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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)

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ACCIDENT ANALYSIS: THERMAL HYDRAULICS SUBCOMMITTEE

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WEDNESDAY

NOVEMBER 17, 2021

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The Subcommittee met via Video Teleconference, at 9:30 a.m. EST, Jose March-Leuba, Chairman, presiding.

COMMITTEE MEMBERS:

JOSE MARCH-LEUBA, Chair

RONALD G. BALLINGER, Member

VICKI BIER, Member

DENNIS BLEY, Member

CHARLES H. BROWN, JR. Member

VESNA B. DIMITRIJEVIC, Member

GREG HALNON, Member

DAVID PETTI, Member

JOY L. REMPE, Member

ACRS CONSULTANT:

MICHAEL CORRADINI

DESIGNATED FEDERAL OFFICIAL:

ZENA ABDULLAHI

ALSO PRESENT:

STEVE M. BAJOREK, RES

PETER J. YARSKY, RES

TAREK ZAKI, RES

C O N T E N T S

P R O C E E D I N G S

9:32 a.m.

CHAIR MARCH-LEUBA: The meeting will now come to order. This is a meeting of the ACRS Accident Analysis: Thermal Hydraulics Subcommittee. I am Jose March-Leuba, Chairman of the Subcommittee.

Because of COVID-19 concerns, this meeting is being conducted remotely. Members in attendance are Vicki Bier, Vesna Dimitrijevic, Greg Halnon, Joy Rempe, and I know we're having technical difficulties with Dave Petti and Dennis Bley, which -- they will be joining us shortly.

(Simultaneous speaking.)

MEMBER BIER: Ron Ballinger looks like he's on.

MEMBER BALLINGER: Yeah, I'm here as well.

CHAIR MARCH-LEUBA: Oh, I -- sorry. Yeah. So Ron Ballinger is, and Greg Halnon is. So today's topic is a presentation by NRC staff documenting a series of oscillatory flow tests performed on a prototypical BWR fuel bundle simulated under stable conditions.

The staff will present the results of their analysis and how to incorporate those results in future trace code calculations. We have not received any requests for public comments, but we will have an opportunity for spur-of-the-moment comments at the end of the meeting. If you are using the phone line link, you will need to use star-6 to unmute yourself.

The ACRS was established by a statute and is governed by the Federal Advisory Committee Act, FACA. As such, the Committee can only speak through its published letter reports. Any comments raised by members today are their individual opinions.

The ACRS section of the U.S. NRC public website provides our charter, bylaws, agendas, letter reports, and full transcripts from the open portions of all full and Subcommittee meetings, including the slides presented there.

The Designated Federal Official today is Zena Abdullahi. A transcript of the meeting is being kept. Therefore, speak clearly and state your name for the benefit of the court recorder. Please keep the microphone on mute when not in use, and don't use video feed to minimize bandwidth problems -- except maybe the presenter.

I apologize, but I have a personal conflict that I cannot get out of at around 12:00 p.m., when we are supposed to finish this meeting. However, if we extend beyond that time, Member Rempe has agreed to serve as the Subcommittee Chair and close the meeting.

At this point, let's request NRC staff to start with a presentation, with introductory remarks from Kim Webber.

Kim, you have the floor.

MS. WEBBER: All right. Great. Thank you so much.

Good morning, Chairman March-Leuba and ACRS members. My name is Kim Webber. I'm the Director of the Division of Systems Analysis. I'm really pleased to be here to talk with you today about a topic that we believe has a lot of interest by the Committee.

Over the last several years, NRR sought assistance from the Office of Nuclear Regulatory Research, or RES, in studying important phenomena surrounding BWR instability to support the licensing of plants seeking to operate within the MELLA+ expanded domain.

Accordingly, my staff's performed numerous studies, analyses, and conducted experiments to better understand how postulated transience without scram in the MELLA+ domain could lead to adverse fuel conditions. They've presented results of those analyses before the ACRS Power Uprate Subcommittee and full Committee in the past.

Today, Dr. Pete Yarsky will present some of his background information, along with the staff's thorough assessment of TRACE against full-scale integral test data from the KATHY Facility. Following his presentation, Dr. Steve Bajorek will provide some information regarding a nondimensionalized approach to analyze the KATHY data.

And now I'd like to turn the presentation over to Pete.

MR. YARSKY: Thank you, Kim.

I'm Dr. Pete Yarsky from the research staff, and I'll be presenting on the TRACE assessment against the KATHY test data. But to start, I would like to give a little bit of background about the motivation behind the KATHY tests and to describe the KATHY test facility and sort of the two variety of tests that we conducted.

For many members of the Subcommittee, this will be a bit of a review. And the new material to present today is the comparison of these data to TRACE calculations, and we'll wrap up with the conclusions. So, first --

(Simultaneous speaking.)

MEMBER REMPE: Peter, this is Joy. I hate to interrupt you, but I tried to wait till the end of the slide. I had a question that's kind of a holdover from prior discussions on this topic.

There has been a lot of interest by vendors who are not involved in the actual KATHY test, as well as university professors, in having access to the data obtained from these tests for their own research or their own desire to try and show that their models work well. What is the status of the data?

MR. YARSKY: Well, some of the data are considered sensitive and are classified under SUNSI data. So we have not been able to release 100 percent of the data to the public. To the extent possible, we have published the data and our findings in a series of papers and a publicly available NUREG report.

And I think at the end of this presentation, we'll be talking about a nondimensional approach that would provide yet a further avenue to make our analyses and our data more publicly available.

MEMBER REMPE: Great. Thank you.

MR. YARSKY: Yeah. Thank you.

And again, just for some background

information, the MELLA+ expanded operating domain represents an expansion of allowable power and flow operating conditions and is shown by the MELLA+ boundary on this power/flow map. And what this expanded operating domain would allow is operation of a BWR plant at a higher power level and a lower flow rate or a higher power-to-flow ratio.

With this expanded operating domain, what it would allow is, under certain conditions, if there is a dual recirculation pump trip, the plant trajectory following such trip would result in conditions of very high power-to-flow ratio as the plant achieves a natural circulation condition.

If we postulated an ATWS event, such as a turbine trip without bypass, this turbine trip without bypass would result in a pressure pulse and a trip of the recirculation pumps and a loss of extraction steam for the feed water heater cascade.

Such an ATWS could be expected to yield unstable conditions with large-amplitude power instability and that this could occur early, and the operators will react to this condition by activating the standby liquid control system to inject boron into the vessel, as well as by lowering the reactor water level to adjust not only the gross core power level but also the inlet core subcooling to try and stabilize the reactor.

The research staff has performed extensive analyses of these kinds of events, and this is showing a typical transient reactor power response to a turbine trip without bypass ATWS instability. And, as shown early in the event, there's a power pulse in response to the turbine trip, which creates the back pressure, and the void collapse resulting from that leads to the power pulse shown here.

After that pulse, there then is a steady increase in the reactor power as the reactor is responding to an increase in inlet subcooling because the extraction steam has been isolated from the feed water heater cascade.

Eventually, the reactor becomes unstable, and oscillations begin to grow. They grow to large amplitude, and there's an unstable phase before operator actions become sufficient to damp those oscillations and ultimately shut down the reactor.

During these oscillations, it's possible for the reactor power oscillation itself to become quite complex. Shown here is a map of 3D bundle powers, indicating in one case that we analyzed a bimodal oscillation where the reactor power is not only oscillating in terms of its gross magnitude, but also, it's shifting from one side of the core to the other side of the core in a regional-type oscillation.

What this implies is that it's possible for there to be very large-amplitude power oscillations in the individual bundle, and those oscillations could be larger than what's implied by the oscillation in the core power itself.

In our TRACE analysis --

MEMBER REMPE: Peter, this is Joy again. I'm sorry to bother you, but apparently there's been some issues, still, Jose, with Dennis Bley getting in. I see that the public line -- apparently, Corradini just got in -- has the problem with -- I mean, Dennis is texting Mike, Scott --

(Simultaneous speaking.)

CHAIR MARCH-LEUBA: Dennis is in.

MEMBER REMPE: Okay. Great. I just wanted to make sure that -- especially --

(Simultaneous speaking.)

MEMBER REMPE: -- line wasn't open.

CHAIR MARCH-LEUBA: Yeah. I don't know with Petti. I think Petti's in, too. So --

MEMBER REMPE: Yeah. Apparently, Dave also said that Mike Corradini and the public line folks got in. So that was my biggest concern, too. We were having trouble with the public line.

So, anyway, go ahead, Peter. Sorry.

MR. YARSKY: Okay. No problem.

What I'm showing here is a figure from that same TRACE calculation. And what we predicted using TRACE was that there would be a period of cyclic dryout/rewet followed by a temperature excursion. And that temperature excursion would be exacerbated by the bimodal nature of the oscillations. And in this case, we predicted that the temperature could exceed 2,200 F, indicated on this figure with a line at 1,478 Kelvin.

So, to go sort of through this fuel heat-up and temperature excursion, using TRACE, we predicted this mechanism. The oscillation magnitude will increase during the transient, and the fuel will initially undergo cyclic dryout/rewet during the oscillation period.

But as that oscillation magnitude grows, the rewet period of the cycle becomes insufficient to remove all of that heat. So you'll dry out and you'll heat up a little bit, but when you rewet, that rewet portion isn't enough to bring you all the way back down to where you started in temperature. And, as a result, the temperature will slowly ratchet up during the cyclic dryout/rewet period.

And we predicted that, eventually, the temperature will reach the minimum stable film boiling temperature, and the cladding surface will lock into film boiling, and once there, there'll be a subsequent temperature excursion, and that this mechanism could lead to potential fuel damage.

So, in short, MELLA+ operation exacerbates the consequences of ATWS. And we predicted that under ATWS-I conditions, the cladding surface may fail to rewet, leading to fuel damage, and that in practice, it's difficult to ensure core coolability if some portion of the fuel may become damaged, particularly in cases where you're looking at complex power oscillation contours.

For instance, you may have a rotating mode of the instability, which could subject a large fraction of the fuel to these kinds of conditions. So this predicted heat-up mechanism was very important for us to study and was the subject of an experimental program at the KATHY Facility.

The KATHY Facility is a full-scale bundle test facility primarily used for critical heat flux testing. It's full reactor pressure, and it tests a full-scale electrically heated fuel bundle. One of the features that makes the KATHY Facility unique is that it can be reconfigured in such a way as to supply either forced circulation, or a downcomer can be, essentially, valved in to allow the facility to operate in natural circulation mode.

And in addition to having that capability to operate in natural circulation mode, the KATHY Facility also incorporates a control module called SINAN. And the SINAN module performs calculations based on certain sensed conditions, such as inlet flow rate, and can calculate void fraction and use that in a reactivity kinetics program to simulate void reactivity and Doppler feedback, allowing the test loop to serve as a simulated reactor where the feedback is simulated by this external control system that can adjust the voltage on the electrically heated components.

We selected this facility for those unique capabilities, and we wanted to design a heater rod assembly that would be representative of the operating fleet. And here in the NRC fuel bundle that we designed, we wanted to make sure it had all of the features of modern BWR fuel. So this includes part-length rods, water rods, and spacers that are typical of modern BWR fuel assemblies.

We have a somewhat typical radial power distribution where we can use rods that have different mechanical designs that allow different power peakings. And in this experiment, we conducted our tests with bottom-skewed axial power shape. This is generally more limiting from a stability perspective.

So, in our experimental work, we first wanted to, of course, verify or study the fuel heat-up mechanism that we predicted during oscillatory power and flow conditions. And we wanted to do so under conditions that were most typical of ATWS-I scenarios.

A follow-up to that, of course, was to assess and validate TRACE against these data. We performed extensive testing in the failure to rewet conditions in the Kathy test loop in December of 2016. When we conducted these tests, there were two varieties of tests that we conducted.

The first variety are tests that we did without using the SINAN simulated feedback. And in these tests, the way they were conducted was to steadily and slowly increase the bundle power till we were first able to induce instability, and then we kept going. We kept increasing the power until we were able to go through the phase of cyclic dryout/rewet and ultimately until we drove the assembly to the point of fuel heat-up.

We conducted a second type of test where we used the SINAN feedback module to simulate reactivity feedback. And in this case, instead of adjusting the power, we slowly increased the strength of the feedback to induce instability and to subsequently induce heat-up.

So here's a sample of one of those tests without feedback. And here, we're showing that the bundle power is slowly increased in steps until a failure to rewet is observed. So this is showing the power. What we are showing here is the flow rate so that even once we induce the instability, we're able to grow the amplitude of the flow oscillation by increasing the power.

And, eventually, we drive the assembly into a failure-to-rewet condition. So this is what sets up the fuel temperature excursion. In the TRACE calculations, the predictive mechanism dictates the fuel heat-up occurs once the cladding surface fails to rewet. And this failure to rewet occurs in the TRACE predictions once the temperature exceeds the minimum stable film boiling temperature.

What we did in sort of a preliminary

analysis based on the data was record the maximum thermocouple temperature observed prior to any failure to rewet. And this would be an indication of the highest temperature achieved before the cladding surface fails to rewet.

So he was giving an idea. This is the same test, the Test 407.1. And, first, this is showing on the left-hand side of the figure successive dryout/rewet cycles. Of course, this is fully consistent with what TRACE predicts. But, also, you can observe the ratcheting mechanism that TRACE also predicted and now we're observing in the tests.

Eventually, there is the temperature excursion. This is what we say is the failure to rewet. Instead of allowing this temperature excursion to occur, though, if the temperature increase is observed over a full period of the oscillation, that's how we diagnose a failure-to-rewet condition.

And to protect the experiment, the reactor -- not the reactor power. The bundle power is reduced to protect the experiment. And so that's why you see the temperature turn around in this figure. But we're able to show that we have the temperature excursion and the failure to rewet.

CHAIR MARCH-LEUBA: So, Pete, can you go

back to that slide? At time 1095, we see a plateau of the temperature, and then a little bit later, you see a completely -- that clearly is the shutdown. What happened at 1095 again?

MR. YARSKY: So, around 1095, we do a step reduction in the bundle power. So it's not as though the entire bundle power is reduced to zero. We step it down by a significant fraction --

(Simultaneous speaking.)

CHAIR MARCH-LEUBA: Like roughly 10 percent or 20 or --

MR. YARSKY: I would say roughly 20 percent, in that neighborhood.

CHAIR MARCH-LEUBA: Yeah. What that shows, in my mind, is that whatever is happening thermohydraulically on the film is maintained even with lower power.

MR. YARSKY: Yeah, for a short period. And then there is the rewetting.

(Simultaneous speaking.)

MR. YARSKY: You can see around 1098, right? But there is that period where it's still in film boiling before it rewets, and that's why it's relatively flat.

I just wanted to take a second to say,

instead of fully dropping the power down to zero, the reason why it's only reduced a bit is so that we can keep the loop hot for the next test.

MEMBER HALNON: So this is Greg Halnon. Without the reduction, we would expect the temperature to continue to increase?

MR. YARSKY: Yes. Without the power reduction, the excursion would continue. But it would likely continue to the point of damaging the test.

MEMBER HALNON: Yeah. So is there a threshold that you know of -- I mean that you drop the power down below a known threshold, or is it just enough to get it to start decreasing?

MR. YARSKY: A lot of this is sort of based on the experience of the owners to know, maybe we do it by 20 percent or 25 percent or 10 percent.

MEMBER HALNON: Okay.

(Simultaneous speaking.)

MEMBER HALNON: -- fuel for what's required to protect their equipment.

MR. YARSKY: Exactly.

MEMBER HALNON: Yeah. Okay. I got it. Thanks.

MR. YARSKY: Yeah. But for our purpose, we wanted to study this heat-up mechanism. And if the excursion persists over a full period, then we know that the cladding surface is failing to rewet. We know that we're on this trajectory. So the experiment is still confirming the mechanism even though we're not driving it all the way to fuel damage. We know that it will head in that direction. We know it's on that course.

MEMBER HALNON: Well, it's a steep line either way.

MR. YARSKY: Right.

MEMBER HALNON: I mean, we're talking five seconds or less than five seconds.

MR. YARSKY: We know that we're in a bad neighborhood, right? So we terminate the test. But I think that we've learned from the test the condition under which we've entered this trajectory.

So here's -- for a separate test. This is Test 20703 on Rod 87 -- is that the peak for highest temperature achieved before the excursion may occur several periods before the excursion itself. And so, in our preliminary analysis, we wanted to pick up what the highest temperature was for which we observed rewetting.

And this could be an indication of the temperature at which the surface would fail to rewet, given the nature of how we conducted these tests with sort of a slow, step-wise approach in either power or reactivity feedback.

Here's showing a zoom of that same data showing that the peak temperature may occur a few periods before the excursion.

I want to now show a sample test with feedback. This is showing the dynamic power during Test 801.02. And you can see the power oscillating. This power oscillation not only shows how the amplitude increases as we strengthen the simulated reactivity feedback but also how the average power increases as the bundle is destabilized.

In our initial assessment of the data, the first thing we did, as I said, was to record these failure-to-rewet temperatures. And we found that the maximum was around 700k; the minimum's around 600k, with an average in the neighborhood of 650k.

This temperature corresponds relatively well with the homogeneous nucleation plus contact temperature. Now, this homogeneous nucleation temperature is the lowest temperature, theoretically, at which liquid will spontaneously nucleate into vapor. So it represents a sort of theoretical minimum for the equivalent of the minimum stable film boiling temperature.

We wanted to compare our measured failure-to-rewet temperatures to this theoretical temperature and just see how they line up. When we did this, we also compared the failure-to-rewet temperature to a variety of other models of Tmin, such as Groeneveld-Stewart, Henry Shumway, and Peterson and Bajorek.

And what we found are that those models that use the homogeneous nucleation or homogeneous nucleation plus contact temperature really are right in the neighborhood of our observations for the failure-to-rewet temperature.

When we did a preliminary comparison of TRACE to sort of post-process data, we found that if we were to dial in the minimum stable film boiling temperature in a value range between 600 and 638 Kelvin, that we were able to get fairly good agreement between the experimental results and the TRACE results.

However, dialing that minimum stable film boiling temperature in the TRACE model up even a little bit more into, say, the 630 or 640 Kelvin range would completely preclude the occurrence of the failure to rewet.

So the analysis of the fuel consequences can be quite sensitive to assumptions about the minimum stable film boiling temperature as it relates to the predictive fuel heat-up mechanism.

So, as an interim approach based on our initial analysis of the data and as a conservative approximation, we recommended, and in our own analyses have adopted, the approach of setting the minimum stable film boiling temperature equal to the homogeneous nucleation temperature plus contact temperature.

And we've been successfully using this approach to analyze ATWS-I from MELLA+ BWRs to support licensing determinations. However, we have taken the opportunity now to perform a more detailed assessment of TRACE through a more thorough study of the KATHY experimental results.

CHAIR MARCH-LEUBA: Oh, yeah, I wanted to ask, this Tmin homogeneous plus contact -- have you benchmarked it against all of the experiments, and does it fit all of them? Or are there any outliers?

MR. YARSKY: Oh, in terms -- okay. So what we have done in the TRACE assessment activity is to run TRACE calculations using this approach and comparing it to the data. And I think that that will maybe address your question more thoroughly.

I was stepping through sort of what we've been doing since we conducted the tests, but before we completed the TRACE assessment, was to utilize this Tmin equals homogeneous nucleation plus contact temperature approach because our initial look at the data and the theoretical basis for homogeneous nucleation plus contact temperature means that it should be a conservative approach. But it does seem to line up with the data in our initial look.

In what I'll be presenting next, we've done a number of TRACE calculations using homogeneous nucleation plus contact temperature, as well as other Tmin models, and compared the results against the data. And I think that will show which particular tests were outliers, which particular tests agreed well.

Is that sort of what you're getting at?

CHAIR MARCH-LEUBA: Yeah. I wanted to know your feelings -- you and Steve have been looking at this data with a fine comb -- if you had a feeling that you had just got lucky, or does it really hold for the majority of the test data? And I think you're saying that it holds.

MR. YARSKY: Yes. So, when we -- I mean, this is a spoiler. We will show how it -- it gives a reasonable prediction. However, it's consistently on the conservative side. But, as we showed in this slide, even if you're just a little bit on the non-conservative side -- so say the true minimum stable film boiling temperature is 620. You'll predict the heat-up.

But if you're off by 20 or 20 degrees, it completely changes your prediction of the consequences. So it's good to be reasonable, but in this case, if you're slightly conservative, that's probably the best place to land.

CHAIR MARCH-LEUBA: Yeah. I -- go ahead.

MR. YARSKY: So in our Stage 1 TRACE assessment, this is conducted in three steps. There are two stages to the overall TRACE assessment activity. In Stage 1, we just kind of wanted to see where we were. And in Stage 2, we wanted to get a better understanding of what next steps we might want to take in terms of improving TRACE models.

So Stage 1 can be thought of as a more traditional TRACE assessment, which is just run the code, compare to the experimental results, and see, are you reasonable? Are you conservative? Are you in sufficient agreement? What is the degree of agreement between the TRACE calculations and the experimental results?

Again, this took us three steps. The first was to use steady-state experimental results to adjust empirical parameters, and in particular the spacer loss coefficients and critical heat flux multipliers. This is a very standard approach.

In Step 2, we defined figures of merit associated with key phenomenology and phases of the transient. So, for those members who aren't familiar with the MDAP process, you may have one event, but that one event may be characterized by discrete phases.

And what we wanted to do is we wanted to have figures of merit that captured the different phases that are represented by the experiment. And so, while the experiments themselves were conducted primarily to study the fuel heat-up process that occurs when there's a failure to rewet, the test itself represents a number of phases.

There's a phase of the experiment where the bundle was stable. There's a phase when it becomes unstable, but the oscillations are small amplitude. There's a phase where the oscillations have grown to the point where the bundle is undergoing cyclic dryout/rewet phases. So we wanted to, for each of those phases, have a variety of figures of merit that we could compare.

And then, of course, in Step 3, we wanted to compare the TRACE results to the experimental figures of merit using both the default TRACE model as well as our interim approach. So this means using a Tmin value based on Groeneveld-Stewart, which is the default, and a Tmin value based on homogeneous nucleation plus contact temperature, which is the interim approach that we just described.

So the figures of merit that we looked at -- of course, there are temperature-related figures of merit, and there are pressure-drop-related figures of merit. We also looked at the TRACE-calculated void fractions, but this was not a figure of merit that we defined as part of the comparison process, but just a figure of merit that we defined to help us analyze the experiment and the result so the system would get a better physical picture of what was going on in the analysis part.

But we looked at the distribution of pressure drops as well as maximum temperature and the temperature of a specific location.

So this is just giving a sample of the comparisons because we conducted very many tests, and there are very many figures of merit. I just wanted to give a representative sample here that we could discuss. We have a very long report with a large number of these kinds of figures, and they kind of all show a very similar result.

So this experiment is SINAN 12301T01. So this is a very interesting test because in this particular test, we started the test off by initiating what would be similar to a loss of feedwater heater AOO is how we initiated the test. And this was done by dropping the feedwater temperature in the test.

What we show here in this comparison is if we use TRACE with the default option for Tmin, which is the Groeneveld-Stewart, is that we do not observe any failure to rewet in the test when we simulate it. However, in the test, we do observe a failure to rewet towards the end.

However, if we run TRACE with the Tmin equals homogeneous nucleation plus contact temperature, we do observe the failure to rewet and the temperature excursion. However, it occurs a little bit earlier in the TRACE calculation relative to the test.

Now, in the way we conducted the calculation, the reduction in power occurs at the same clock time. It doesn't occur at the same time following failure to rewet. So that's why the temperature remains high in the TRACE calculation until the same point in time when the power reduction takes place.

And this is fairly consistent across all of the different tests is that when we use the Tmin equals homogeneous nucleation plus contact temperature, the TRACE will predict the start of the temperature excursion a little bit early. But overall, because it's capturing the same behavior, we consider this to be relatively reasonable but on the slightly conservative side.

So, if we summarize how we address all of the different phenomena that we wanted to capture with all these different figures of merit, using our standard categorization, overall, when we use Tmin set to homogeneous nucleation plus contact temperature, we're able to garner reasonable, slightly conservative levels of agreement for all the figures of merit over all the phases. This includes, also, the -- when we look at the pressure drops, which is giving us an indication of, are we capturing the instability itself?

However, when we used the default model, the Groeneveld-Stewart, the Tmin temperature just appears to be too high, and we very rarely predict a failure to rewet when using that option even though all of the tests were driven to the point of failure to rewet with temperature excursion.

So now, in Stage 2, we talked a lot about how the TRACE calculations are sensitive to the minimum stable film boiling temperature. But we wanted to do a more in-depth study using statistical analysis techniques to study the impact of different constitutive models on the assessment in such a way as to identify candidate constitutive models for possible improvements.

This relies on a two-step process, which relies on using uncertainty parameters that are in TRACE that are used for uncertainty quantification. We can use that same tool and that same mechanism to drive sensitivity calculations and ultimately use a Morris screening technique to determine which constitutive models in TRACE have the biggest impact on affecting the agreement between TRACE and the experiments.

What this will ultimately do is not only give us an idea of what are the important constitutive models, but a relative ranking of how those models impact the degree of agreement between TRACE and the experiment.

