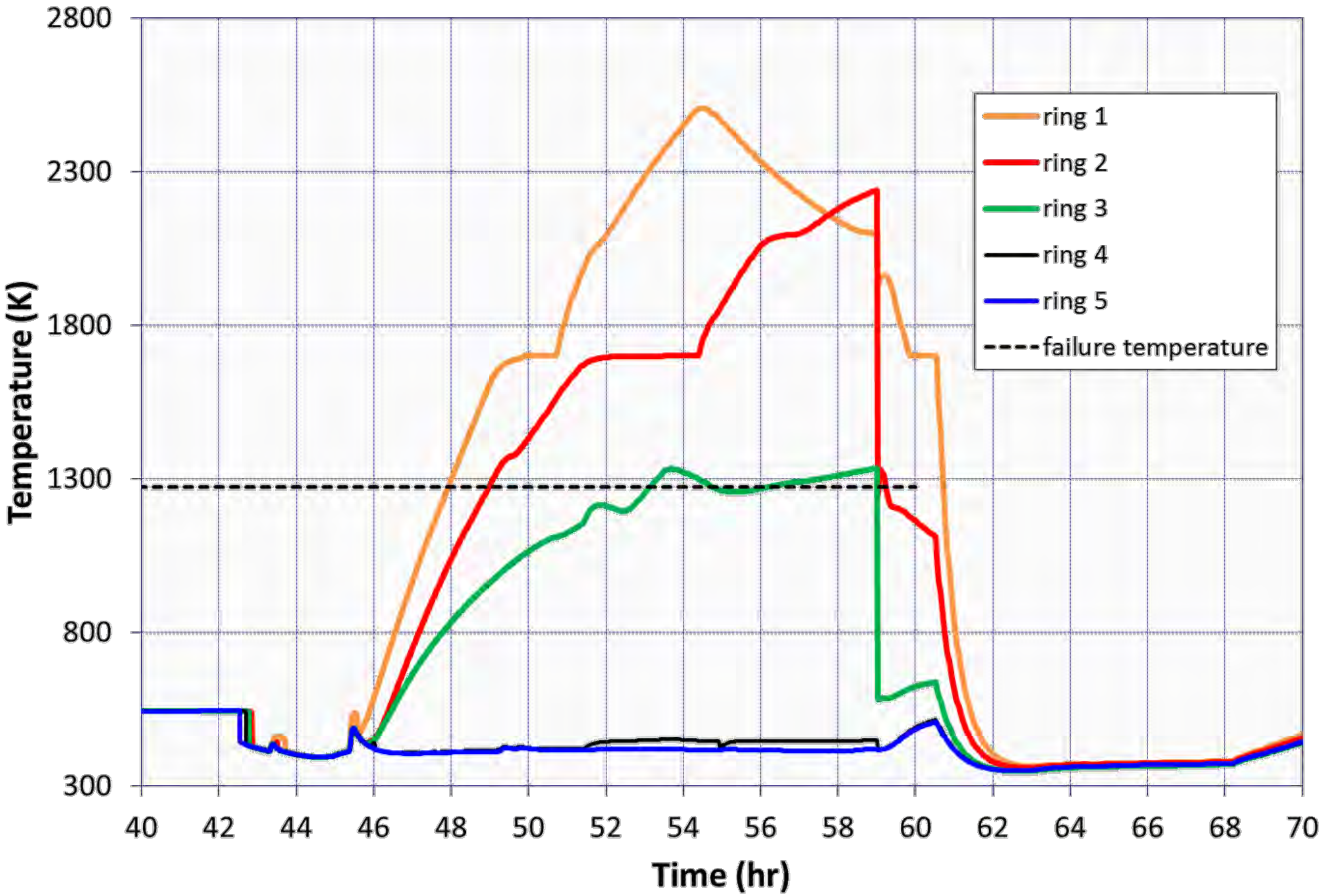


Another containment pressure study



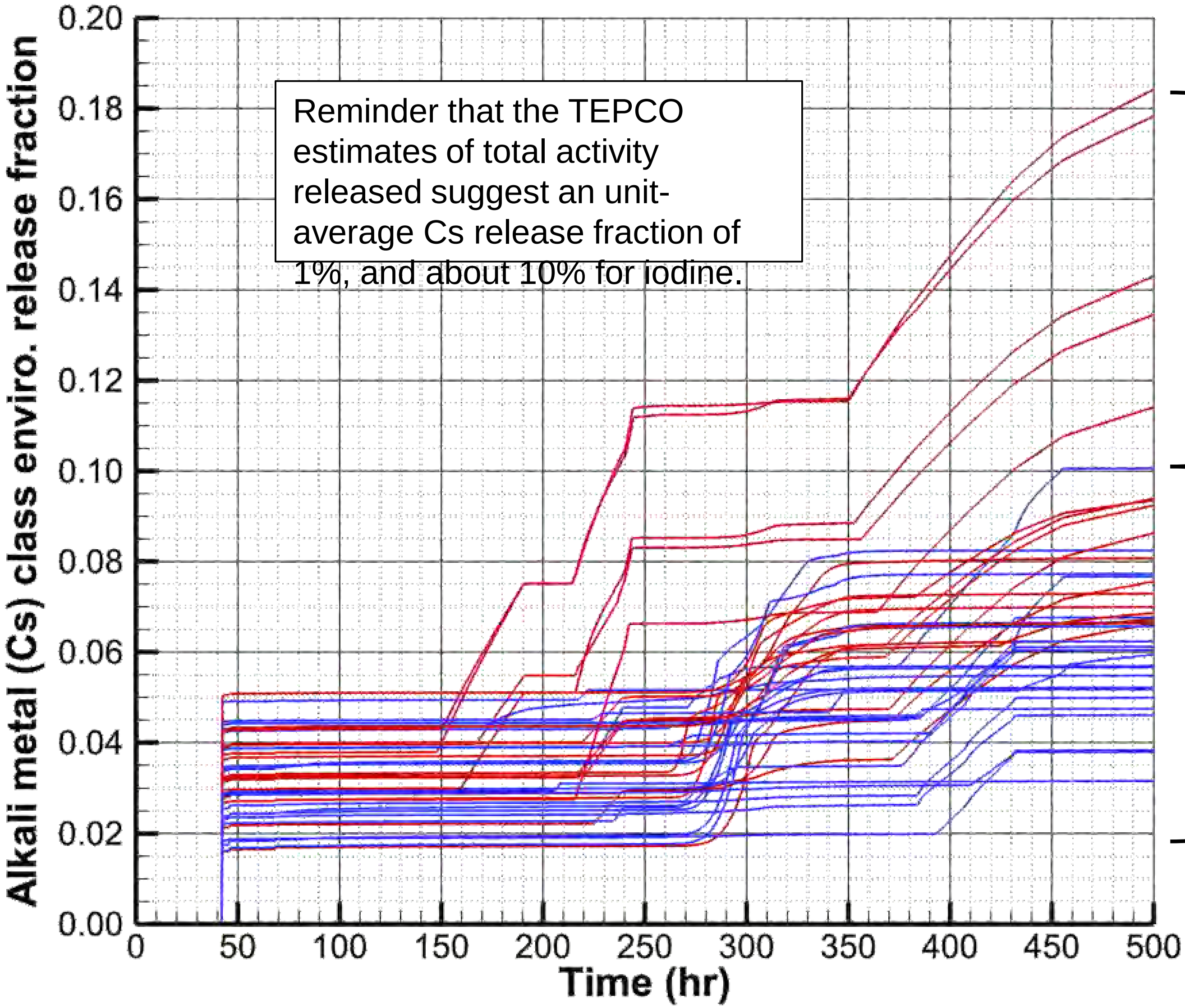
- Cases with low pressure assume that the torus room never drains (however there is no more makeup water after 30 hours);
- flood water is allowed to heat up according to MELCOR predictions
- A containment airspace leak still appears to produce overall pressure trend in agreement w/ plant data

Lower head penetration temperatures



Cesium release fraction

(The only parts of reactor building modeled in this calculation are the region under the shield plug and the torus room.)



Neglect red curves: cases with excessive containment pressure

3 week calculations suggest that unit 3 continued releasing after 100 hours, particularly after large reduction in water injection

Iodine release fraction