What we wanted to do here, of course, was to verify or confirm our understanding of the importance of the selected option for minimum stable film boiling temperature, but also understand if there are other constitutive models that are playing an equivalently important role or are perhaps interacting in such a way that we don't want to miss anything.

So we defined new figures of merit. We have three new figures of merit for this purpose, and they're illustrated on this figure. I'm going to take a little bit of time to sort of explain what we're looking at.

So, instead of characterizing the consequences, which is what we normally do with TRACE, we want to characterize, how well does TRACE agree with the test? And so we've come up with three different numbers.

The first is looking at a temperature-related figure of merit, and this compares the maximum temperature that TRACE predicts to the maximum temperature measured in the tests. And then we take that difference, and that difference ideally should be small, but that difference can characterize how well

TRACE and the experiment agree in terms of peak temperature.

Similarly, we can define the time of the failure to rewet that is measured in the test as well as what's predicted in TRACE, and we can calculate the difference in that timing.

And, lastly, not just capturing time and temperature, we can look at the integral of the temperature difference over that whole phase of time. And that integral difference gives us a third figure of merit to characterize the agreement between TRACE and the test.

So the first figure of merit is sort of the difference between the green line and the blue line. The second figure of merit is the difference in time represented by the blue shaded area. And the third figure of merit is the blue shaded area plus the beige shaded area -- and then averaged over time.

So now, in the second stage, we follow a two-step process. So I know it's a little confusing because we've had two stages and several steps, but here, we have a two-step process in Stage 2. And the first step, we do what's called a single parameter variation, or one-at-a-time variation.

And we study, by conducting a series of

sensitivity calculations, how much each of these figures of merit change when we vary just one parameter and one constitutive model at a time. The purpose for doing this is to sort of cut a slice through all of the possible variety of available constitutive model parameters that can be adjusted to come up with a smaller subset that we can analyze in a second step.

In the second step, we do multiparameter variation. So this allows us, in a Monte Carlo approach, to shift the values of several parameters at once, run many, many, many calculations, determine sensitivity coefficients, and use a Morris screening technique to establish, what are the key parameters that are dictating the difference between TRACE and the experiment?

So this is showing the result of the first step individual parameter variation on the integral FOM for six no-feedback tests and 17 feedback tests. And what we can do is we can draw this red line to scoop up which parameters we want to keep for the second phase.

Clearly, there are a number of parameters that have very weak influence on the FOMs, and there are some that have substantially more impact. So here we're showing that we've drawn a line to pick up, say, these top-five parameters that we want to preserve going into the next step when we look at multiparameter variation.

If we look at the time-based FOM, we're slicing and picking up these top eight. And when we look at the temperature FOM, we're selecting the top 15. Now, you may say, wait. It looks like some parameters in FOM temperature might still be important, but you're not capturing them with the slice.

And it turns out we selected these slices kind of judiciously because some of these parameters it looks like we're leaving out with this FOM temperature, we actually picked them up in the other two cases already. So, if we look at FOM integral, we pick the top five.

But when we consider all three FOMs, we're picking up the top ten because five other ones were considered important according to the other FOMs. And with FOM temperature, we're picking up the top 19 at the end with how we've done the slicing.

And so this is the same series of figures, but when we consider the duplication of parameters, it shows how much we're actually capturing. So this is for FOM integral, for FOM time, and for FOM temperature. And so that tells us which parameters we want to vary.

The next important thing is, what is Morris screening? So, now that we're going to do several-at-a-time variation, we're going to do a number of sensitivity calculations. We're going to vary all of these parameters, and we'll sample one case, with all the parameters kind of being randomly distributed over a range.

We'll sample one of those cases and then calculate the derivative of the FOMs with respect to a single parameter. But we'll do multiple samples over the full-analysis face phase. And this will allow us to calculate a distribution of the sensitivity of the FOMs to the input parameter, but over a wide range of values of the other parameters.

So we have now a distribution of the sensitivity coefficient. And if we plot the mean and the standard deviation of that distribution, that gives us an idea of how important that phenomenon represented by that particular constitutive model is. If it has a very high mean value, which would be the Mu*STAR, that means its sensitivity coefficient on average is very large.

That means that the physical process represented by that constitutive model is very influential on the figure of merit. If at the same time, it has a high mean value but a high standard deviation, that means that not only is it very influential, but that it has a nonlinear effect or it has a strong coupling, or a strong interaction, with one of the other physical processes.

And, conversely, if it has a low mean and a low standard deviation, that just means it's not important. It's not having a strong influence. So, if we do -- when we go through that process, we can calculate these values of the sensitivity coefficient and its standard deviation for all of the parameters that we've captured in the second step.

So there are 19 parameters that we're capturing. We're crunching the numbers, and then this is showing the composite results for all six of the tests without feedback as well as showing one single experiment for one of the FOMs plotting the standard deviation and the sensitivity coefficient.

What's important to capture here, what we want to look at in the composite figure, are values of the mean sensitivity coefficients that are large coincident with large standard deviation. And those are telling us not only the most influential parameters but also the ones that have -- potentially are strongly coupled to other phenomena or can really change the results in terms of the figure of merit in a nonlinear way.

MEMBER BLEY: Hey, Peter? Dennis Bley. I must have been down a rabbit hole for 30 years. I've never run across Morris screening before. That looks pretty interesting to -- you're getting a range of change with respect to each of the figures of merit to --

(Simultaneous speaking.)

MR. YARSKY: Yeah. It's like it's taking the sensitivity coefficient, but what you're going to end up doing is -- that sensitivity coefficient, you're sampling it over your full range of uncertainty. So we're using some techniques that -- we're using these techniques in an off-label way.

Many of these techniques were developed for uncertainty quantification purposes. But we're using them -- instead of trying to quantify uncertainty, we want to see how much influence does this parameter have on average over the full phase space?

MEMBER BLEY: Well, and that's part of

quantifying uncertainty. That's --

(Simultaneous speaking.)

MR. YARSKY: Right. Right.

MEMBER BLEY: So --

(Simultaneous speaking.)

MEMBER BLEY: -- that a little bit.

MR. YARSKY: We're using it off label, but we're using machinery and techniques that have been developed for a more well established purpose.

MEMBER PETTI: Peter, just a question. On the bottom right, the little dots --

MR. YARSKY: So these little boxes represent if there's an outlier. So the -- you're going to be testing my memory. The way the bands work I think is the line inside the band is the mean. And then I think it's two Sigma for the thick part and I think three Sigma for the line. And then the dot is like if it's outside of that. That's the outlier.

MEMBER PETTI: Okay.

MR. YARSKY: I mean it might not be exactly that, but I'd have to look it up in the report, but when there's a dot, it really means that this is really far off. There's one case that's really outside of the mean. So I hope that answers your question. If you need more detail, we can back open the report and I can get the real numbers out for you.

MEMBER PETTI: Thanks.

MR. YARSKY: And then here are the results with feedback. And I think what you'll see in the two tests here is that the standout constitutive model is parameter 10-10, which is the minimum stable film boiling temperature.

And so now that we've done this detailed statistical evaluation the importance I'm making of the key constitutive models is not surprising. The one that had the most impact and the most variation is minimum stable film boiling temperature, which is what we went in suspecting, and this analysis has confirmed that.

The runners-up for next importance are annular-mist flow interfacial drag. This is also not -- it's not as strongly influencing as minimum stable film boiling temperature, but it is -- also not surprising is this is this is really affecting void fraction.

And then the next one is critical heat flux, which also makes sense because this is affecting the dryout/rewet phase. I know that these second two parameters, while important, are less influential and nonlinear than the minimum stable film boiling temperature. And to a certain extent these two are affected by the upfront normalization process where you adjust things like space or losses to match pressure drop and where we adjust the critical heat flux multipliers to get the right critical power. And then there are additional phenomena there identified here but are not nearly as important as these ones.

In conclusion we found that TRACE produces reasonable but slightly conservative predictions. The fuel heat up during postulated ATWIS-I when the Tmin option is set to homogenous nucleation plus contact temperature. However, that slight conservatism we found that the consequences can be really very sensitive and non-linearly so to whatever is assumed in your calculation with respect to the failure to rewet temperature. And so we think it -- our interim approach we think is still reasonable and will remain our standard practice even though it is slightly conservative, but overall we think it's pretty reasonable.

When we conducted our detailed assessment of the key models using advanced statistical techniques, we found that the TRACE predictions are consistent with our expectation, and we even took these numerical values and compared it to our PIRT. The PIRT is generally developed in a non-quantitative and a more qualitative way based on expert panel opinion, but we can compare it to the quantitative results from our statistical analysis and our Monte Carlo exploration of the phase space. And we found that they're in agreement. So this exercise has really also served as a quantitative approach to confirming the conclusions of our PIRT.

And lastly, while we do think that better agreement could be garnered with improvement to the minimum stable film boiling model at this stage we don't think it is necessary because we're doing a pretty good job, though slightly conservative. But I think that the -- it remains prudent to stay slightly conservative, but our analysis does indicate that we could do a better job of agreeing with the data if we fine-tuned a little bit more what we with minimum stable film boiling temperature.

And so with that I'd like to conclude the first presentation and address any of your outstanding questions.

MEMBER PETTI: Just a question on -- you basically talk about this non-linear (audio interference) that need to be on the conservative side. What's the uncertainty in the measurements? Ten degrees is not an awful lot of deviation to get such a large change. So --

MR. YARSKY: Right. No, this is a very excellent.

MEMBER PETTI: -- (audio interference).

MR. YARSKY: Yes, this is a very excellent point because the thermocouples are not perfect instruments. There is some measurement uncertainty in the temperature. I believe that I'd have to go back and look at the NUREG to figure out what that temperature is, but I think it's about 5K, which is substantial when you look at the sensitivity because when we talk about non-linear effect, it's really do you experience failure to rewet or do you not? It's kind of like a binary switch that you hit or you don't hit, right?

So like the -- if the -- all of the experiments go to failure to rewet. If your calculation does not go to failure to rewet, you're going to have a really substantial difference in your figure of merit, right? So it's going to say the agreement is very poor. But if you ratchet down that minimum stable film boiling temperature say by 5 or 10 kelvin, all of a sudden your calculation shows failure to rewet. Now your agreement is quite good. And so that's the non-linearity aspect of it is that you either -- is that you have this bifurcation where you either hit failure to rewet or you don't in the calculation that creates this non-linear sensitivity.

That's why we think it is rather prudent to sort of look at your failure to rewet temperature data and try and bound it as opposed to try and characterize it with like a mean and standard deviation.

CHAIR MARCH-LEUBA: I agree with that because from the practical point of view what you are trying to identify is whether it rewets or not.

MR. YARSKY: Right.

CHAIR MARCH-LEUBA: And the actual temperature it reaches is not important. To start with these are very low frequency, very low probability events and while this is -- this calculation is driving you to evaluate the operator actions that they would have to do to prevent from failure to rewet from happening. So I think your approach is very good and I like it.

I have a question, and I know you cannot speak for NRR, but while you were (unintelligible) we were always requiring vendors to use homogeneous nucleation temperature plus contact on their calculations using their code instead of their correlation. Is that correct?

MR. YARSKY: Yes, that is by my recollection when --

CHAIR MARCH-LEUBA: Yes.

MR. YARSKY: Not necessarily when I was at NRR, but I was engaged in performing confirmatory analysis to support licensing actions. And with my recollection for those specific projects I recalled the vendor calculations being performed in a consistent way with the homogeneous nucleation temperature.

CHAIR MARCH-LEUBA: And we don't foresee today any new MELLLA++ that would require these type of calculations, but if they do happen my expectation will be that NRR will know -- even the vendors will know to use homogeneous plus contact approach.

MR. YARSKY: Right. So this is -- we released this finding of the homogeneous nucleation plus contact temperature approach relatively soon after conducting the tests. And our latest more in-depth thorough analysis indicates we still want to keep doing this. So it's really not a change. There's really no change in our guidance or our process or our approach.

CHAIR MARCH-LEUBA: Okay. Thank you.

MR. YARSKY: It's just I think that our more thorough analysis has sort of indicated that -- if you want to call it lucky or insightful, is that we've landed on the right approach in our interim analysis.

CHAIR MARCH-LEUBA: And it makes some sense, some physical --

MR. YARSKY: Right.

CHAIR MARCH-LEUBA: -- sense.

MR. YARSKY: Right.

CHAIR MARCH-LEUBA: So it's not completely empirical.

MR. YARSKY: There is like a theoretical basis for what we suggested at first and I think what we're observing now.

CHAIR MARCH-LEUBA: Okay. Thank you.

Members, you have any more questions for Pete?

(No audible response.)

CHAIR MARCH-LEUBA: So we are a little bit ahead of the schedule and we are going to get into the non-dimensional analysis. Do you want to take a 10, 15-minute biological break, because it's early in the morning for some people?

(No audible response.)

CHAIR MARCH-LEUBA: So let's take a 15-minute break and come back at 10:50, 10 minutes before the hour. Okay? And by time we'll have changed presenters and have the new slides on the screen. So we are on break, on recess.

(Whereupon, the above-entitled matter went off the record at 10:32 a.m. and resumed at 10:49 a.m.)

CHAIR MARCH-LEUBA: So let's go back in session. We're still in open session. You are not going to present anything proprietary, correct, Steve?

MR. BAJOREK: That is correct?

CHAIR MARCH-LEUBA: Okay. So go ahead and do your magic. Maximize the -- yes, perfect.

MR. BAJOREK: Okay. There we go. Well, good morning, everyone. My name is Steve Bajorek. I'm from the same Division of Safety Analysis as Pete Yarsky and Tarek. And what I'd like to do next is talk about some of the non-dimensionalization of the KATHY data.

In the first presentation today, especially towards the end when we started to take a look at TRACE and how it could predict some of these phenomena, you could see that there was actually a fairly large number of physical processes that could influence and affect this failure to rewet.

So what I want to do next is kind of take a step back and simplify things by looking at the experimental data and trying to see what does it tell us about the parameters and the things which are most important and can we come up with a way of showing when we'll have this failure to rewet in terms of several of the more important quantities that affect the data?

Now part of this originated because of some concerns on keeping the data proprietary. There was a lot of sensitivity from the experimentalists on whether someone might be able to take the data and back out some information that they considered economically vital to them. So we wanted to be very protective of the data. We understand the importance of protecting the information.

So as this discussion of what's proprietary and is not proprietary, we said well let's take a look at how we can present the data but not do so in a way that would give away those things which are very important to the experimental organization.

We also recognized that the data was

showing that the conditions could lead to this failure to rewet, so there were some safety implications that we needed to show in a way to others that hey, there are conditions that will certainly lead to this. And we wanted to try to come up with a way that the NRC, our reviewers and our own evaluation, come up with quick screening method by which we could point to conditions that would give us failure to rewet and possibly lead to damage.

So I went back and looked at probably the more fundamental works in flow instability which had been done by Ishii in the mid-'702. Now most of the work that he did was looking at density wave oscillations, but his work was fairly general and could cover a large number of situations. He took the mass/momentum/energy equations, non-dimensionalized those and derived several dimensionalist parameters that were indicative of when you should have certain stabilities and how those stabilities could develop. This isn't all of those, but I've listed some of the ones which were more important including the Froude, the Reynolds, the subcooling number, a phase-change number and the density ratio.

Now of these the subcooling number and the phase-change number were attributed to be the most influential. Others became very -- were also important. The Reynolds number. A couple of them I left off. Actually it was kind of great to see in the models that were becoming very important to TRACE. The wall drag and the interfacial friction. Those were two other parameters that turned out to be important in sensitivities in Ishii's studies. But it was the subcooling and the phase-change number that tended to be the most influential.

The reason for that is the subcooling number tended to be more stabilizing. The larger that was, that more -- it kept your fluid in a subcooled condition, prevented oscillating from occurring.

However on the other hand the phase-change number was such that as it became larger and as your exit quality became large, this was more destabilizing. And looking at a large number of situations Ishii was able to develop a map which sort of has a little bit of a horseshoe curve to it. And his instabilities would originate in this crosshatched region as you had a sufficiently large phase-change number and a subcooling number which was moderately low.

So we thought well, let's take a look at the KATHY data in terms of these two numbers. In one way it's kind of very interesting because we talked a lot about Tmin, the minimum stable film boiling temperature. And in one way you see something very similar here. In the stability you have subcooling, your ability to cool the liquid, versus generation of the voids, whereas Tmin is essentially a balance between getting energy away from a surface as opposed to getting energy conducted to the surface. So it's kind of similar in one way when you think of it that.

So the first thing we did is let's take a look at all of the tests in general, the tests with SINAN, the non-SINAN tests, and what we're really seeing in those. And very typically over the first 100, couple of 100 seconds of the test everything is stable. And then depending on whether you're driving it with the SINAN component, with the power, or you're stepping up the power in the non-SINAN test, you start to get oscillations. Many times this occurred first in the flow rate which is shown in the purple and sort of in the middle one of this slide. Eventually the power would start to become oscillatory and more and more unstable.

Down at the bottom you see the temperature in this case for one of the rods that went through a failure to rewet. Now well after you started to get oscillations in the mass flow rate and the power oscillations in the temperature this ratchetting of dryout, going back towards saturation, starts to creep in into those temperature oscillations until the power and the flow becomes such that you go through the failure to rewet.

So I said well, let's try to characterize these -- really these four periods that we see where there's oscillations or steady behavior in the flow. And in some of the nomenclature that we'll have in a couple of the figures we'll have a three-letter index to tell us whether the temperature mass flow rate and the power is either stable, oscillatory; I used a U for unstable for that; oscillatory is probably a better term, or if when it's very clearly a failure to rewet.

And by this we'll be able to take a look at the KATHY data and characterize the four periods generally such that we see everything's stable, period 1. Another period, period 2, where temperature is stable but the flow or the power starts to become oscillatory. And then we start getting close to the failure to rewet. The rod temperatures begin to oscillate. The power is oscillating. The flow rate's oscillating. There's a return to rewet, but we know that by -- from many of the tests that if we continue to ratchet up the power or reduce the flow eventually we're going to get to this clear failure to rewet while the other two parameters are oscillating, and that's sort of a very short period 4 because we want to protect the equipment.

MEMBER HALNON: Okay. So --

MR. BAJOREK: So if you go back and you take a look -- I'm -- yes?

MEMBER HALNON: Steve, this is Greg Halnon. Just real quick on that period 3 it looks more of a transition period to me where -- they were transitioning to film boiling, but can you sustain sort of a period 3 without it going to a period 4?

MR. BAJOREK: As long as you remain below your minimum film boiling temperature. Okay. As long as that -- the power and the flow is such that you keep that rod in transition boiling. Okay?

(Audio interference)

MR. BAJOREK: And that's sort of a hybrid so you can stay in there and the temperature won't get away from you, but once you get above Tmin, that temperature is so high, you no longer have that good liquid-to-wall contact. And then all of a sudden you're cooling is largely by radiation.

MEMBER HALNON: Okay. So as long as you don't increase the power to where that Tmin is going to increase --

MR. BAJOREK: That's correct.

MEMBER HALNON: -- you can sustain it? Okay.

MR. YARSKY: And, Greg, if you look at Steve's slide, he's going to show you we sit -- in the experiments we can sit in that period 3 for a long time.

MEMBER HALNON: Okay.

MR. BAJOREK: Right. Right.

MEMBER HALNON: So that was my question, whether or not it was just a transition period that was going to occur -- go beyond that anyway or if it was sustainable and --

(Simultaneous speaking.)

MR. BAJOREK: Yes, it's sustainable under the right conditions, but I think when we start to see the temperature, the flow rate and the power oscillating -- and the power, the mean power slowly increasing, I think we realized that that is a condition you really don't want to be in because you're sort of on the knife edge. As conditions get just a little bit worse that is going to send you through that failure to rewet. So as you run the tests, once you've collected enough data and you're not quite there, you don't want to push you luck too much.

MEMBER HALNON: Okay. Got it. Thanks.

MR. BAJOREK: Okay. So we go back and we take a look at the flow and the power as we did earlier. And now we'll start to characterize the four periods in this case. And up until 800 seconds everything is stable. Then we get this stable temperature, but oscillatory power, oscillatory flow that starts to grow until about 1,600 seconds in this test. And then this period 3 takes over where everything is oscillatory and approaching -- which in this test did give us a failure to rewet. So we kind of see all four of these periods as we characterize this.

So what I did is I -- we took all of the tests that were available to us -- and this just shows when the temperature starts to go oscillatory, go through all of those tests. And in the middle of each of those periods: steady, steady with -- steady temperature, unsteady other parameters, to completely unsteady -- went to the middle of those and said well, let's pick out the conditions that we get from the experimental data, determine what is the subcooling number, the Reynolds number, and also the phase-change number.

And we did this -- and this figure kind of shows everything, and that's kind of where the nomenclature is. Everything where you -- the temperatures were steady occurred to the left of the phase-change number of 20. And you kind of see two different groupings here because the tests were run at two different subcoolings. And I think that's the upper distribution and the lower distribution.

Once you exceed a phase-change number of 20, okay, now everything was oscillatory and in some cases we go through this failure to rewet. And can you -- I think you can see my cursor.

CHAIR MARCH-LEUBA: Yes, we can see it.

MR. BAJOREK: Okay. Good. Yes, you can see that. And you can see these kind of brown downward-facing triangles. Those are your failure to rewet cases. They're sort of mixed in with others where everything is uncertain -- not uncertain, excuse me -- un-oscillatory, which is why we sort of look at those data as being very, very close to achieving this failure to rewet. But every time we saw that failure to rewet it was at the phase-change number of 20 or greater.

Now as we look at this idea of cooling, keeping the rod surface cool versus generating void, one of the other parameters that Ishii found that was important to influence that boundary had been the Reynolds number. Now we don't have enough data to really map out the curve as had been done in some of the Ishii studies because we only had two subcoolings and we only had two pressures. You have to vary that over a much broader range in order to really map everything out.

However, Reynolds number should also influence this because it's another way of helping -- telling you that you have good or poor convective heat transfer. So I said let's define another dimensionless parameter, the product of the subcooling and in the Reynolds number, and recast the same data in that manner. And now we sort of get a different type of curve. Failure to rewet is greater than -- nominally greater than a phase-change number of 20.

And it was always when you had relatively low subcooling and lesser convective heat transfer with a lower Reynolds number as you did not have a large phase-change or you had good cooling or high subcooling up in that kind of quadrant in the upper left. No, you never go to that failure rewet. But down here in this lower quadrant, okay, this was the -- these were the conditions in the tests that led to oscillatory behavior and that failure to rewet.

CHAIR MARCH-LEUBA: If these -- finish. Let me know when you're finished and I'll ask the question.

MR. BAJOREK: Let me see. Okay. Well, go ahead and ask your question, please.

CHAIR MARCH-LEUBA: All right. Can you go back to the previous slide, slide 9?

Okay. What I see here is a large -- very little dependent on any subcooling. When you double it, you go from 1 to 2, it's not that much.

MR. BAJOREK: Yes.

CHAIR MARCH-LEUBA: There is not much change of the MPCH of 20. Right?

MR. BAJOREK: Right.

CHAIR MARCH-LEUBA: However, you would -- if you triple it, you will get numbers higher. And now you go back to 10, to slide 10, the next one. If you have an subcooling greater than 3, for example, you will be outside that square above the line of 6,500 -- 65,000.

MR. BAJOREK: Yes.

CHAIR MARCH-LEUBA: Do you see what I mean?

MR. BAJOREK: Right. Right. Yes, I --

CHAIR MARCH-LEUBA: So I kind of like the MPCH 20. I'm not sure I can justify the subcooling line.

MR. BAJOREK: I think I agree with that because -- we'll take a look at another slide that I have coming up. This is what does the code say about this? And we'll get to that to the second.

But where we're at right now is the data is suggesting a criteria, okay, that you have this failure to rewet when you have the phase-change number of 20. And that might be it. Okay? You're also subject when you're down at these relatively low Reynolds subcooling number, because what -- I think what that says is that the next ones you might want to be concerned with are these over here. Okay>?

So you may have conditions where this phase-change number may give you failure to rewet, a lower value, if you were to drop these numbers over here slightly. So that's just sort of a preliminary boundary of where we see the -- what the data is showing us right now. Now --

MEMBER BLEY: Steve? This is Dennis Bley.

MR. BAJOREK: Yes.

MEMBER BLEY: I kind of agree with Jose on this. I don't see much -- unless you've got something more that's -- than what's showing up on these charts, that 65,000 just doesn't seem to be a real trigger for anything.

MR. BAJOREK: I think so. It was something that showed up in that second one and -- I'm going to jump ahead a couple, three here, sort of a backup slide -- and we did some preliminary work, try to say well -- we took one of the MELLLA+ calculations that had been done at the time, and we did this about three years ago -- what was TRACE showing us?

And we had two different transients. One of them showed a failure to rewet. I think that was the one that Pete Yarsky showed in his earlier figures that gave us the high temperatures. Phase-change number greater than 20. Okay? The other one did not go through a failure to rewet. And that's over here. Again a phase-change number less than 20. So it may well be that it's all wrapped up in the phase-change number. And where we're at in terms of the subcooling and what the convective heat transfer is may be playing a second or a third role.

Now this was all done as kind of a

preliminary screening because realize we still have work to do on this. We did this at a time where we didn't have all of the KATHY electronic data, and this was picking that data right off of the figures in the middle of these periods. Okay? It was also done by using a couple of assumptions where -- what will lead to this condition would be overpower with undercooling. So in calculating this phase-change number and the subcooling number we're looking at minimum flow, maximum power during this period.

That might not be the best way of doing it. We might really want to look at the mean power or perhaps a square root sum of the squares, okay, to come up with that. And since that time we have awarded a couple of grants to universities to take the experimental data and now take it the next part of this to re-look at it, use all of the data that's available to them and see whether these parameters are the most appropriate ones, whether it's a phase-change number of 20 that is sort of the criteria, or how that would vary if we went up in pressure, down in pressure, or had higher or lower subcoolings.

And secondly, examine the code simulations when we have this failure to rewet to see are the codes predicting that on about the same basis.

So we wanted to show you this just as a means that, one, we think we can take the data, non-dimensionalize it in a fashion that we can use it as a screening device, give it -- give some of this to universities, other vendors as a way of indicating where you think failure to rewet can and will occur, but without giving away all of the experimental data.

MEMBER REMPE: So, Steve, let me quiz you about something you just said before this last comment. You said you've made some grants to several universities, and I believe the words you used were to -- and allowed them access to all the data for further evaluations. Are you indeed giving them access to all the data or are you giving -- tying one hand behind their back by only giving them part of the data?

MR. BAJOREK: I believe we've given them some of the data but not necessarily all of that.

MR. YARSKY: Well, Steve, for the grant that you're talking about we did give them all of the data but the researchers are under an NDA for the portions --

MR. BAJOREK: Right.

MR. YARSKY: -- that are sensitive.

MEMBER REMPE: Okay. That makes sense. Thank you.

MR. BAJOREK: Yes, it's difficult dealing with some of the grantees because officially we aren't allowed to interact with them now. The grants have to be conducted by the principal investigator without dialog between them and the staff.

CHAIR MARCH-LEUBA: Hey, Steve, is this a new requirement or is something -- there's not -- no contact with your contractors?

MR. BAJOREK: It is not a contractor. It's the difference between a contract and a grant.

CHAIR MARCH-LEUBA: Oh.

MR. BAJOREK: A contract yes, but if it's a grant, we are forbidden to give any kind of direction. And the instructions to us has been we can't even talk to them.

CHAIR MARCH-LEUBA: And is this coming from the NRC lawyers?

MR. BAJOREK: That's -- I believe that is --

CHAIR MARCH-LEUBA: Is there something that can be changed, because it makes no sense.

MR. BAJOREK: I wholeheartedly agree, but I believe that's the message.

CHAIR MARCH-LEUBA: Kim wants to say something.

MS. WEBBER: Yes, Jose. So the Integrated University Program, of which this is one of the recipients of funding from that program, statutorily we cannot direct the research. In this particular case the staff reviewed their grant proposal along with many others, and many of the proposals were accepted. And for any of those grant recipients we cannot direct their research. And that is something that Office of Research worked very closely with OGC, our lawyers, to figure out what we could and couldn't do relative to communications with grant recipients. And so --

CHAIR MARCH-LEUBA: So these --

MS. WEBBER: -- it's very clear. So it's --

CHAIR MARCH-LEUBA: Well, I hear you say that it doesn't come from our lawyers; it comes from Congress.

MS. WEBBER: Well so even the --

CHAIR MARCH-LEUBA: And they created the program?

MS. WEBBER: Yes, it's my understanding -- and I haven't read the legislation recently, but the interpretation of the legislation is that the purpose of the Integrated University Program is to support nuclear engineering and nuclear fields to get not only research completed, but to support nuclear programs in general that then -- the resources used to support faculty appointments and fellowships and even this research go to prepare the pipeline to put students and folks into the nuclear field. And so that --

CHAIR MARCH-LEUBA: This makes a lot more sense. NRC is a conduit to the distribute the money.

MS. WEBBER: Correct.

CHAIR MARCH-LEUBA: It's not really -- yes, okay. I retract my comment.

MEMBER REMPE: Well, actually --

CHAIR MARCH-LEUBA: Okay. Joy, you have --

MEMBER REMPE: -- we'll hear about -- it used to be called the Integrated University Programs, but we heard from Ray it's called the University Nuclear Leadership Program. But we're going to be hearing about the projects in an upcoming meeting and we can discuss this more at that time, too.

MS. WEBBER: Correct. Thanks, Joy. The only thing that I was -- the only additional thing that I was going to say is that I think we're in -- coming up on year three in this new area where some of the $16 million that we fund these opportunities --

some of that money is used to fund research and development, whereas in the past prior to three years all of that funding went towards faculty development and fellowships and trade schools and other organizations more for the educational side of it. But in the last two years, going on three years, we've been working with OGC to help us carve out some funding that will actually promote research in areas of interest to the NRC.

So that's what this -- this is one grant recipient who is actually doing some research, as I think Pete and/or Steve pointed out, that are doing something of interest to us. So that's where it's a little bit of a sticky situation given the context, but I think, Joy, to your point, at the future presentation there will be people much more knowledgeable about it than probably I am.

MEMBER REMPE: Yes, we can explore it a bit more. And again, I'm still kind of stumbling over this wall that precludes any sort of interaction. Since the research is of interest to NRC it might be good to be a little bit more flexible about that, but maybe we can explore that a bit more.

CHAIR MARCH-LEUBA: Steve, I assume you're down to your last slide?

MR. BAJOREK: I am done now unless there are additional questions.

CHAIR MARCH-LEUBA: Any questions from the members for both Steve, Pete or Kim?

(No audible response.)

CHAIR MARCH-LEUBA: I heard something yesterday about members -- five seconds for members' comments and doughnuts. We'll assume that there are no more questions, so I'm going to open the floor to members of the public.

If anybody wants to make a comment, place it on the record, you can do it now. Please state your name. And if you are using the phone line, you need to un-mute yourself using *6.

(No audible response.)

CHAIR MARCH-LEUBA: Okay. Five-second rule again. There are no comments.

At this point I just wanted to say I'm really interested. I mean it's a great thing that NRC performed these tests because it has shown us something that we didn't expect, right? And it of value and it is of value to continue to analyze it and try to ensure that both NRR test confirmatory calculations or performed reviews of vendors or applicants -- that we keep this data in mind. Okay?

So with that said, thank you very much. Excellent job.

Anybody has an additional comment?

MEMBER BLEY: Yes, just a question for Peter. Going back to the Morris comparison stuff. Is that something you guys have been using for a while? And if it's not, I think there's pretty broad application for that in a white paper for folks in other areas around the NRC. It might be very useful.

MR. YARSKY: Yes, Dennis, that's a very excellent point. This is, as far as I can tell the first deployment of this technique at the NRC. It's being utilized within a larger framework at the University of Illinois for the objective of uncertainty quantification, but we're using it here just for a more limited purpose. And on the report I made a point of including kind of like a white-paper-level description of the technique to make it more accessible to the more thermohydraulically-inclined of -- and of the staff that we interact with so that hopefully it can gain some more traction.

MEMBER BLEY: Well, it's not just that. I mean, they'll read this for interest anyway, but folks in PRA reliablity, for example, and many other areas who try to do uncertainty quantification and who do sensitivity studies, this gives a pretty good tool for clarifying the important factors involved in those kinds of cases. And a separate white paper would be nice because it would open it up to people who won't be working through the details here associated with thermohydraulics.

Anyway, nice piece of work. I liked it.

MR. YARSKY: Thank you.

CHAIR MARCH-LEUBA: I think Vicki is in line.

MEMBER BIER: Yes, I just have a quick follow-up on Dennis' comment. Like Dennis I had no idea about this method until today, so I'm probably bringing coals to Newcastle or whatever. I'm sure you know much more about this than I do, but just from my quick kind of Google research during the meeting this morning it looks like the original Morris method had problems when there were negative effects or negative coefficients or whatever, and there's a modern version that corrects for that. I assume you guys are aware of that distinction and dealing with that, et cetera?

MR. YARSKY: Yes, Vicki, that's a really great question. That's very true. What we do -- if you go back to the -- I guess I can go back to the slide and show this, if I can share again. Just give me one moment and I'll bring this back.

(Pause.)

MR. YARSKY: Yes, this is a problem. And so a very astute observer would notice that -- I mention here the Mu and the Mu*STAR and that later on we are presenting results from Mu*STAR.

So this is the more modern technique that addresses the --

MEMBER BIER: Okay. Got it.

MR. YARSKY: -- (audio interference) of coefficients. Yes, so when you have to do it sometimes you get negative coefficients and when you start averaging you end up erasing the sensitivity. So you have to kind of absolute value the negative ones before you do the averaging. So it's not capturing -- so it becomes a quantitative measure of the sensitivity but not necessarily the direction of the sensitivity.

MEMBER BIER: Right. No, I understand that because I know other things that I've dealt with like coefficient of variation becomes sort of meaningless if the quantity is centered around zero, et cetera.

MR. YARSKY: Yes.

MEMBER BIER: So there's a lot of things

that have that problem.

MR. YARSKY: Yes.

MEMBER BIER: So thanks for the explanation.

MR. YARSKY: But it's -- you shouldn't think of the mean value here as being necessarily the true mean value of the sensitivity because it will positive value the negative coefficients. So it's giving an idea of is this sensitive or not without explicitly quantifying that average because sometimes that average might be around zero. Right? So it would erase itself out. But that's in fact right --

MEMBER BIER: Thank you.

MR. YARSKY: -- and that's what we have to take into account. So that's the (audio interference) --STAR is how that's (audio interference) in the nomenclature.

CHAIR MARCH-LEUBA: Joy, I believe you want to say something?

MEMBER REMPE: Yes, I also really appreciate Peter and Steve taking the time to give these presentations today and updating us.

I guess I have a question for you, Jose. I know we do this sometimes for reg guides, but I think this is a good activity that's been done by the research organization that's very practical and getting good results. Do you think it might be worthwhile just having an item in the upcoming P&P for December? So it wouldn't require any more presentations, but just saying the subcommittee did review this work, they had a very favorable impression that this is a worthwhile effort that's produced -- or is producing some very useful results, or something to acknowledge what --

CHAIR MARCH-LEUBA: I would love to do that. I'll --

MEMBER REMPE: -- (audio interference) have it issued and the meeting minutes?

CHAIR MARCH-LEUBA: I would love to have a trial balloon of what I'm proposing to do for these situations. So I'll take the action item of writing a couple of paragraphs similar to what we do for reg guides.

MEMBER REMPE: That's what I'm thinking exactly.

CHAIR MARCH-LEUBA: Yes. Write two or three paragraphs from what I've seen what the topic is and then P&P accepts it, or rejects it, and we ask Scott to send a letter saying thank you for coming to this meeting. We loved it. We don't have any followups. And attach the paragraph.

Yes, I think we should add it to P&P if we can.

MEMBER REMPE: Okay. Thanks.

CHAIR MARCH-LEUBA: Kim?

MS. WEBBER: Yes, I'm not familiar with that process because we don't do the reg guides, so I'm just curious to better understand what that process entails.

CHAIR MARCH-LEUBA: With reg guides one members gets assigned a new reg guide --

MS. WEBBER: Okay.

CHAIR MARCH-LEUBA: -- typically an update. That members reviews it on paper and then the member makes a proposal to the Committee whether we will have a Committee -- a presentation and a letter on it or not.

MS. WEBBER: At the Full Committee meeting or --

CHAIR MARCH-LEUBA: This is done during the Full Committee in what we call the P&P, the Process and Procedures.

MS. WEBBER: Okay.

MEMBER REMPE: But is part of the Full Committee. It's not prior to -- sometimes we have a

P&P Subcommittee during Full Committee week. This is part of the Full Committee meeting activities.

CHAIR MARCH-LEUBA: So my concern as that we're talking about this, Kim, is that sometimes we have an item like this where we don't have any issue whatsoever with it. I mean we love it. And therefore we just drop it and don't write a letter on it.

MS. WEBBER: Okay.

CHAIR MARCH-LEUBA: And I mean we only write letters when we have problems and we have recommendations.

MS. WEBBER: Okay.

CHAIR MARCH-LEUBA: So I've been saying there has to be a way to -- so our executive director can send Kim a letter saying we reviewed it in the subcommittee; we don't have any problems.

MS. WEBBER: Oh, okay.

CHAIR MARCH-LEUBA: Thank you very much.

MS. WEBBER: And so does that mitigate a presentation at a Full Committee meeting or --

MEMBER REMPE: Yes.

CHAIR MARCH-LEUBA: Yes. Yes.

MEMBER REMPE: There would be no presentation required by you guys. It's just a -- in this case a way of saying we liked what we heard and it would be something that would be approved by the Full Committee.

MS. WEBBER: Okay.

MEMBER REMPE: Unless of course someone raises their hand and doesn't like it, but that's what we are proposing.

CHAIR MARCH-LEUBA: Yes, it does not involve any work on your part, on research's part.

MS. WEBBER: Okay. Yes, I just wasn't familiar with that process.

CHAIR MARCH-LEUBA: Yes.

MS. WEBBER: But I think it would be helpful to have your statement that you loved this work and that you don't need to write a letter because you feel that this work is very technically mature and all the good words that you might want to say.

CHAIR MARCH-LEUBA: It's not our recommendation from the Committee, but a sign of approval of what you're already doing. So it doesn't raise to the level of a letter.

MS. WEBBER: Okay. Okay. Thanks for explaining that.

CHAIR MARCH-LEUBA: Okay. Any further comments or questions?

(No audible response.)

CHAIR MARCH-LEUBA: If not, we're going to adjourn, but there is an administrative issue off the record.

Zena, can you confirm this afternoon's meeting? Does it start at 1:00 or at 2:00?

MEMBER BALLINGER: This is Ron. I've been trying to get an answer to that and I have been unsuccessful. I'm assuming it's at 2:00. It's my meeting.

CHAIR MARCH-LEUBA: The agenda says 1:00, so --

MS. ABDULLAHI: Let me explain. So when the meeting was scheduled it was scheduled for 1:00, however, there seems to be a general plan that we should take -- to it 2:00 to 6:00. But since this was scheduled from 1:00 and the agenda says 1:00, we will start at 1:00.

Larry, are you on?

MR. BURKHART: Yes, I --

CHAIR MARCH-LEUBA: We can do something similar to what was done here. There was some confusion whether it was 9:00 or 9:30. And if somebody's on the line, if somebody shows up at 1:00, we tell them come back at 2:00. It is up to Ron to tell us what he wants to do, I guess.

MR. BURKHART: So this is Larry. The agenda that's on the website says 1:00, so we should start at 1:00.

MEMBER BALLINGER: So let it be written, so let it be done.

CHAIR MARCH-LEUBA: Okay. So the meeting was already adjourned. Thank you everybody for your comments.

MS. WEBBER: Thank you very much.

MEMBER CHAIR REMPE: REMPE: Yes, thank you.

(Whereupon, the above-entitled matter went off the record at 10:43 a.m.)

Non-Dimensionalization of KATHY Data

Stephen M. Bajorek, Ph.D.
Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission
Ph.: (301) 415-2345 / Stephen.Bajorek@nrc.gov

ACRS Thermal Hydraulics Subcommittee Meeting

November 17, 2021

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Introduction & Background

- After the KATHY data was obtained, there has been “discussion” on what is Proprietary and what is not Proprietary.

- Non-dimensionalization proposed as a way to:

  1. Protect data that may be considered as Proprietary.
  2. Provide the NRC with a quick means to evaluate licensee analyses for the possibility of severe consequences during a postulated ATWS-I.

Two-Phase Flow Instabilities

- Work initially performed by Ishii helps: [Ishii, M., STUDY ON FLOW INSTABILITIES IN TWO-PHASE MIXTURES, ANL-76-23, March 1976]

The dimensionless parameters derived by Ishii included the following:

Froude number: $N_{Fr} = V_{fi}^2 / gL$

Reynolds number: $N_{Re} = \rho_f V_{fi} D / \mu_f$

Subcooling number: $N_{sub} = \dfrac{\Delta i_{12}}{\Delta i_{fg}} \dfrac{\Delta\rho}{\rho_g}$

Phase-change number: $N_{pch} = \dfrac{q_w'' P_h L}{A_c V_{fi} \Delta i_{fg}} \dfrac{\Delta\rho}{\rho_g \rho_f}$

Density ratio: $N_\rho = \rho_g / \rho_f$

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Stability Map

Stabilizing

N_{sub}

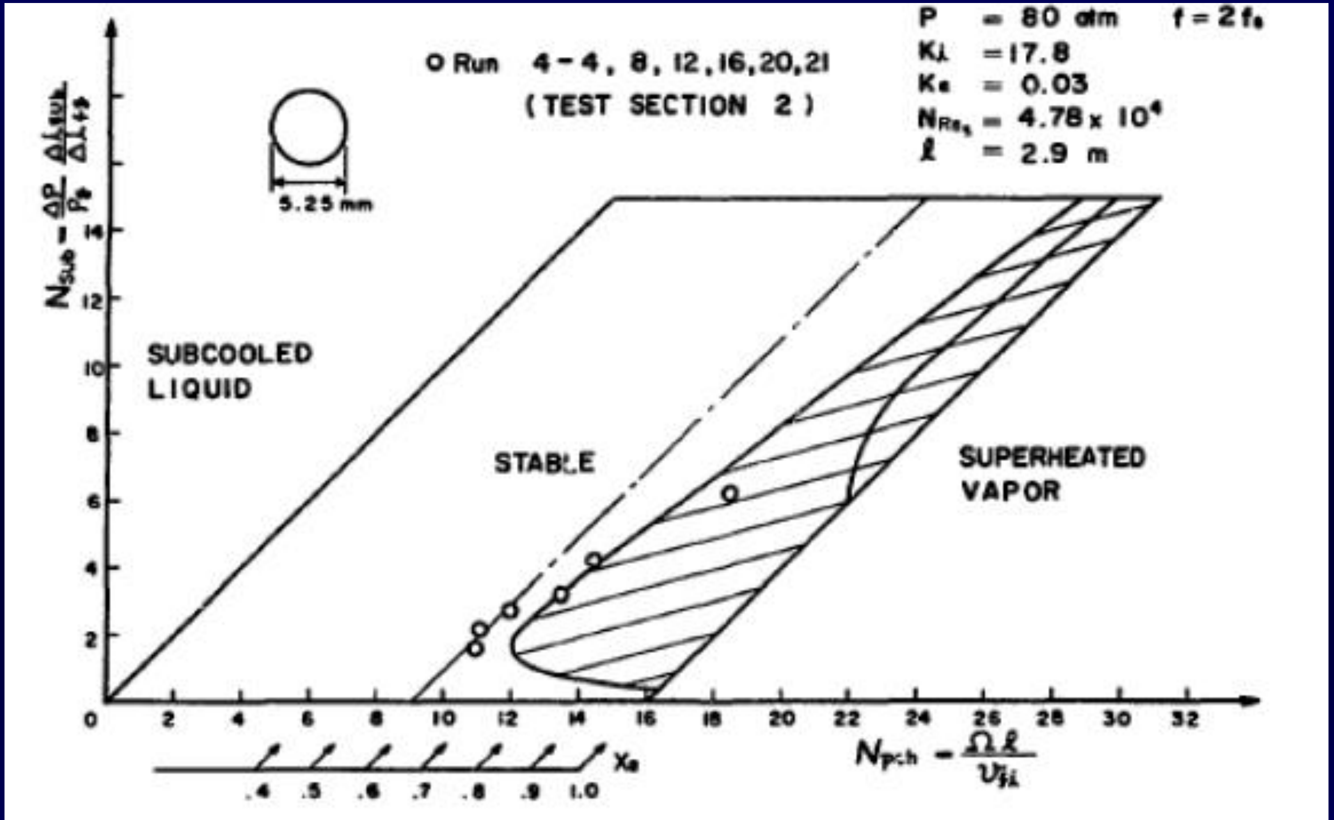
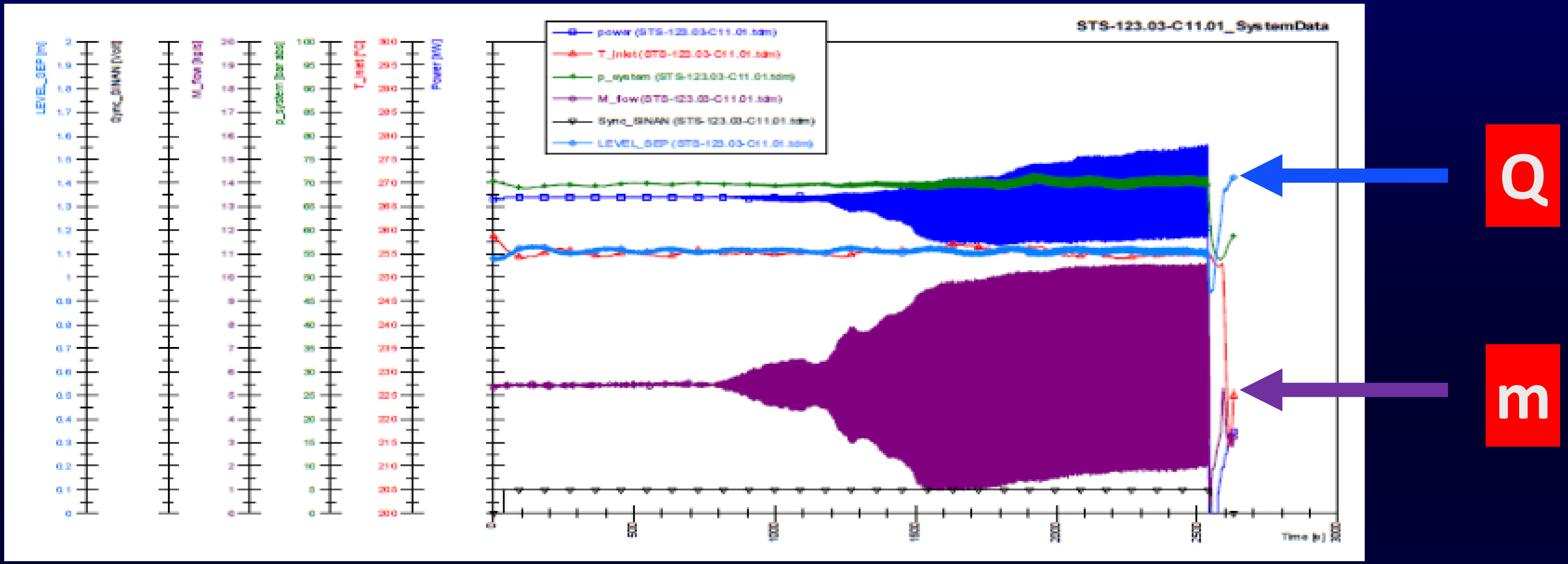


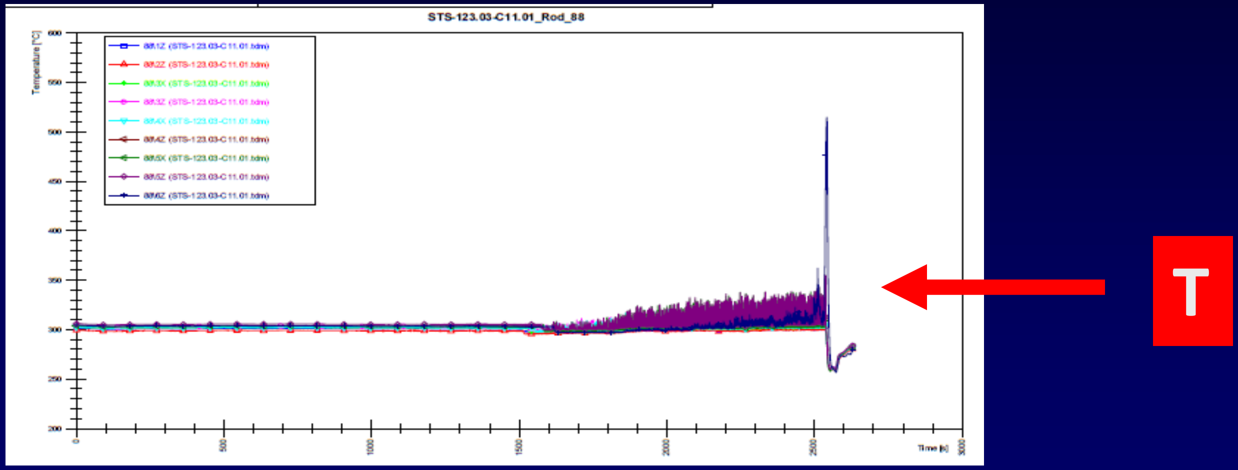
Fig. 16. Comparison with Solberg's Experiments. The solid lines indicate the computer solution and the dashed line the simple criterion.

N_{pch}

Destabilizing

Test "Periods"





Data Characterization

- For each test, characterize each of four periods based on main parameters (rod temperature, flow rate, power) & condition.
- Nomenclature: **T** **m** **Q**
- Conditions: S = “stable” U = “oscillatory” with F = “FTR” for rod temp.

To simply and quickly characterize the data, assume a nomenclature for rod temperature, flow rate, and bundle power as follows:

SSS = rod temperature, flow rate, and power are all steady without oscillation (Period 1).

SUU = rod temperature is steady, while flow rate and power are oscillatory (Period 2).

UUU = rod temperatures, flow rate and power all oscillate, but there is a return to rewet by the rod temperatures (Period 3).

FUU = rod temperature fails to return to rewet, while flow rate and power oscillate (Period 4).

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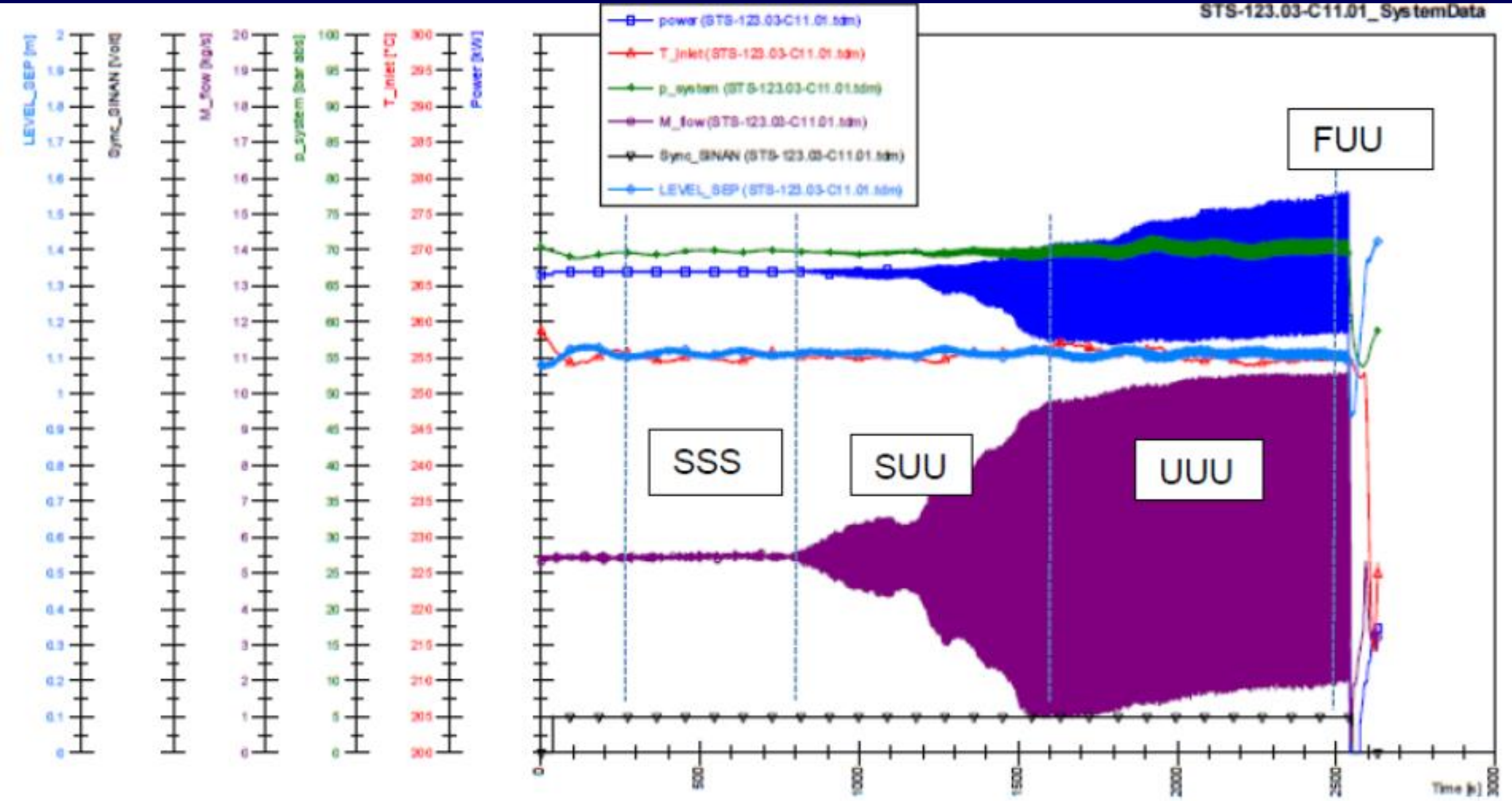
Power and Flow rate



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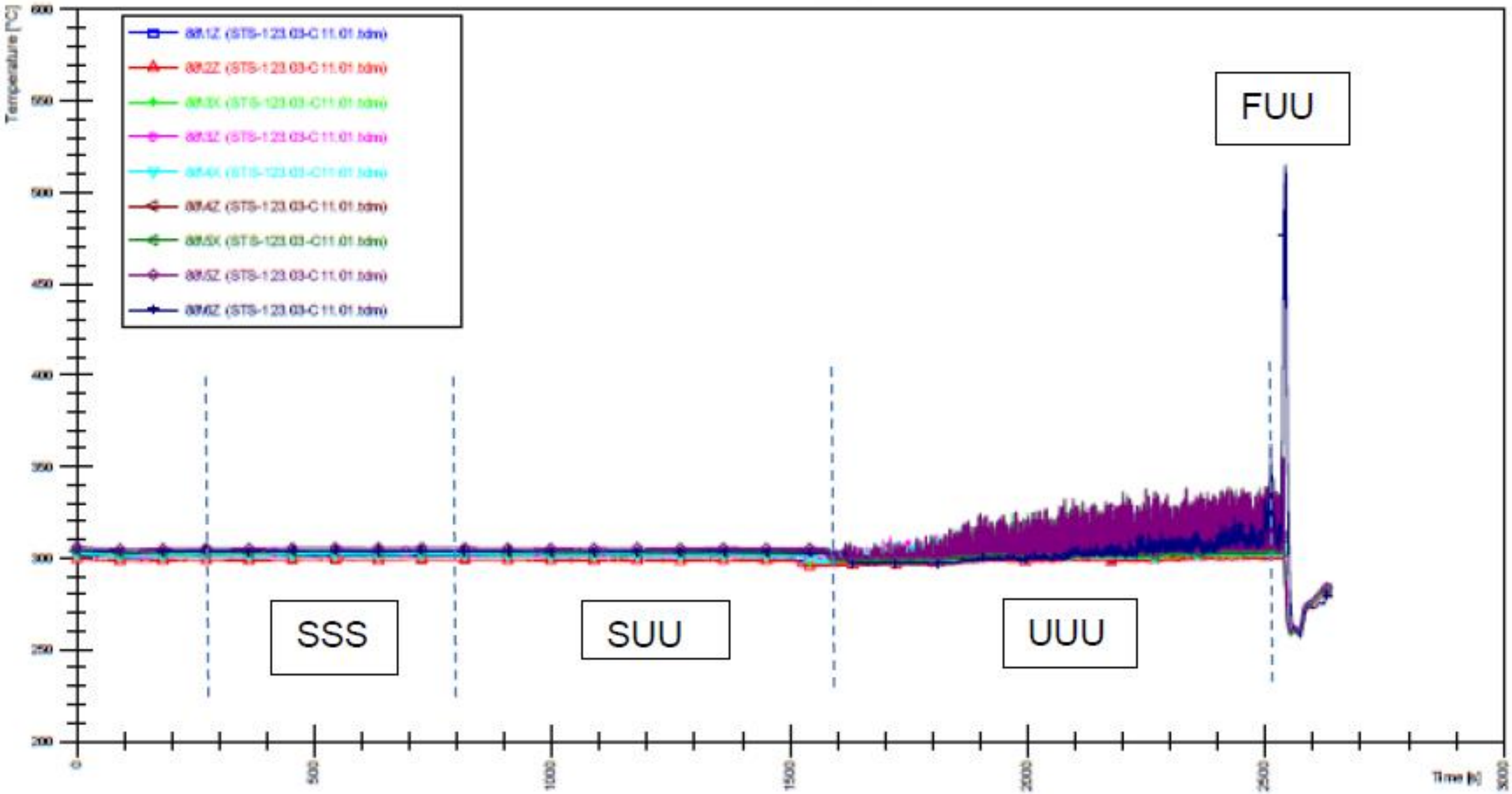
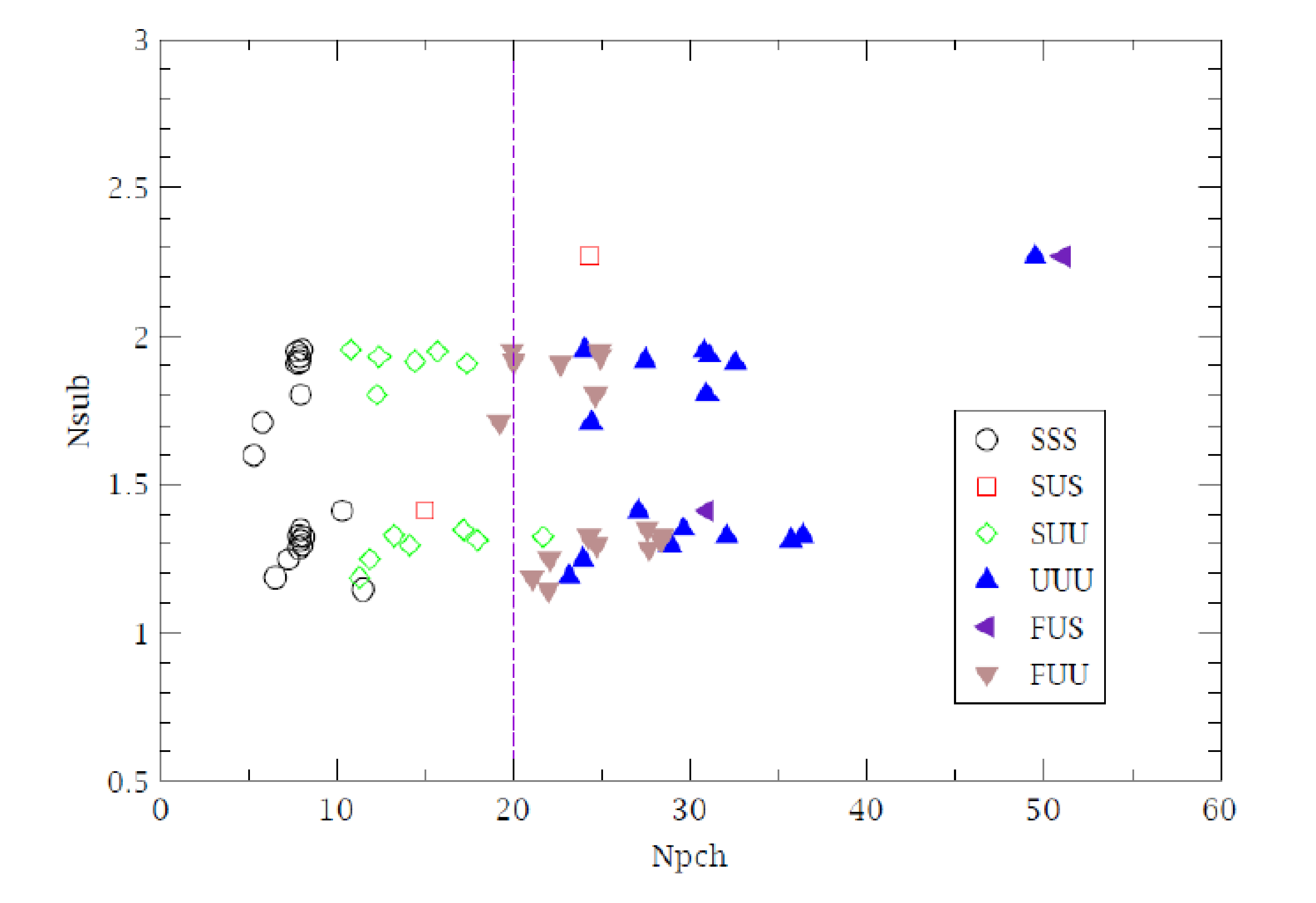
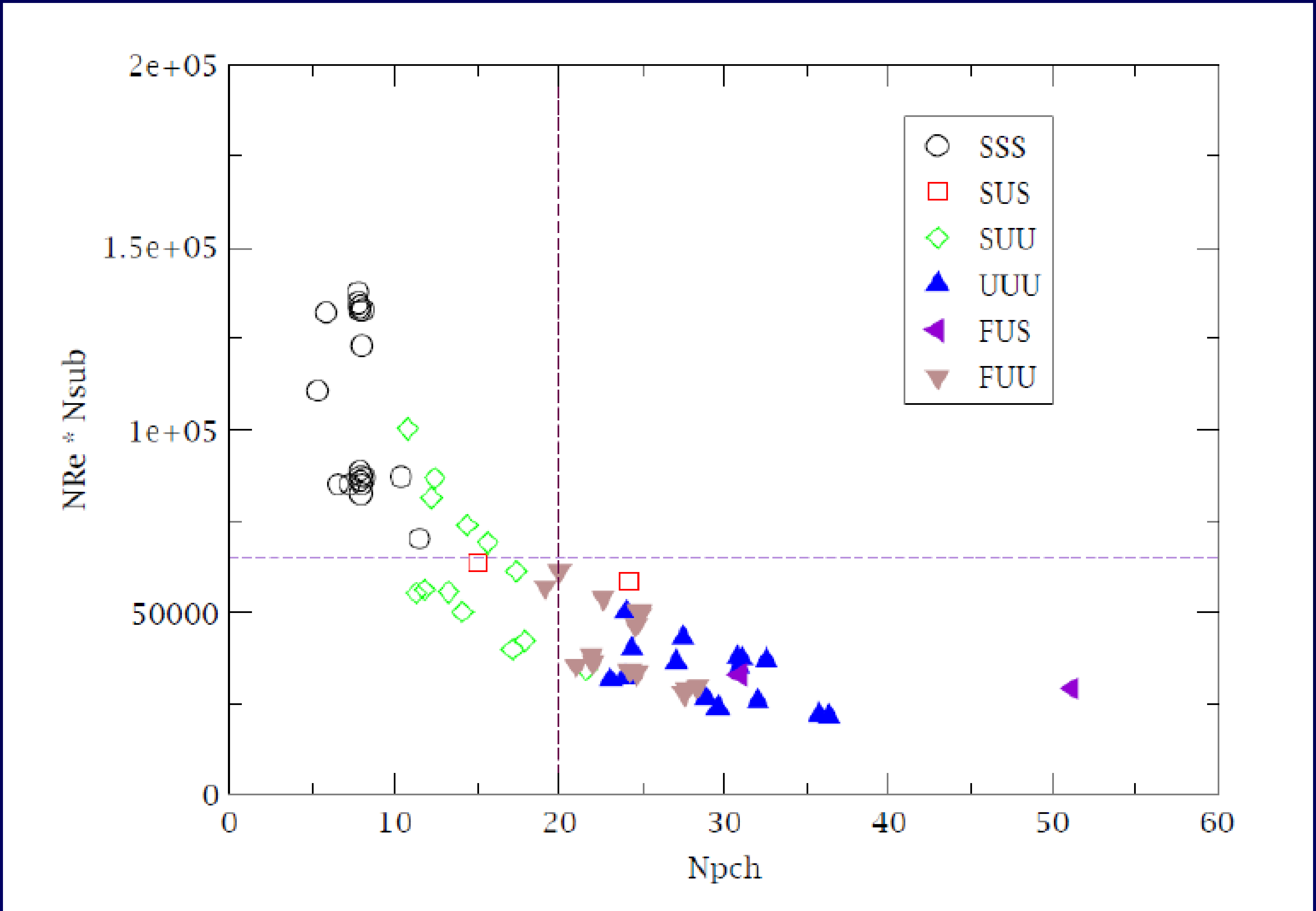
Rod Temperature



N_{sub} vs N_{pch}



$N_{re}N_{sub}$ vs N_{pch}



Failure to Rewet

- **Possible when:**

$$N_{pch} \geq 20$$

and

$$N_{Re} * N_{sub} \leq 65000$$

Future Directions

Recommendations

- Utilize all of the KATHY (electronic) data to obtain or estimate non-dimensionless parameters using local conditions.
- Examine the non-dimensional parameters and assumptions on flow rate and power in their calculation.
- Examine code simulations of FTR (i.e are codes predicting this trend?)

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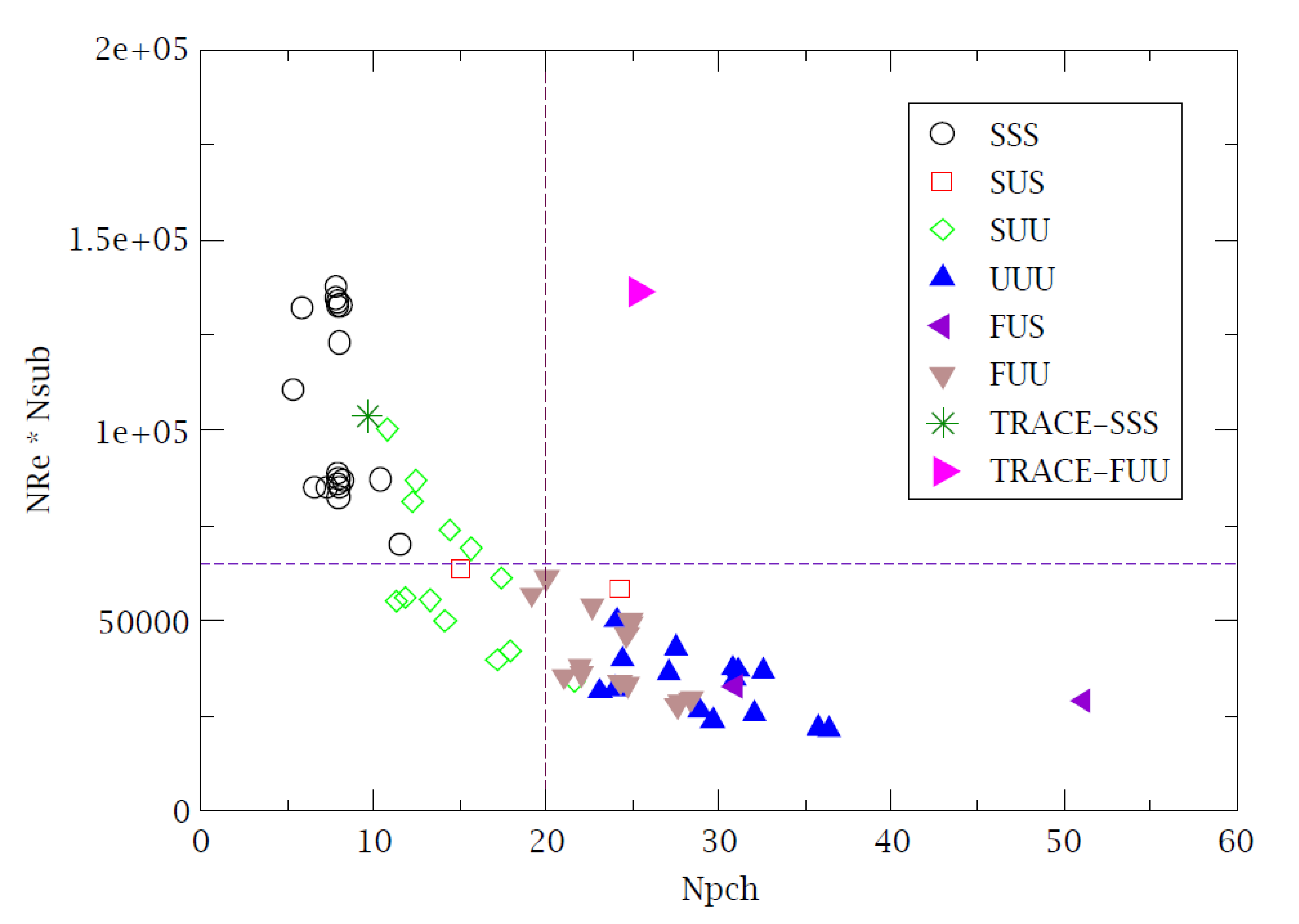
Where is TRACE ?



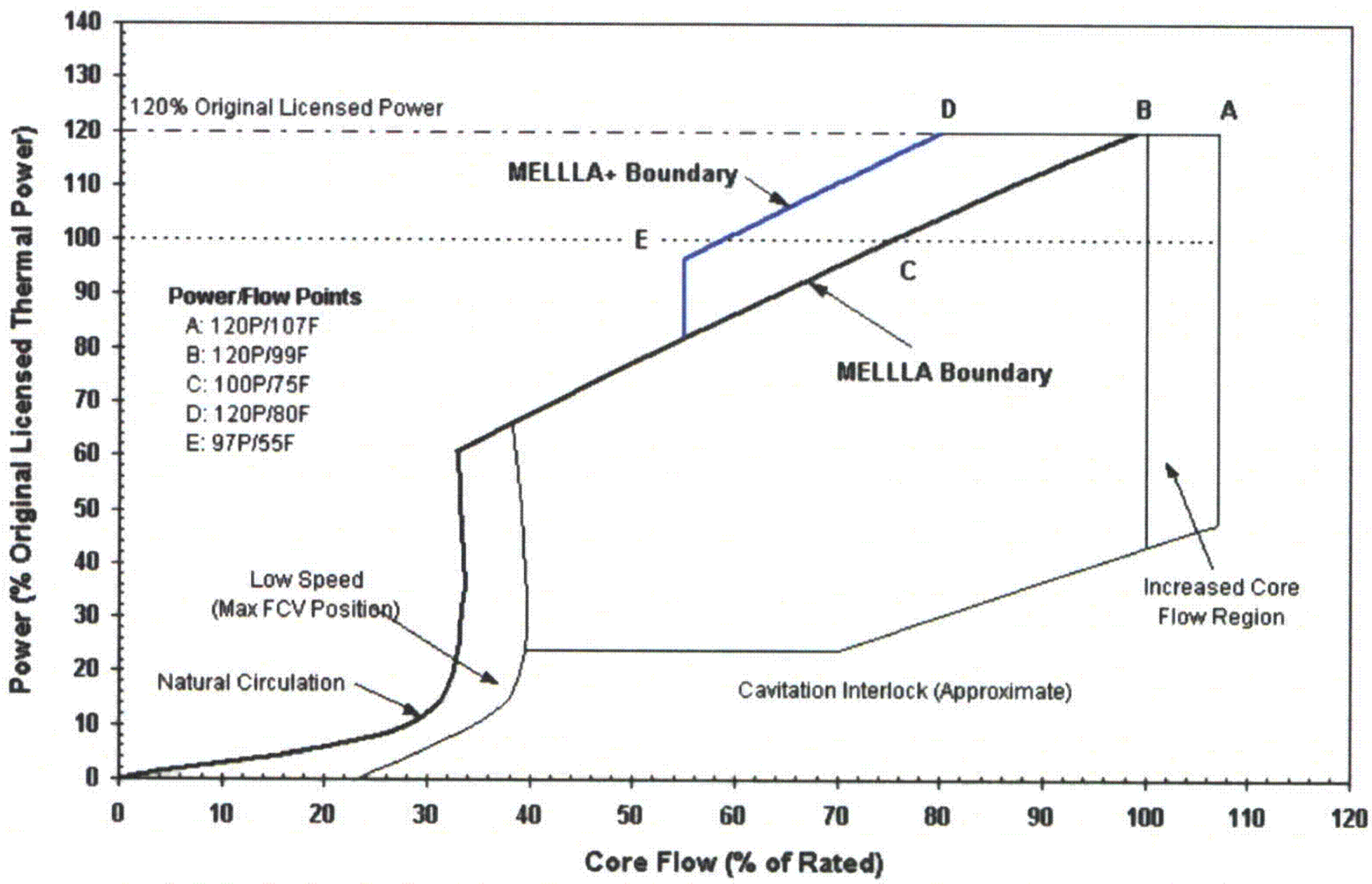
Presentation to the ACRS Thermal-Hydraulics Subcommittee on TRACE Assessment against KATHY Test Data

P. Yarsky, T. Zaki and S. Bajorek
RES/DSA

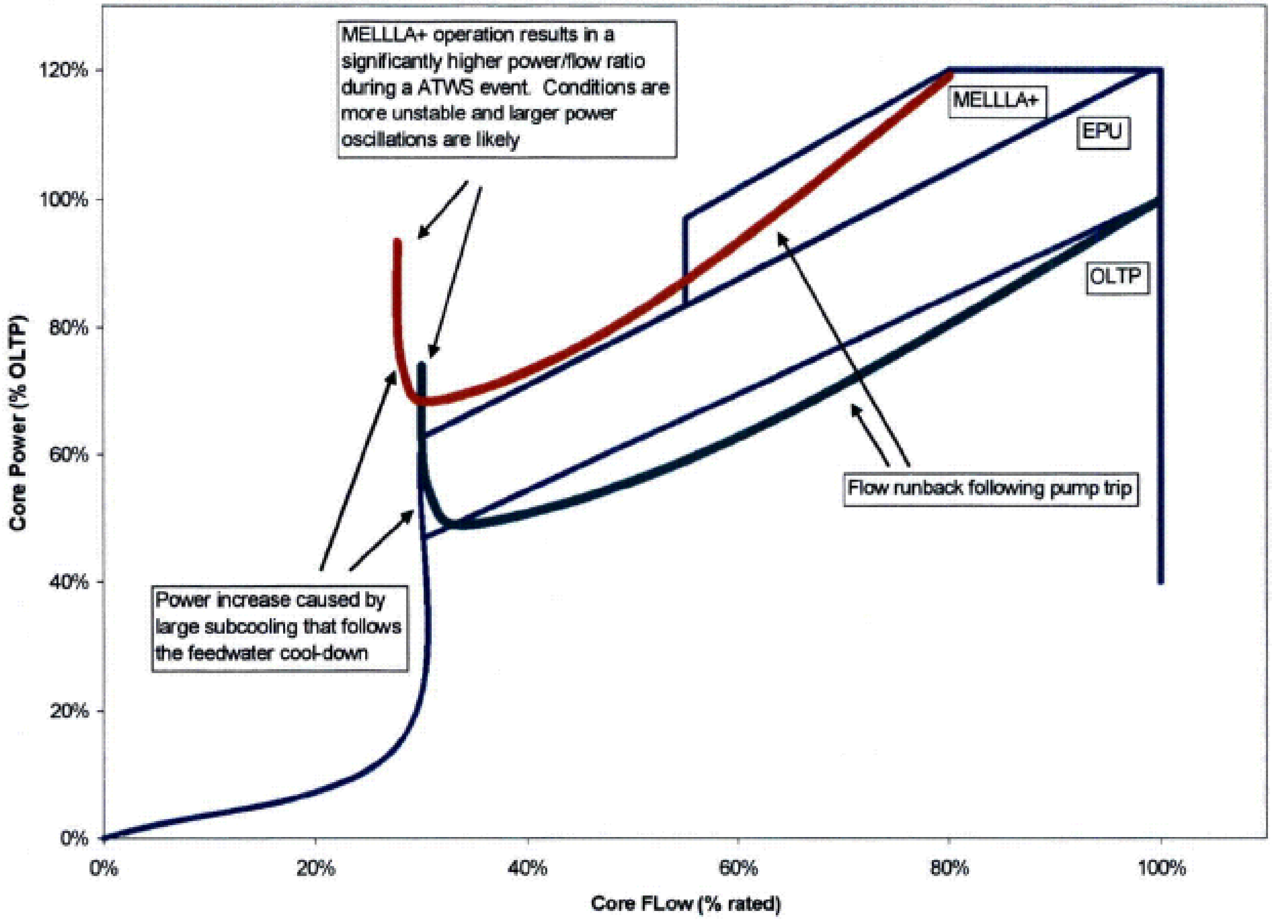
Outline

- Background and Motivation
- KATHY Test Facility Overview
- Description of Tests
- Failure-to-Rewet Temperature
- Comparison of Data to Models
- Conclusions

MELLLA+ Power/Flow Map



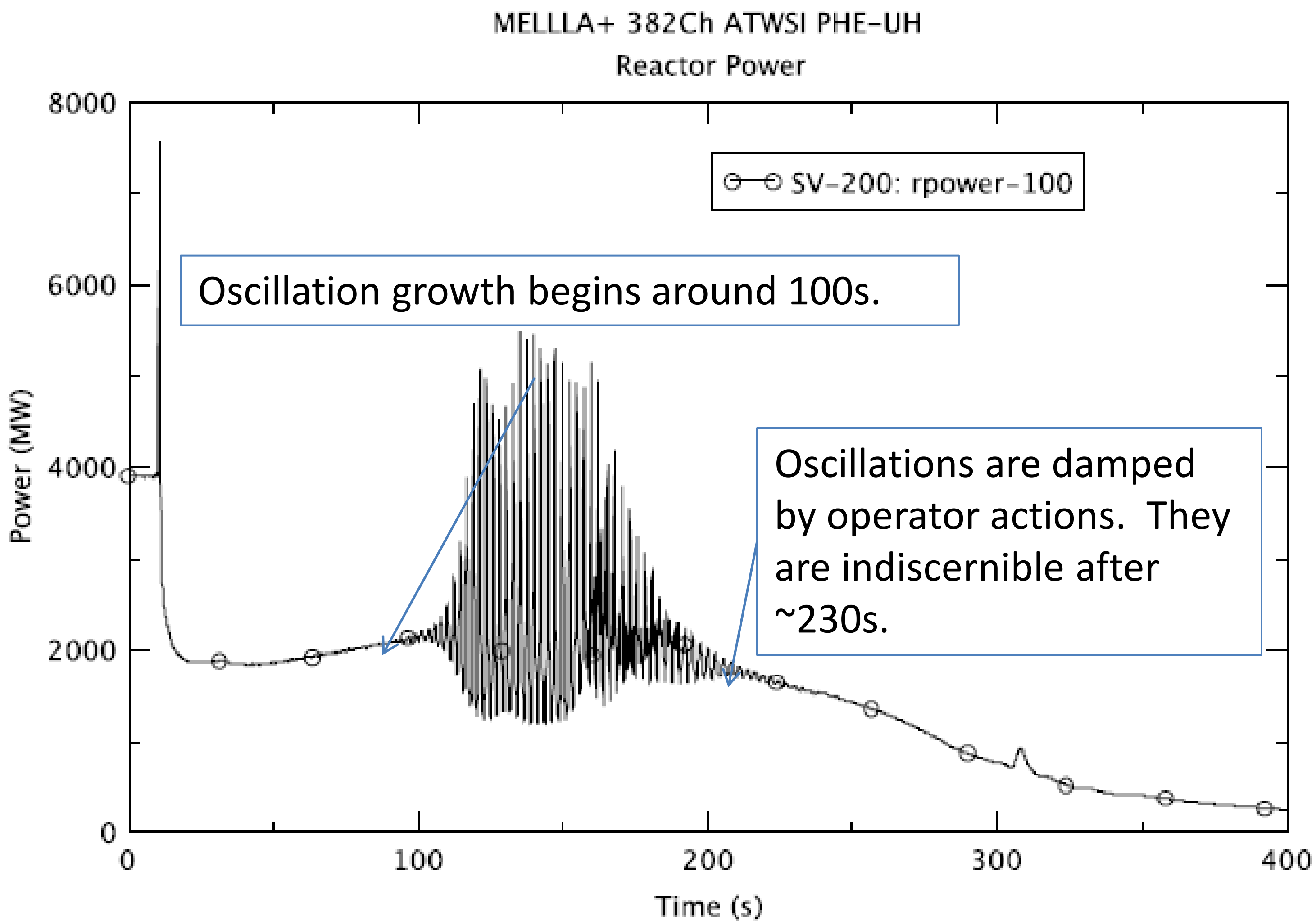
Operating Domain and 2RPT



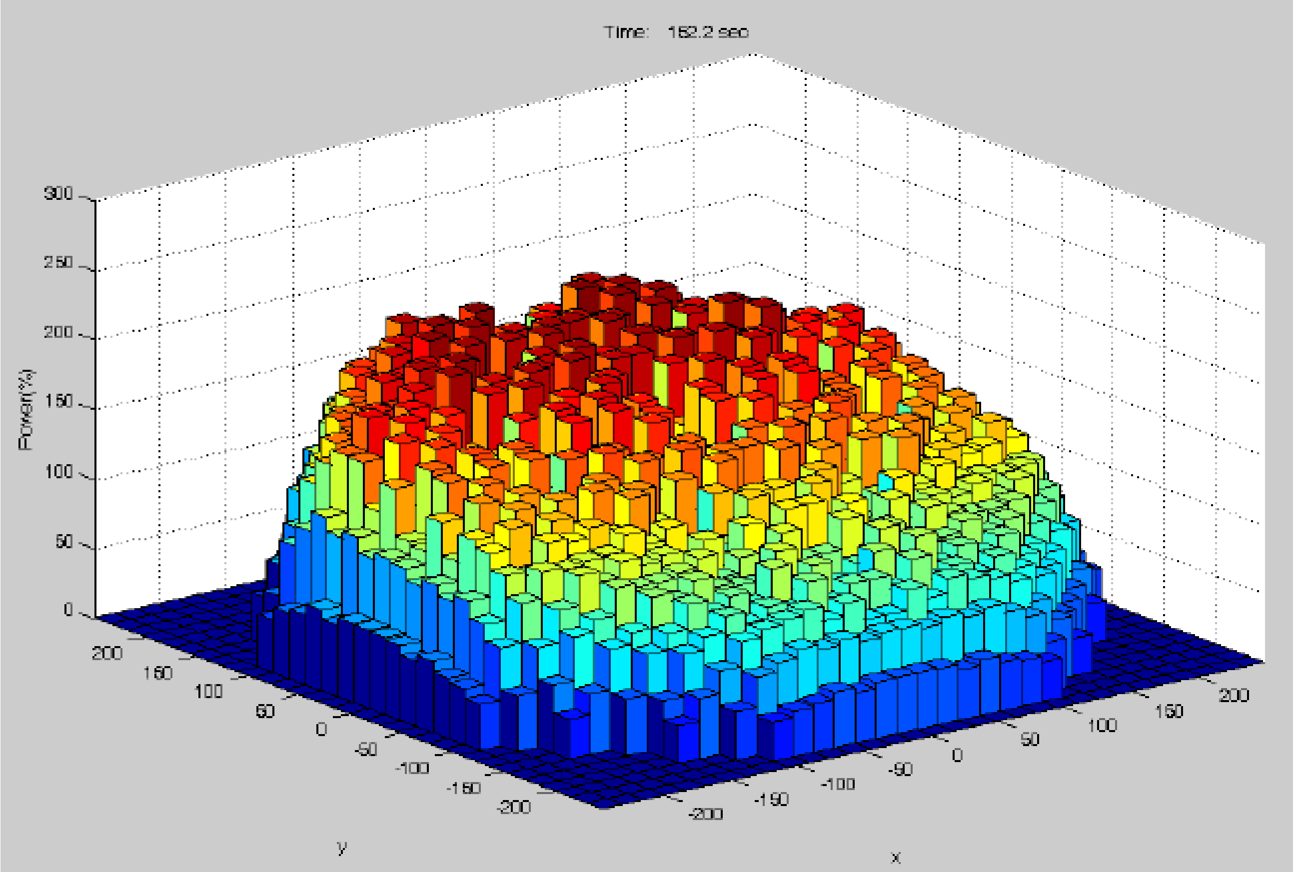
Overview of ATWS-I

- ATWS event considered is a turbine trip event with turbine bypass capability (TTWBP).
- The TTWBP results in a pressure pulse, a trip of the recirculation pumps, and a loss of extraction steam to the feedwater heater cascade.
- The TTWBP ATWS is expected to yield unstable conditions and large amplitude power instability.
- Operators control reactor water level and inject boron through the standby liquid control system (SLCS) to mitigate the event.

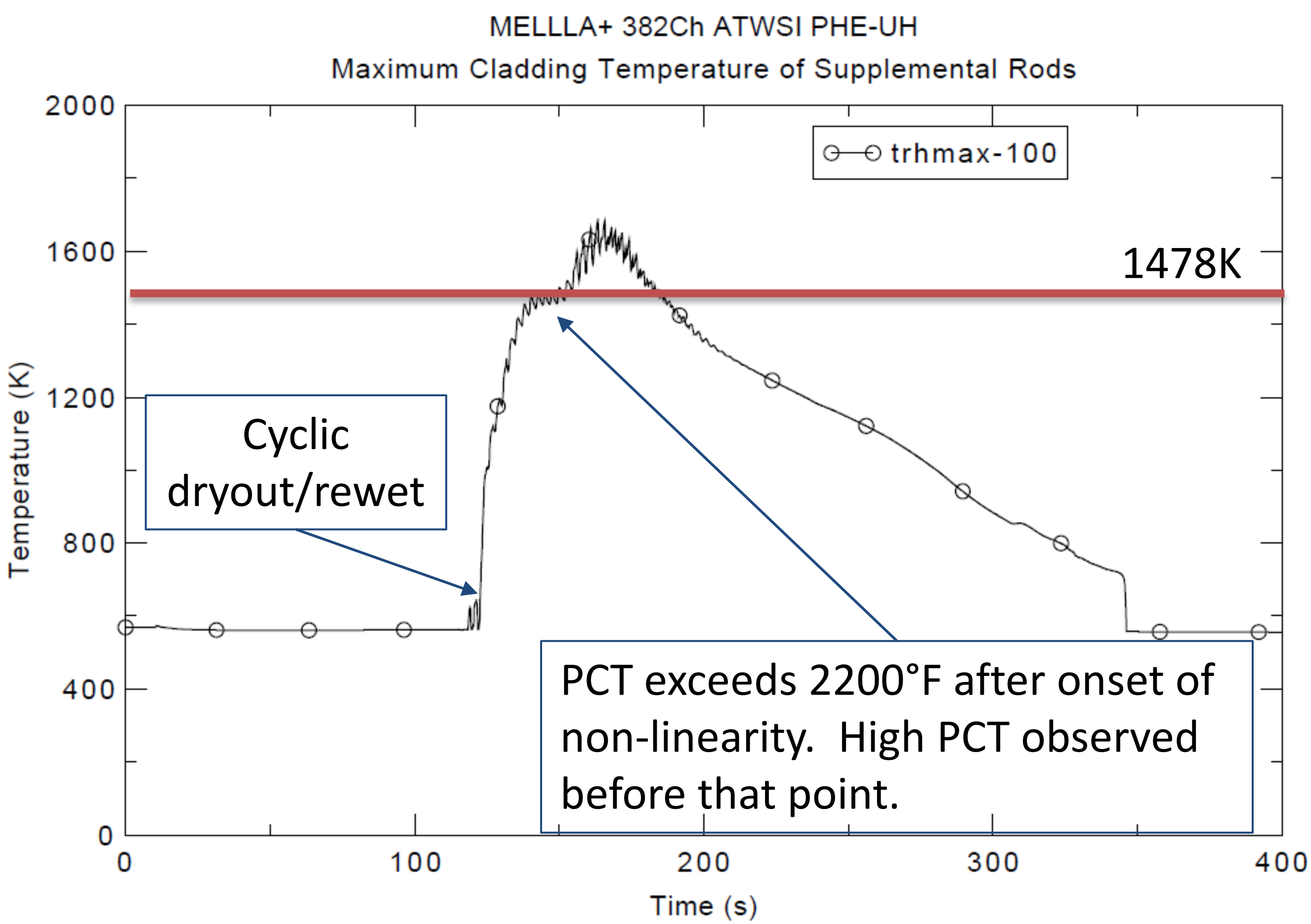
Transient Reactor Power



Bi-modal Oscillations



Peak Cladding Temperature Results



Predicted Fuel Heat-up Mechanism

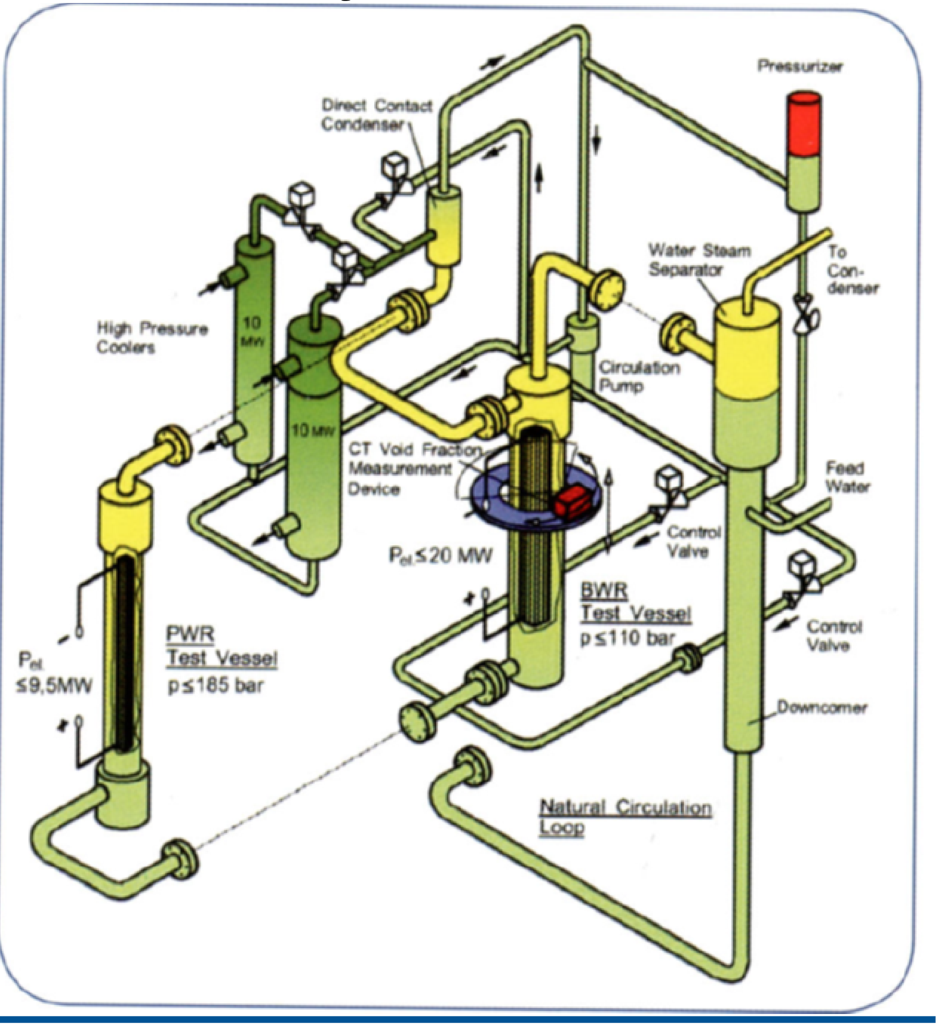
- Oscillation magnitude increases and the fuel undergoes periodic dryout/rewet cycling.
- As oscillation magnitude continues to grow, the rewet period of the cycle becomes insufficient to remove all of the energy accumulated in the fuel during the dryout period. This is accompanied by a “ratcheting” of the fuel temperature upwards after each dryout/rewet cycle.
- Once temperature ratchets up to the minimum stable film boiling temperature, the cladding surface “locks” into film boiling heat transfer.
- Once locked in film boiling, and while reactor power is high, fuel temperature excursion occurs.

Fuel Heat-up and Coolability

- MELLLA+ operation exacerbates the consequences of ATWS and the NRC staff predicts that under ATWS-I conditions the cladding surface may fail to rewet leading to fuel damage.
- It is difficult in practice to ensure core coolability if the fuel might become damaged.
- The heat-up mechanism was the subject of an experimental program at KATHY.

KATHY Facility

- Full scale bundle test facility.
- Full reactor pressure.
- Capability for natural circulation flow rate to perform stability and instability tests.
- Instrumented to measure temperature for CHF tests, adequate for indicating the failure to rewet phenomenon.
- Implements a module called "SINAN" that simulates reactivity feedback.



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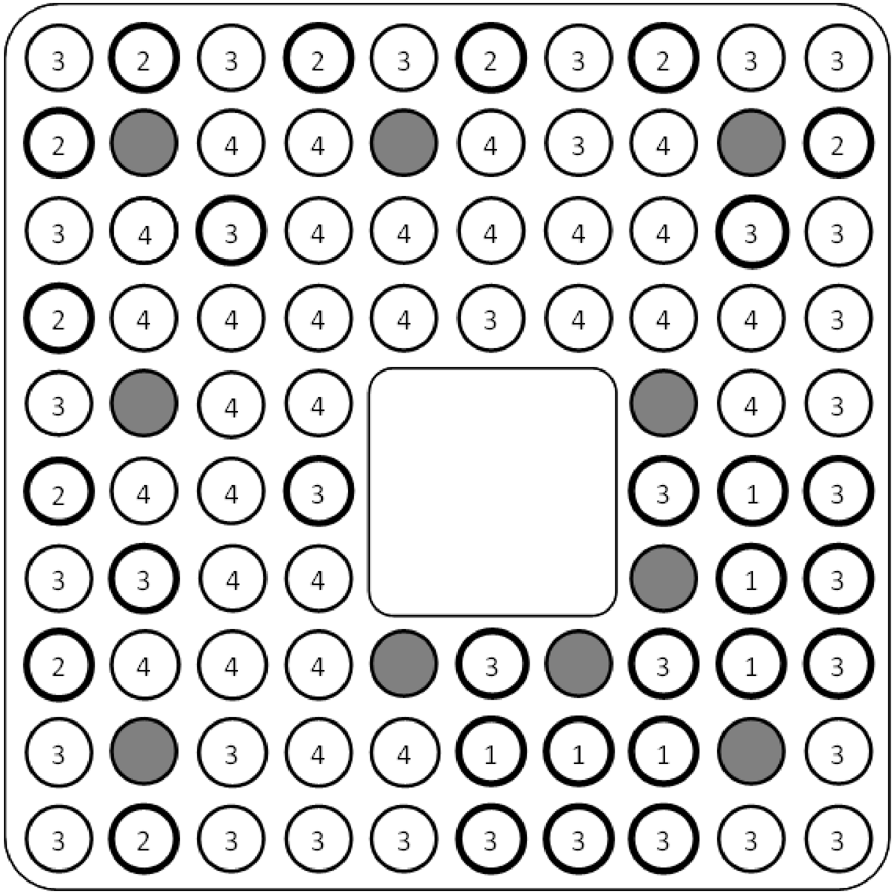
Heater Rod Bundle

Heater rods have a bottom skewed axial power shape.

The assembly includes part length rods, water rods, and spacers typical of modern BWR fuel assemblies.

Type “1” rods have higher radial peaking factor than Type “2” and so-on.



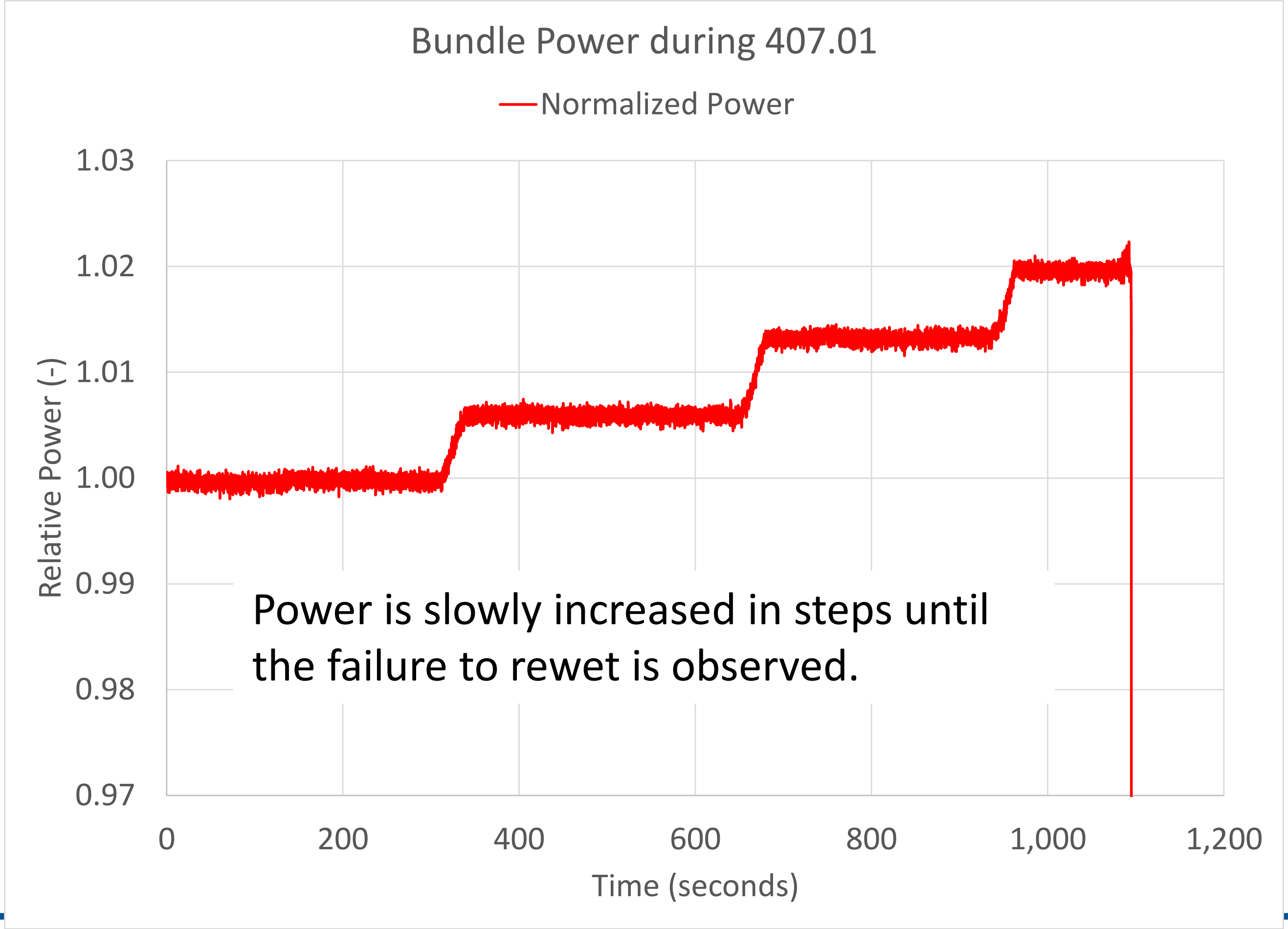
Experimental Work

- Experimental study of fuel heat-up mechanisms during power/flow oscillatory conditions typical of ATWS-I scenarios.
- Assessment and validation of TRACE to analyze fuel heat-up during ATWS-I.
- Performed extensive testing of failure to rewet conditions at the KATHY test loop in December 2016.

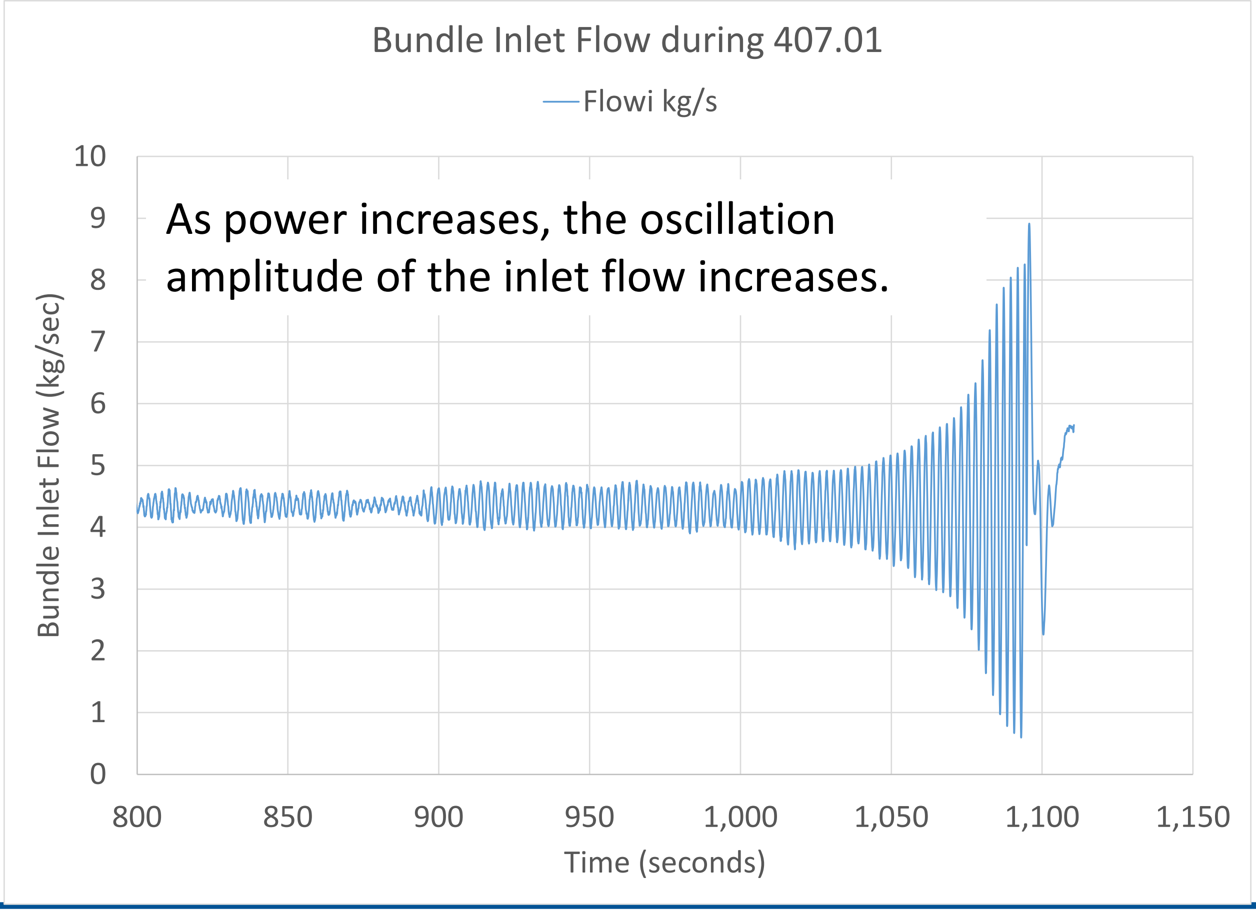
Tests with and without Feedback

- Two types of tests were conducted.
- Tests without feedback did not utilize the SINAN module and power was steadily increased to induce instability and subsequent heat-up.
- Tests with feedback used SINAN and increased the feedback coefficient to induce instability and subsequent heat-up.

Sample Test without Feedback (407.01)



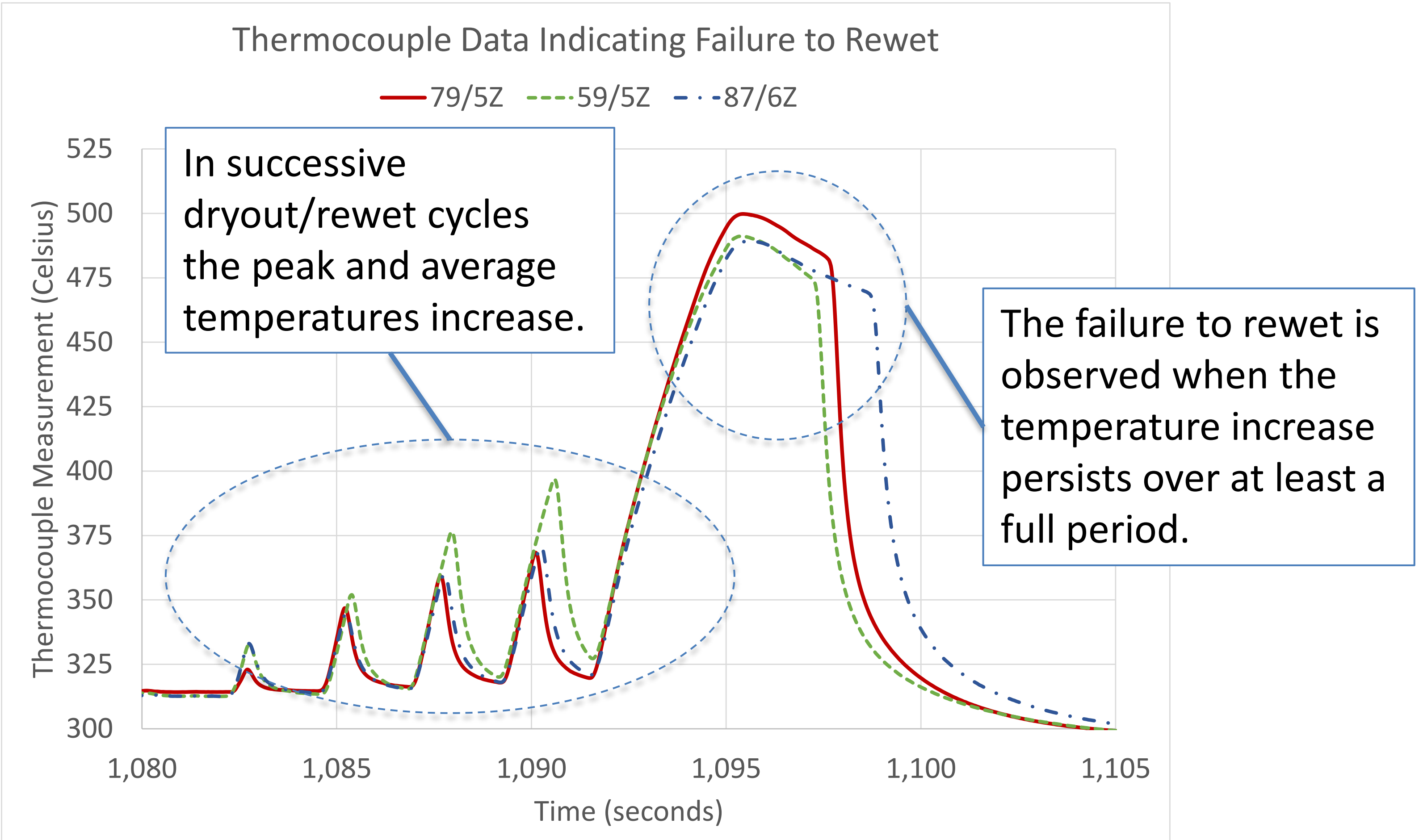
Sample Test without Feedback (407.01)



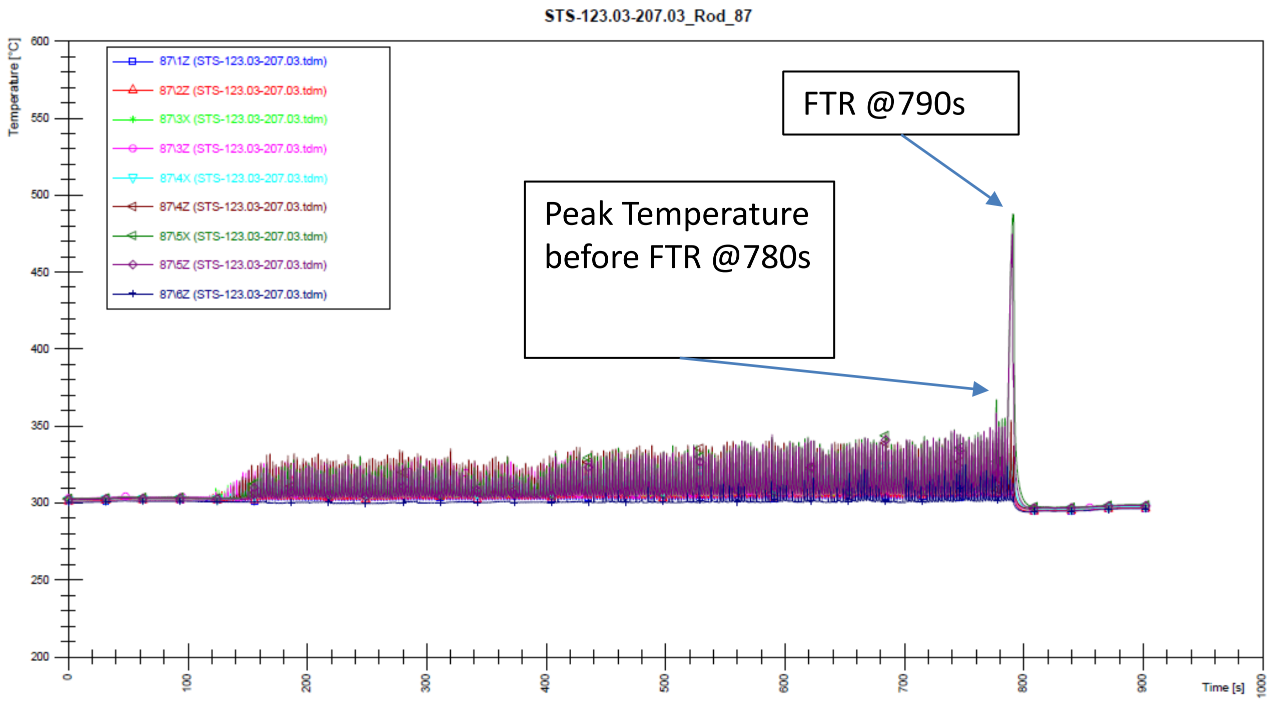
Identification of Failure-to-Rewet Temperature (T_{FTR})

- The predicted fuel heat-up mechanism dictates that fuel heat-up occurs once the cladding surface fails to rewet. This failure to rewet (FTR) occurs in the TRACE predictions once the temperature of the surface exceeds the minimum stable film boiling temperature and the cladding becomes locked in a film-boiling heat transfer regime.
- For each instability test, the staff recorded the maximum thermocouple temperature observed prior to the observed failure to rewet (i.e., the maximum temperature from which the cladding surface was observed to rewet).
- The highest rewet temperature observed in the test should correspond to the T_{FTR} assuming that the rewetting process is purely dictated by the surface temperature.

Failure to Rewet Test 407.01



Thermocouple Measurements for TEST 207.03 ROD 87



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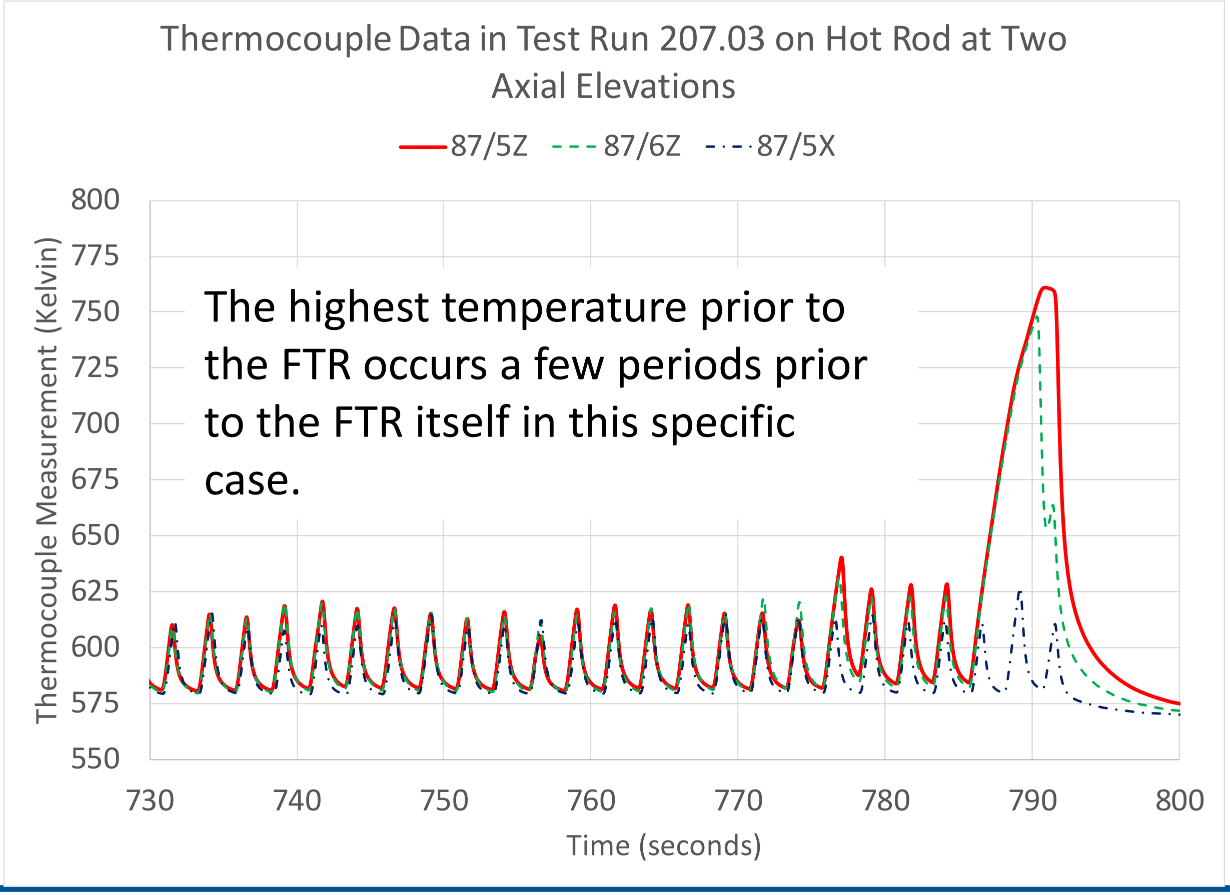
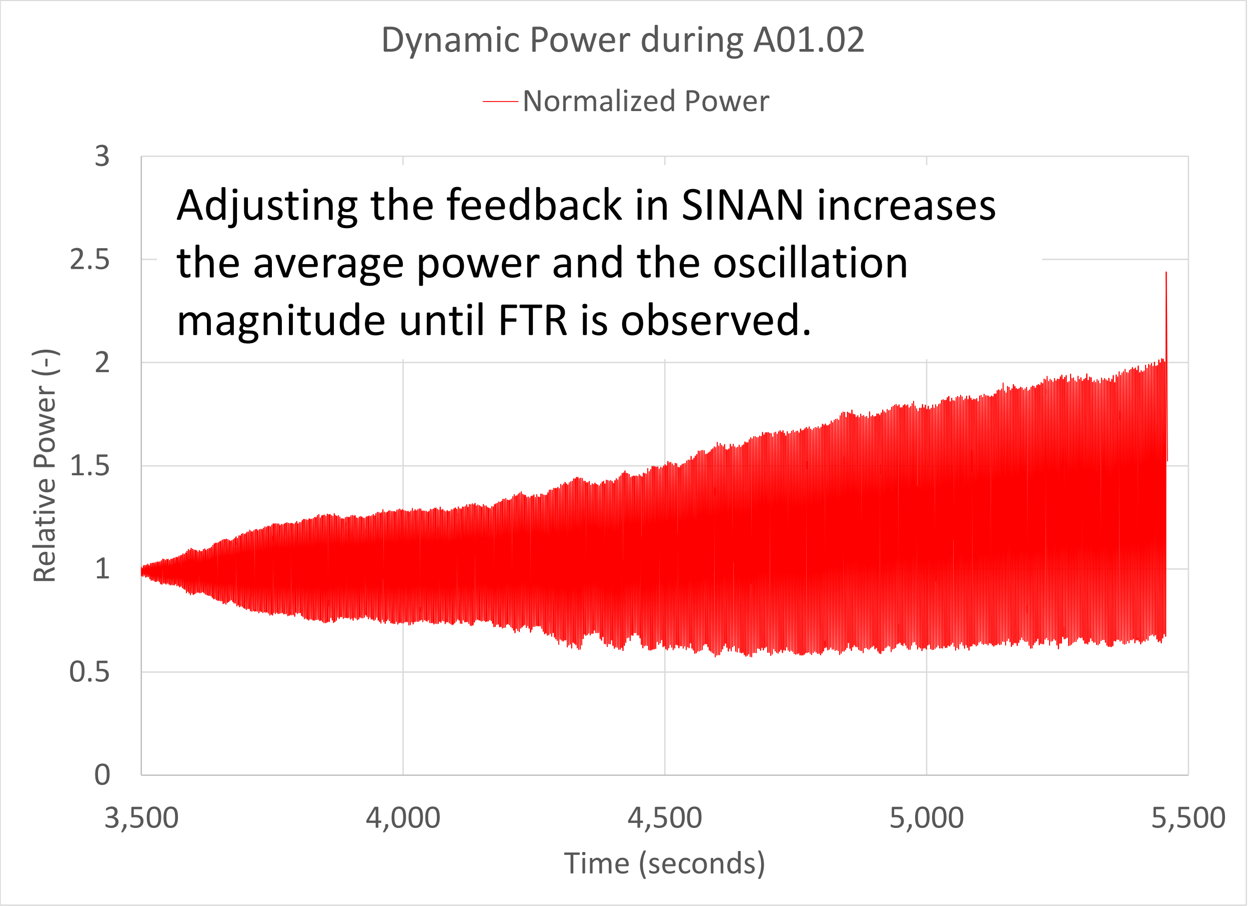
Failure to Rewet Test 207.03



Sample Test with Feedback (A01.02)



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Failure to Rewet Temperature Results

- T_{FTR} Maximum is ~700 K [800 ^{o}F]
- T_{FTR} Minimum is ~600 K [620 ^{o}F]
- T_{FTR} Average is ~650 K [710 ^{o}F]

Peak temperature, T_{FTR}, and surface temperature.

Test Run	Peak Temperature Rod	Maximum Temperature [K]	T_{FTR} Considering All Thermocouples [K]	T_{wall} [a] [K]
101.02[a]	59	760	679	667
110.01	59	725	655	642
207.03	87	761	640	628
310.01	88	764	652	631
407.01	59	764	668	655
A01.02	88	778	619	611
A11.01	88	789	628	619
B01.01	88	781	668	659
B11.01	88	791	627	621
C01.01	88	761	674	665
C11.01	88	788	635	626
D01.01	88	791	674	663
D11.01	88	769	629	619
E01.01	86	780	637	628
E11.01	88	796	658	652
F01.01	88	775	629	618
F11.01	59	772	631	624
F01.03	86	788	617	607
G01.01	88	838	630	620
G11.01	88	787	631	621

[a] See Section 6. The average T_{wall} is 634 ± 19 K.

Homogeneous Nucleation Plus Contact Temperature (T_{HN}+CT)

The staff compared the measured T_{FTR} to the T_{HN}+CT because the homogeneous nucleation temperature is the lowest temperature at which liquid will spontaneous nucleate into vapor. Since homogeneous nucleation is the lowest such temperature, it can be expected to bound the T_{FTR} regardless of any local processes affecting film boiling or rewetting.

$$T_{HN} + CT = T_{HN} + (T_{HN} - T_l)\sqrt{\frac{(k\rho C_p)_l}{(k\rho C_p)_w}}$$

Various Models of T_{min}

T_{min} prediction, in K, by different models.

Correlation	Pressure 7 MPa	7.5 MPa	8 MPa
Groeneveld and Stewart (1982)	684	679	673
Henry (1974)	1199	1205	1209
CTF (Salko and Avramova, 2015)	620	621	622
CTF + contact eff. (Salko and Avramova, 2015)[a]	628	629	629
T_{hn} Lienhard (1976)	605	607	612
T_{hn} Lienhard (1982)	611	612	613
Shumway[b] (Iloeje et al., 1975)	764	752	751
Peterson et al. (2002)[c]	743	737	737

[a] Depends on the surface properties.

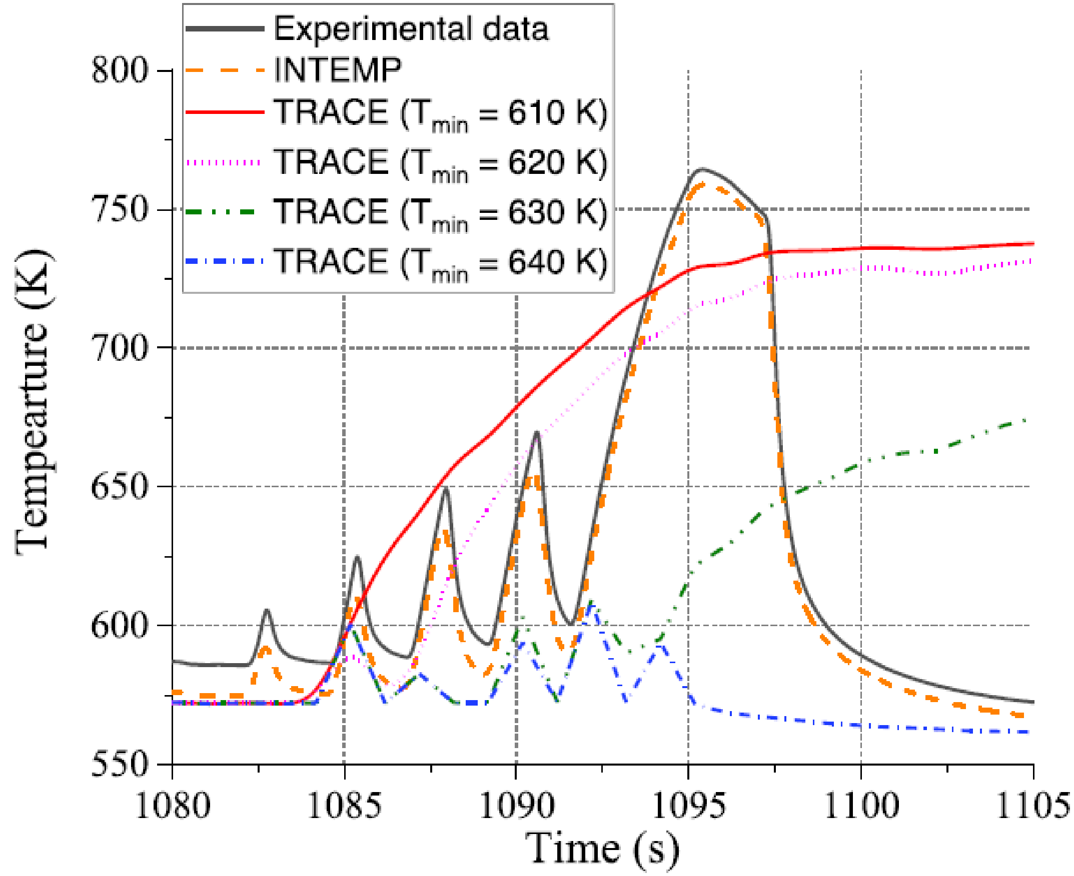
[b] The value reported here for the Shumway correlation does not take credit for the void fraction or velocity terms in the correlation, and is therefore, a lower bound of the correlation prediction.

[c] The value reported here is for when the surface roughness is unknown.

Preliminary TRACE/INTEMP Comparison

Dialing in T_{min} to a value between 600 and 620 K yields TRACE results that predict similar heat-ups with the KATHY measurements.

If T_{min} is too high, TRACE does not predict significant heat-up.



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Interim Approach

- As a conservative approximation, fuel heat-up can be modeled assuming:

  $T_{min} = T_{HN} + CT$
- TRACE has been used successfully to perform confirmatory analyses of ATWS-I events for MELLLA+ BWRs.
- The NRC staff has performed a more detailed assessment of TRACE through a more thorough study of the KATHY experimental results.

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Stage 1 TRACE Assessment

- Step 1: Use steady-state experimental results to adjust empirical parameters (i.e., spacer loss coefficients and critical heat flux multipliers)
- Step 2: Define figures of merit (FOMs) associated with key phenomenology and phases of the transient
- Step 3: Compare TRACE results to experimental results for FOMs using default and interim approaches for T_{min}.

Figures of Merit

No.	Description	Location	Measurement
fom_1	internal heater temperature	maximum	available
fom_2	internal heater temperature	Level 6	available*
fom_3	void fraction	EOHL	not available
fom_4	pressure drop	0.3-2.2m	available
fom_5	pressure drop	2.2-4.1m	available
fom_6	pressure drop	4.2-4.7m	available

Sample TRACE Comparison – Feedwater Temperature Transient

- TRACE with T_{min} = T_{HN}+CT shows slightly earlier heat-up and, consequently, higher temperatures, but timing and rate are in reasonable agreement.
- Higher T_{min} values preclude TRACE prediction of the observed heat-up.

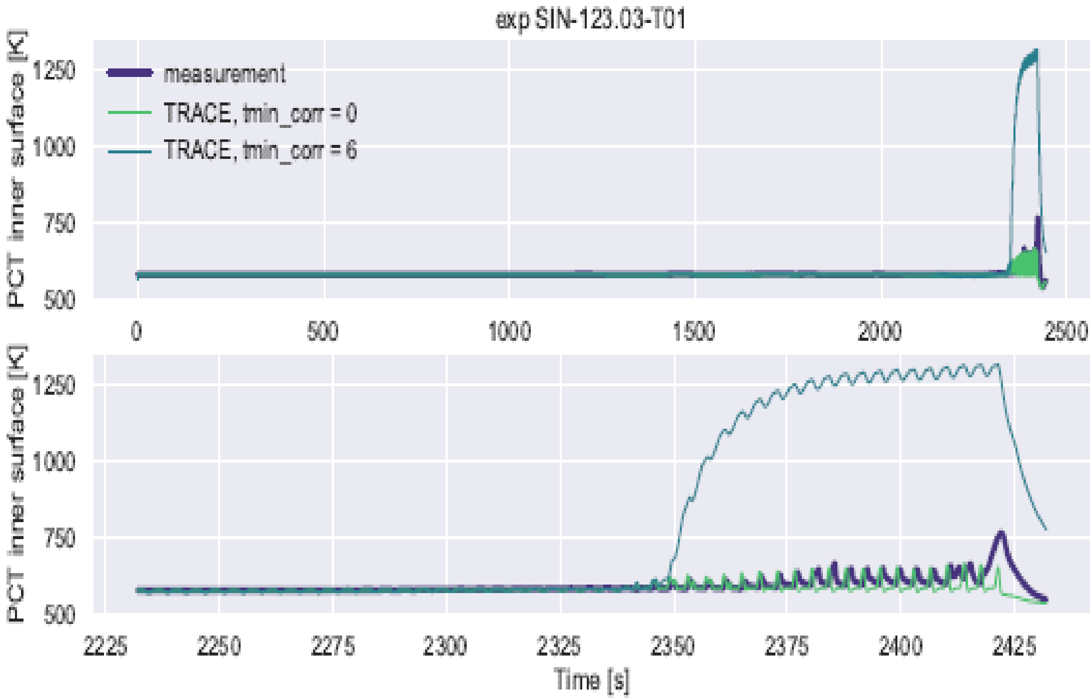


Figure 119: FOM: PCT inner surface [K] (fom_1), exp: SIN-123.03-T01

Summary of TRACE Assessment

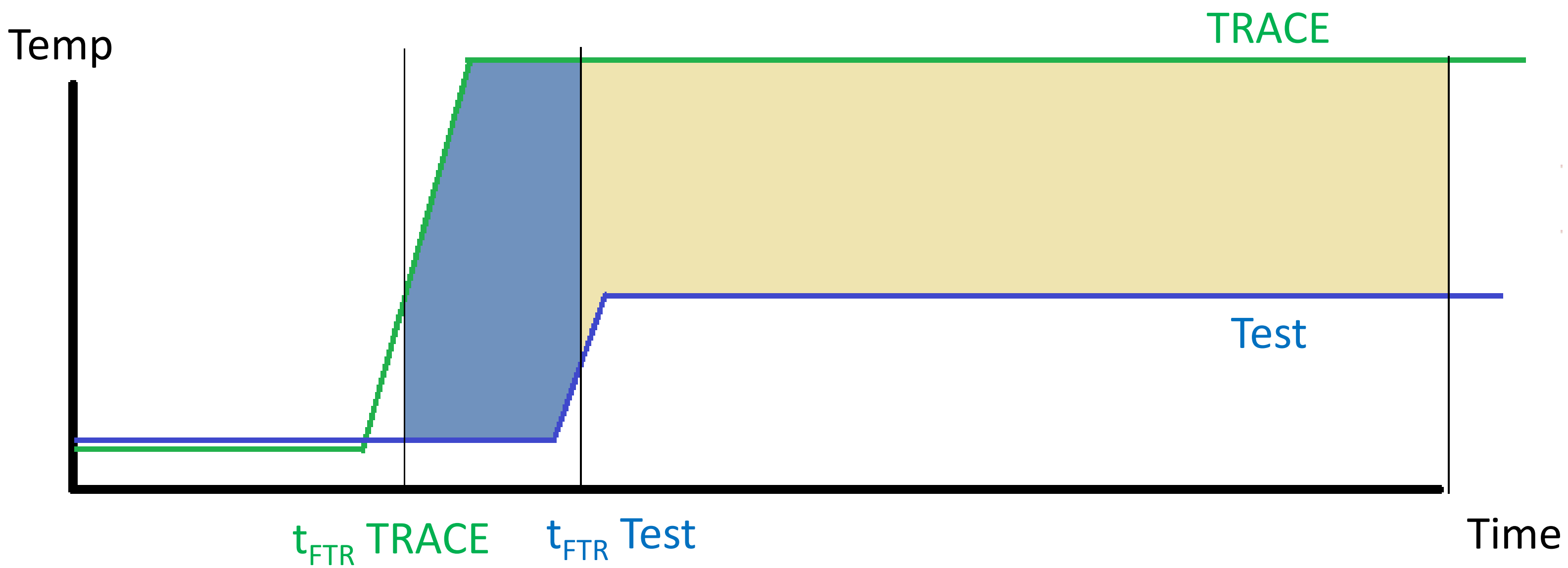
FOM	Phenomena	Level of agreement
Steady-state tests		
pressure drop	-	reasonable
critical power	-	excellent
Instability tests		
fom_1	onset of instability	excellent
fom_2		reasonable
fom_1	dryout/rewet cycles	excellent
fom_2		reasonable
fom_1	failure to rewet	minimal ($T_{min}^{model} = 0$)
fom_2		reasonable ($T_{min}^{model} = 6$)
fom_4 fom_5 fom_6	mean	reasonable
fom_4 fom_5 fom_6	amplitude	reasonable
fom_4 fom_5 fom_6	frequency	excellent

- TRACE in reasonable to excellent agreement for all FOMs when T_{min} is set to the T_{HN}+CT (i.e., Option 6).
- When the default option is used (i.e., Groeneveld-Stewart or Option 0) the temperature related FOMs are in minimal agreement.

Stage 2 TRACE Assessment

- Use statistical methods to study impact of constitutive models on the assessment to identify candidate constitutive models for possible improvements.
- Relies on a two-step process with uncertainty parameters in TRACE, Monte Carlo driven sensitivity calculations, and Morris screening to determine constitutive models with the biggest impact.

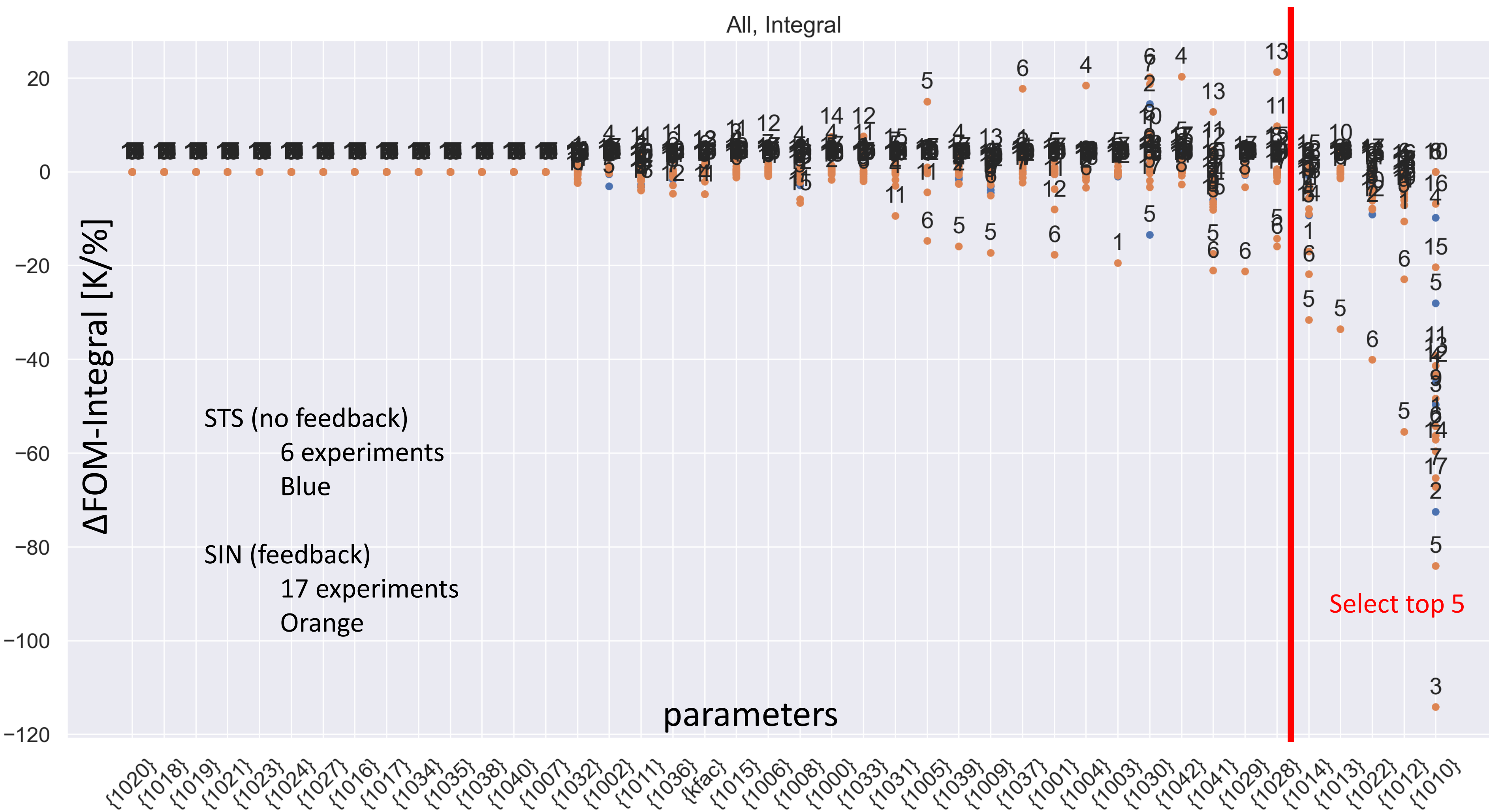
New FOMs

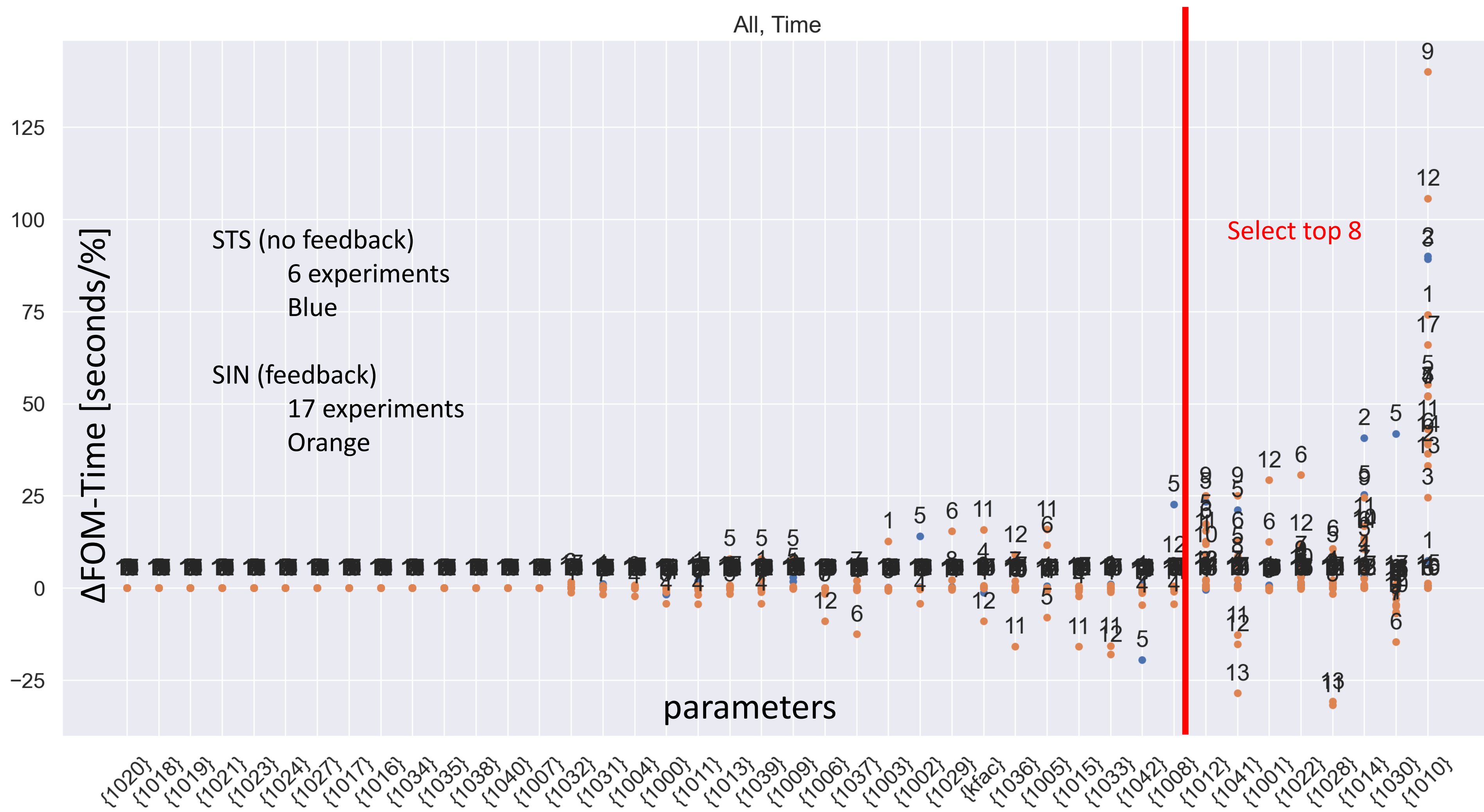


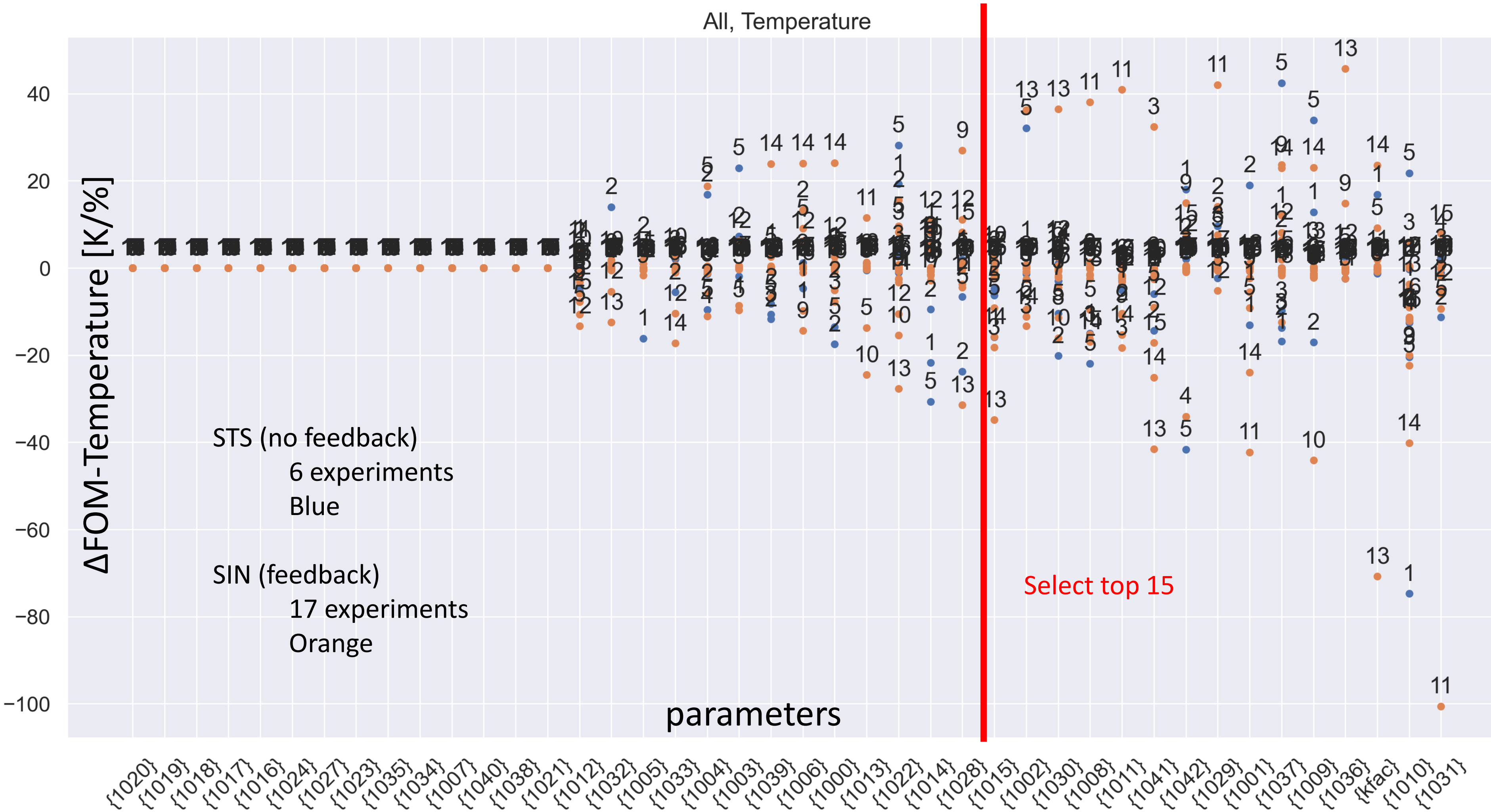
- FOM-Temperature – difference in max cladding inner temperature (~PCT) $T_{max} = max(T(t))$
- FOM-Time – difference in a time of FTR $t_{FTR} = min(time(T(t) > 650K))$
- FOM-Integral – average difference in max cladding inner temperature $I = \int_{t_1}^{t_2} \frac{1}{t_2 - t_1} \Delta T(t) dt$

Two Step Process

- Single Parameter Variation
  - Rank impact of the single parameter on the three FOMs.
  - Slice the important parameters for the second step.
- Multiple Parameter Variation
  - Determine ranges for the important parameters identified in during single parameter variation.
  - Use Monte Carlo techniques and Morris Screening to establish the key parameters.


All, Integral
ΔFOM-Integral [K/%]
STS (no feedback)
6 experiments
Blue
SIN (feedback)
17 experiments
Orange
Select top 5
parameters
{1020} {1018} {1019} {1021} {1023} {1024} {1027} {1016} {1017} {1034} {1035} {1038} {1040} {1007} {1032} {1002} {1011} {1036} {Kfac} {1015} {1006} {1008} {1000} {1033} {1031} {1005} {1039} {1009} {1037} {1001} {1004} {1003} {1030} {1042} {1041} {1029} {1028} {1014} {1013} {1022} {1012} {1010}

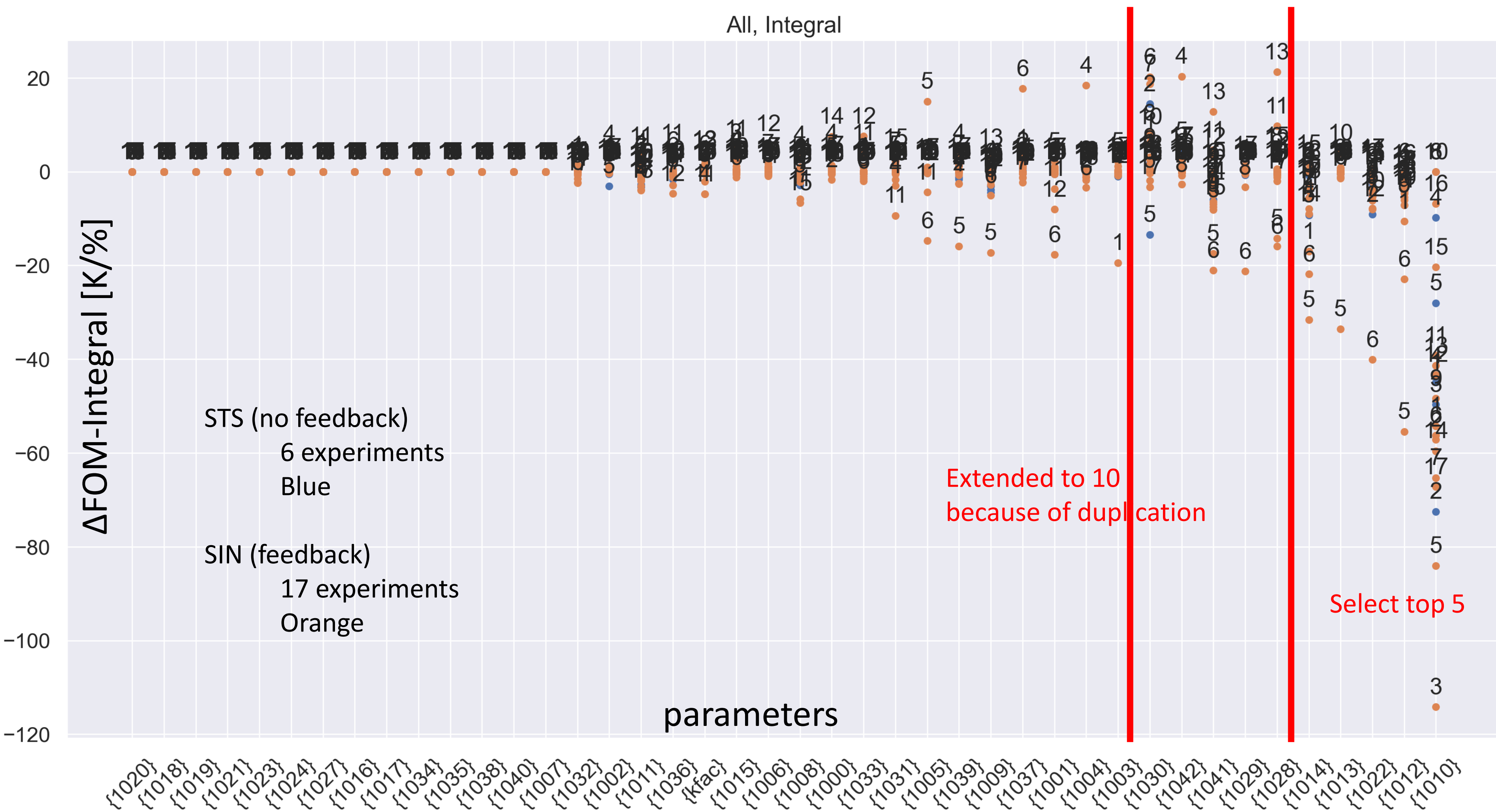

All, Time
ΔFOM-Time [seconds/%]
STS (no feedback)
6 experiments
Blue
SIN (feedback)
17 experiments
Orange
Select top 8
parameters
125
100
75
50
25
0
−25
{1020} {1018} {1019} {1021} {1023} {1024} {1027} {1017} {1016} {1034} {1035} {1038} {1040} {1007} {1032} {1031} {1004} {1000} {1011} {1013} {1039} {1009} {1006} {1037} {1003} {1002} {1029} {kfac} {1036} {1005} {1015} {1033} {1042} {1008} {1012} {1041} {1001} {1022} {1028} {1014} {1030} {1010}

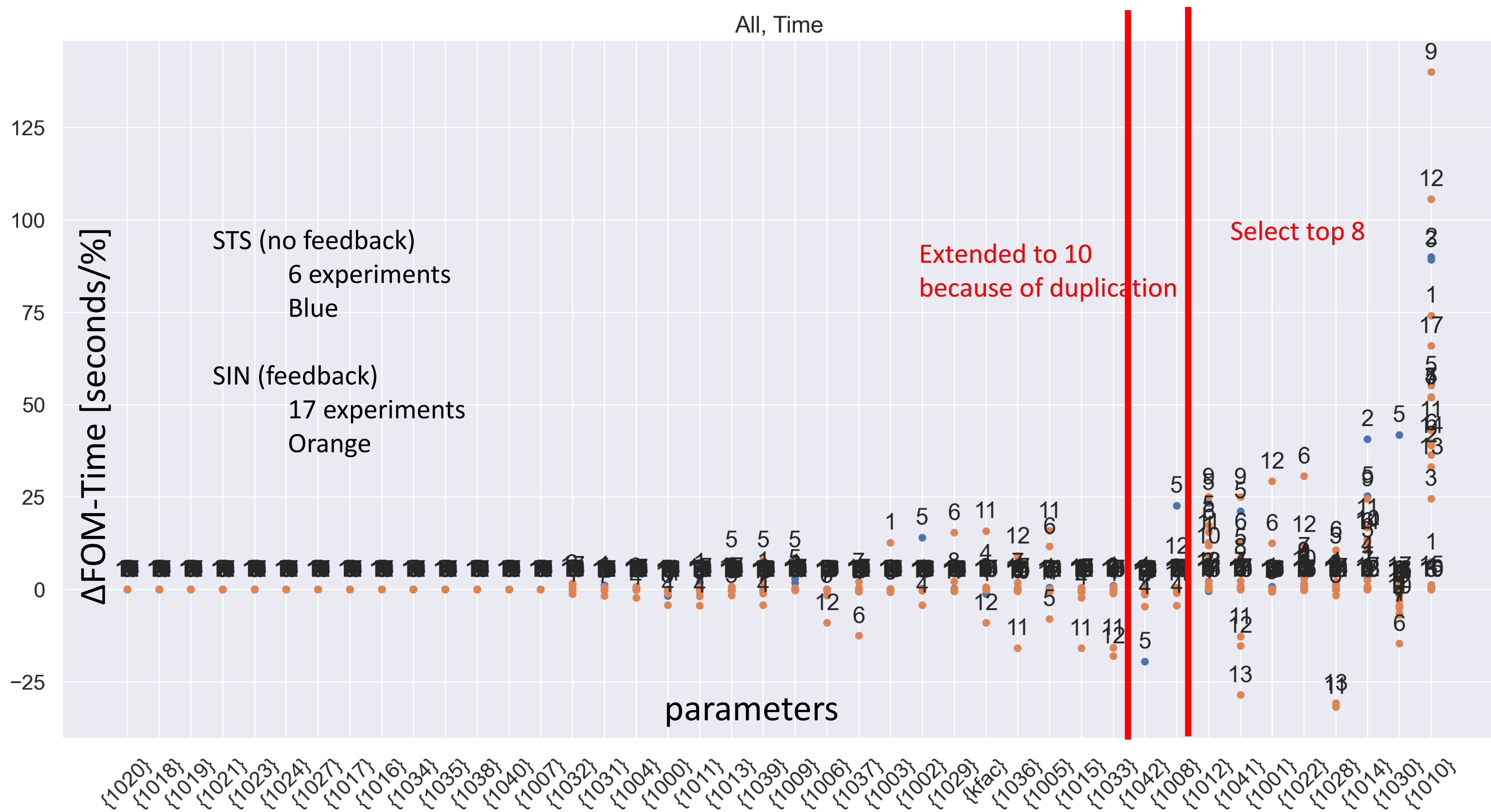

All, Temperature
ΔFOM-Temperature [K/%]
STS (no feedback)
6 experiments
Blue
SIN (feedback)
17 experiments
Orange
Select top 15
parameters
{1020} {1019} {1018} {1017} {1016} {1024} {1027} {1023} {1035} {1034} {1007} {1040} {1038} {1021} {1012} {1032} {1005} {1033} {1004} {1003} {1039} {1006} {1000} {1013} {1022} {1014} {1028} {1015} {1002} {1030} {1008} {1011} {1041} {1042} {1029} {1001} {1037} {1009} {1036} {kfac} {1010} {1031}

Important Parameters

- FOM-Integral
  - Top 5 → 10 parameters
- FOM-Time
  - Top 8 → 10 parameters
- FOM-Temperature
  - Top 15 → 19 parameters

Rank	Integral	Temperature	Time
1	1010	1031	1010
2	1012	1010	1030
3	1022	kfac	1014
4	1013	1036	1028
5	1014	1009	1022
6	1028	1037	1001
7	1029	1001	1041
8	1041	1029	1012
9	1042	1042	1008
10	1030	1041	1042
11	1003	1011	1033
12	1004	1008	1015
13	1001	1030	1005
14	1037	1002	1036
15	1009	1015	kfac
16	1039	1028	1029
17	1005	1014	1002
18	1031	1022	1003
19	1033	1013	1037
20	1000	1000	1006


All, Integral
ΔFOM-Integral [K/%]
parameters
20
0
−20
−40
−60
−80
−100
−120
STS (no feedback)
6 experiments
Blue
SIN (feedback)
17 experiments
Orange
Extended to 10
because of duplication
Select top 5
{1020} {1018} {1019} {1021} {1023} {1024} {1027} {1016} {1017} {1034} {1035} {1038} {1040} {1007} {1032} {1002} {1011} {1036} {Kfac} {1015} {1006} {1008} {1000} {1033} {1031} {1005} {1039} {1009} {1037} {1001} {1004} {1003} {1030} {1042} {1041} {1029} {1028} {1014} {1013} {1022} {1012} {1010}



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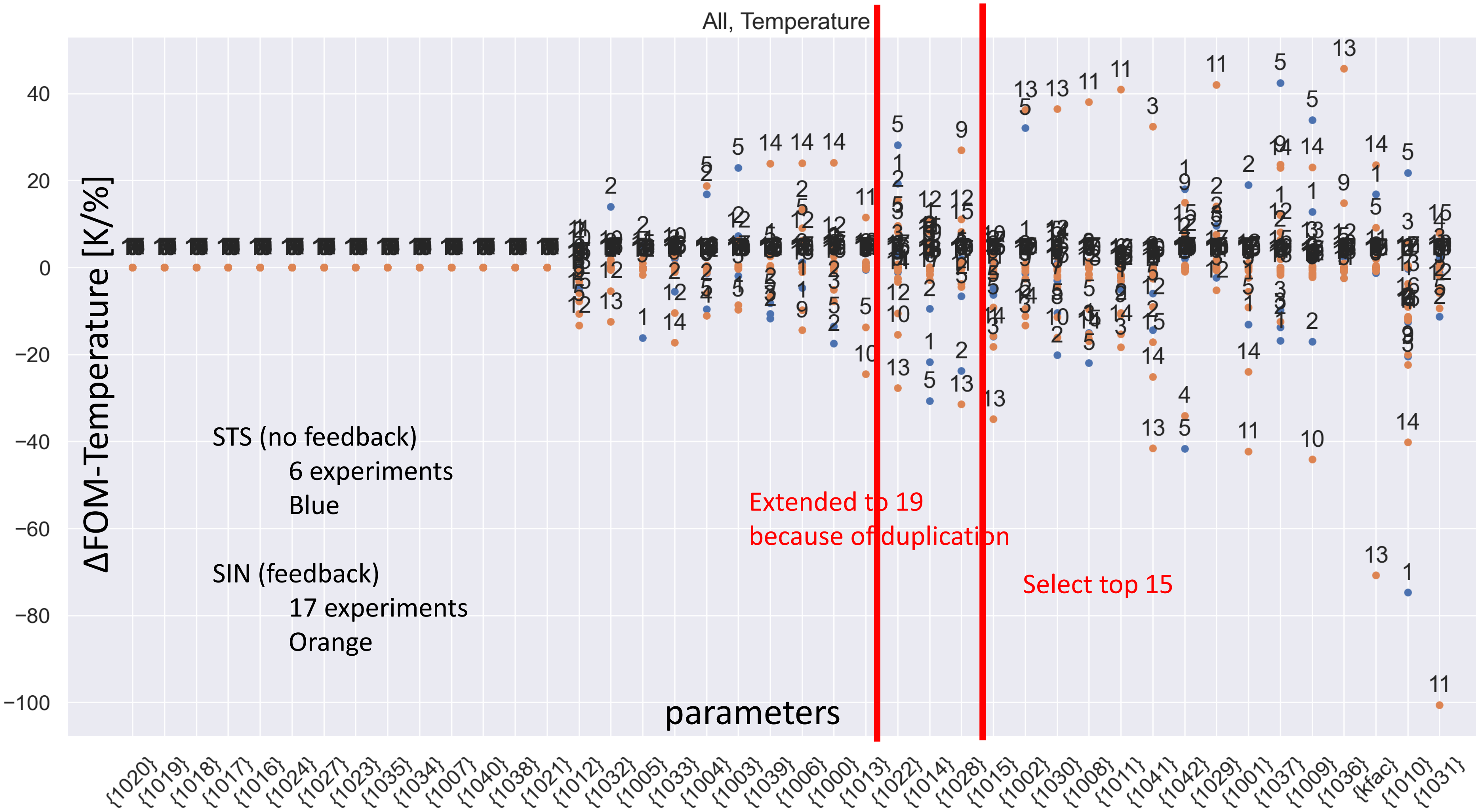
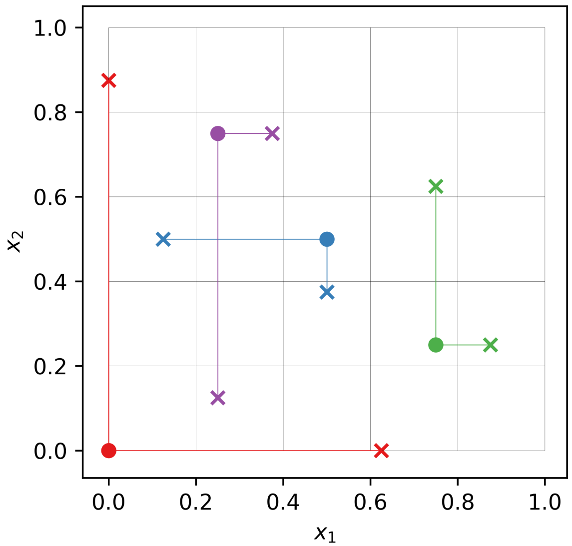
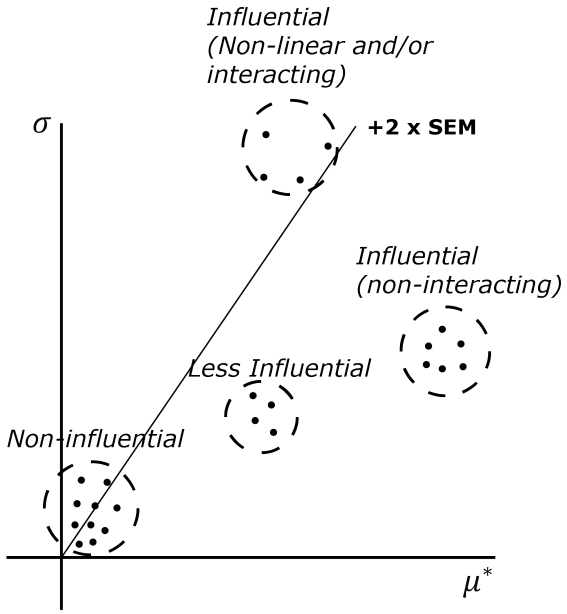

All, Temperature
ΔFOM-Temperature [K/%]
parameters
STS (no feedback)
6 experiments
Blue
SIN (feedback)
17 experiments
Orange
Extended to 19
because of duplication
Select top 15
{1020} {1019} {1018} {1017} {1016} {1024} {1027} {1023} {1035} {1034} {1007} {1040} {1038} {1021} {1012} {1032} {1005} {1033} {1004} {1003} {1039} {1006} {1000} {1013} {1022} {1014} {1028} {1015} {1002} {1030} {1008} {1011} {1041} {1042} {1029} {1001} {1037} {1009} {1036} {kfac} {1010} {1031}

Morris screening

- Qualitative measure of importance (μ/μ^*) and interaction (σ) of input parameters on the output FOM





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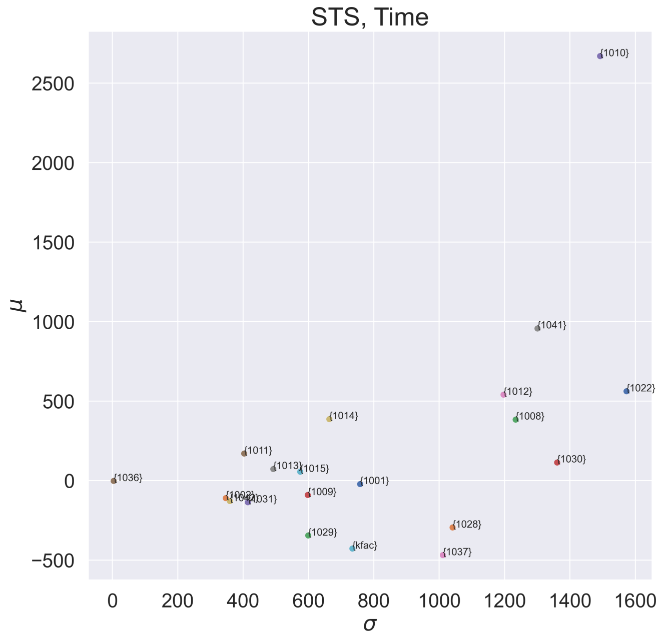
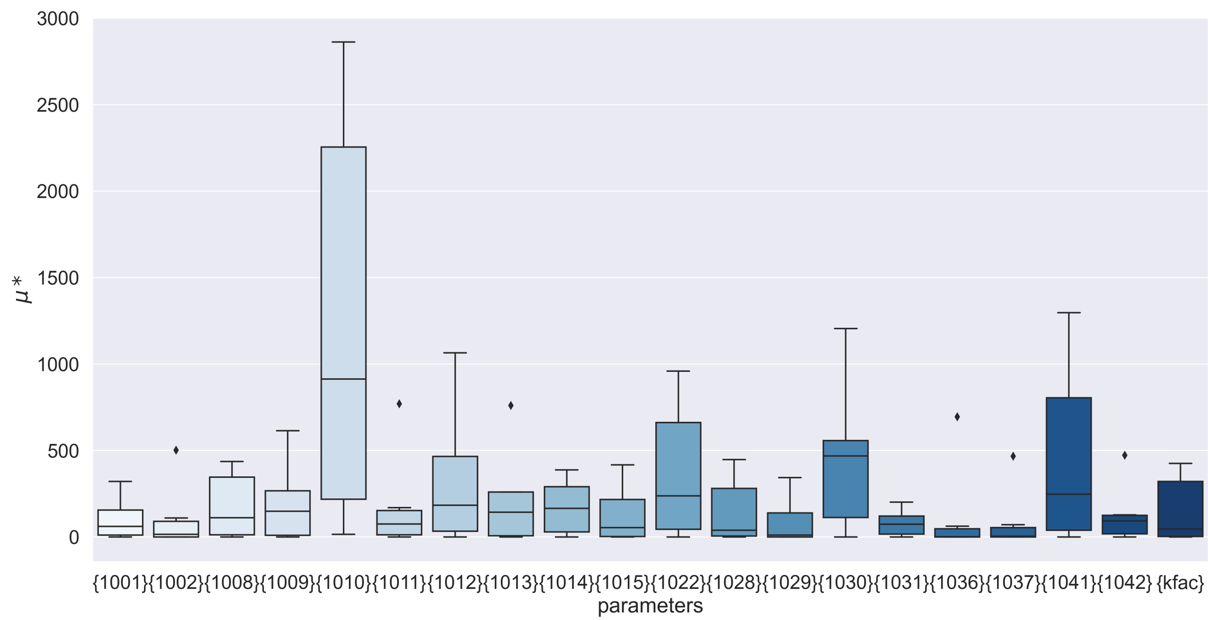
6 Experiments without Feedback

Single experiment



Composite of all experiments



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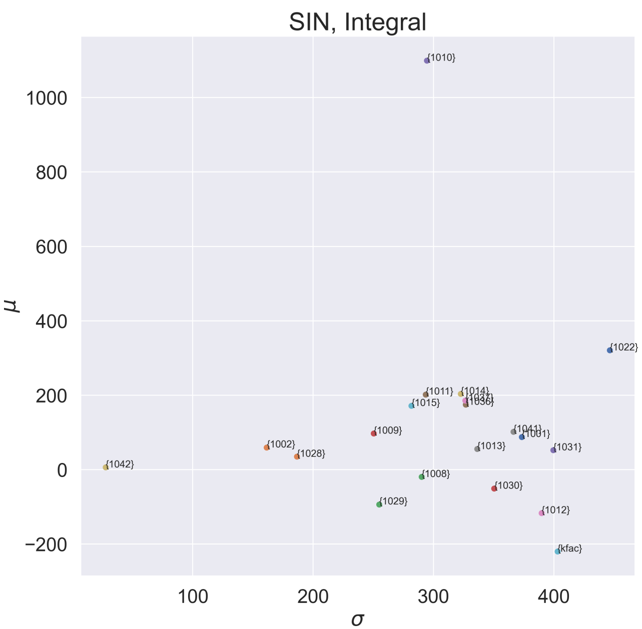
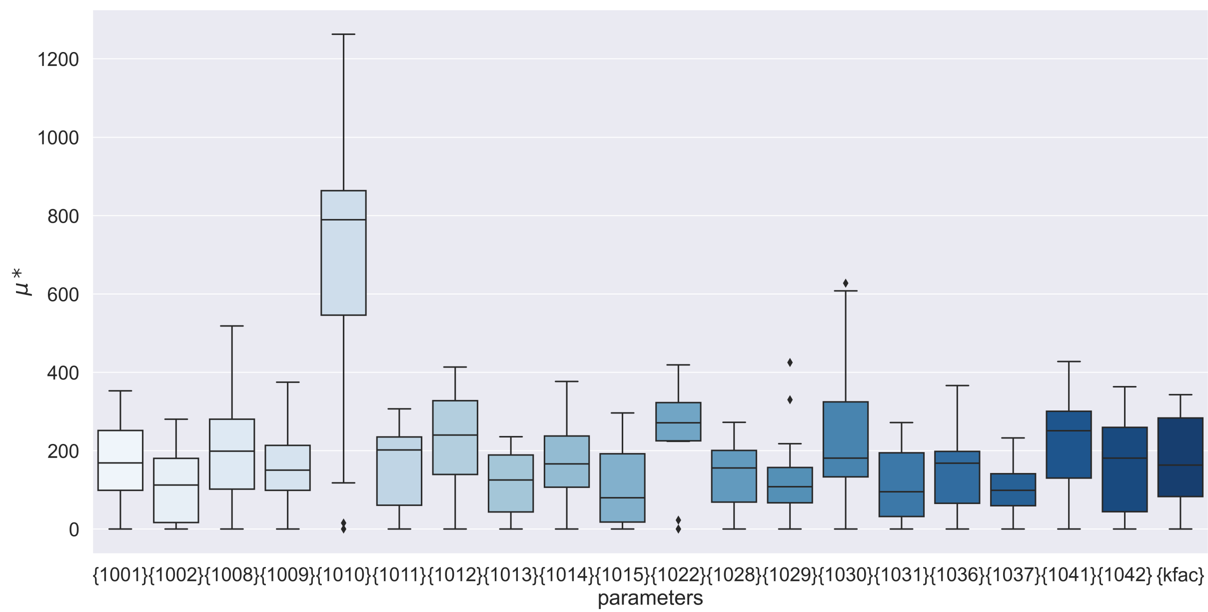
17 Experiments with Feedback

Single experiment



Composite of all experiments



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Key Constitutive Models

- The importance and ranking of the key constitutive models is not surprising
  - **1010 – Minimum Stable Film Boiling**
  - **1030 – Annular/Mist Flow Interfacial Drag**
  - **1041 – Critical Heat Flux**
  - 1012 – Subcooled Boiling Heat Transfer
  - 1022 – Wall Drag

Conclusions

- TRACE produces reasonable, but slightly conservative, predictions of fuel heat-up during postulated ATWS-I when the T_{min} option is set to the T_{HN}+CT.
- This approach will remain our standard practice.
- Detailed assessment indicates that the key models affecting TRACE predictions are consistent with our expectations and Phenomenon Identification and Ranking Table (PIRT).
- Better agreement could be garnered with improvements to the minimum stable film boiling model, but it is not deemed necessary at this stage.

- Questions?

BACKUP SLIDES

Regulatory Purpose

- To provide confirmatory analysis of Anticipated Transients Without SCRAM (ATWS) events for boiling water reactors (BWRs) operating with a maximum extended load line limit analysis plus (MELLLA+) expanded operating domain.
- It is the intent to use TRAC/RELAP Advanced Computational Engine (TRACE) to simulate postulated MELLLA+ ATWS events to study plant transient response, consequences, and effectiveness of mitigating actions.
- The Office of Nuclear Reactor Regulation (NRR) uses the confirmatory analysis results to guide the review. These analyses improve the efficiency of the overall review effort by focusing staff RAIs on key issues and, in certain cases, eliminating the need for some RAIs.

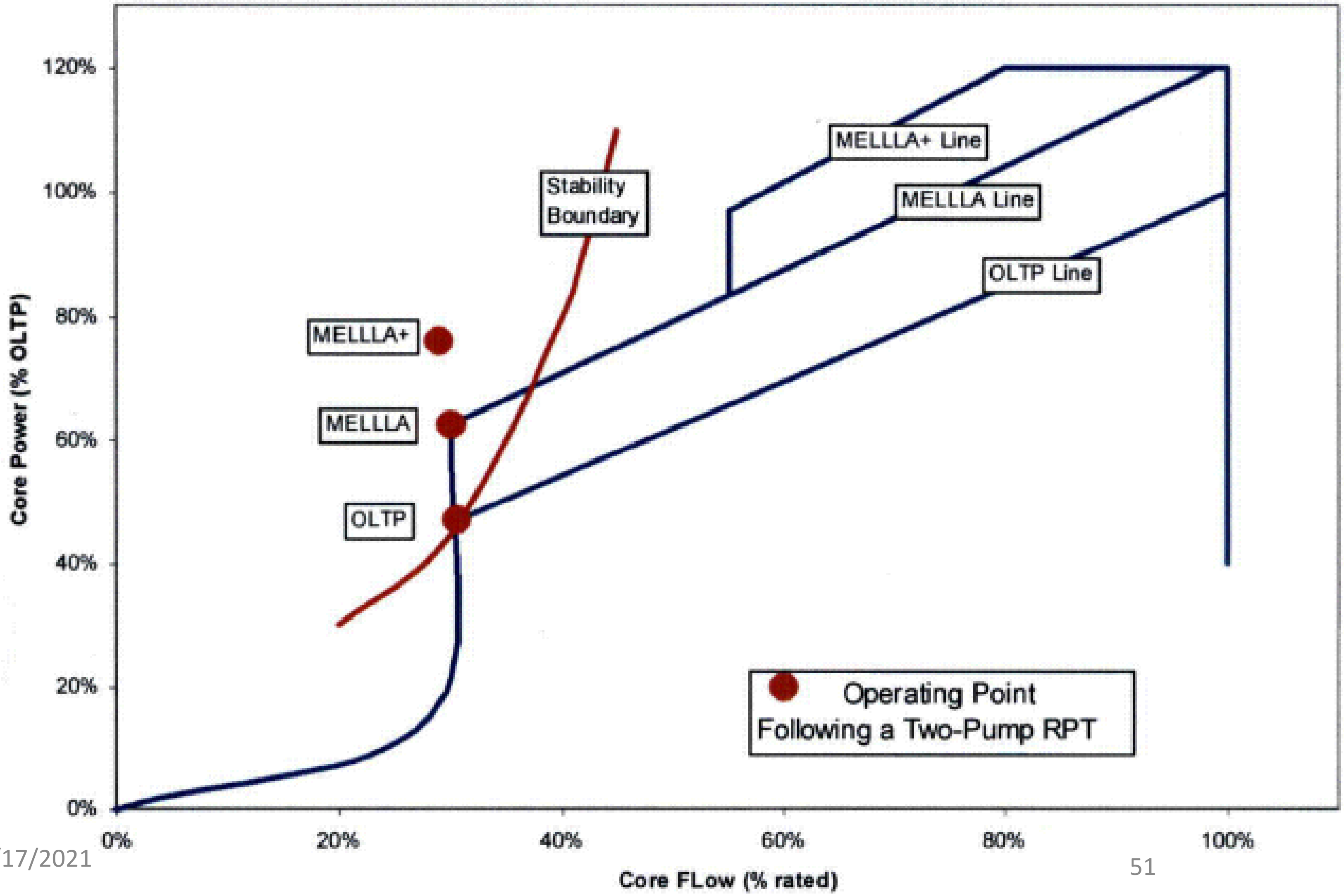
MELLLA+ Domain

- MELLLA+ is an expanded BWR operating domain allowing high thermal power (120% of rated thermal power (RTP)) at low flow (80% of rated core flow (RCF)).
- MELLLA+ operation introduces new aspects to the progression of ATWS events.

Safety Significance of the FCW

- During ATWS events, the reactor power is decreased by a trip of the recirculation pumps (2RPT).
- The power and flow decrease as the pumps run down.
- Power then increases due to a decrease in feedwater temperature.
- When the flow rate is low (80 %RCF), the 2RPT becomes less effective in the reduction of gross core power.

Operating Domain and RPT

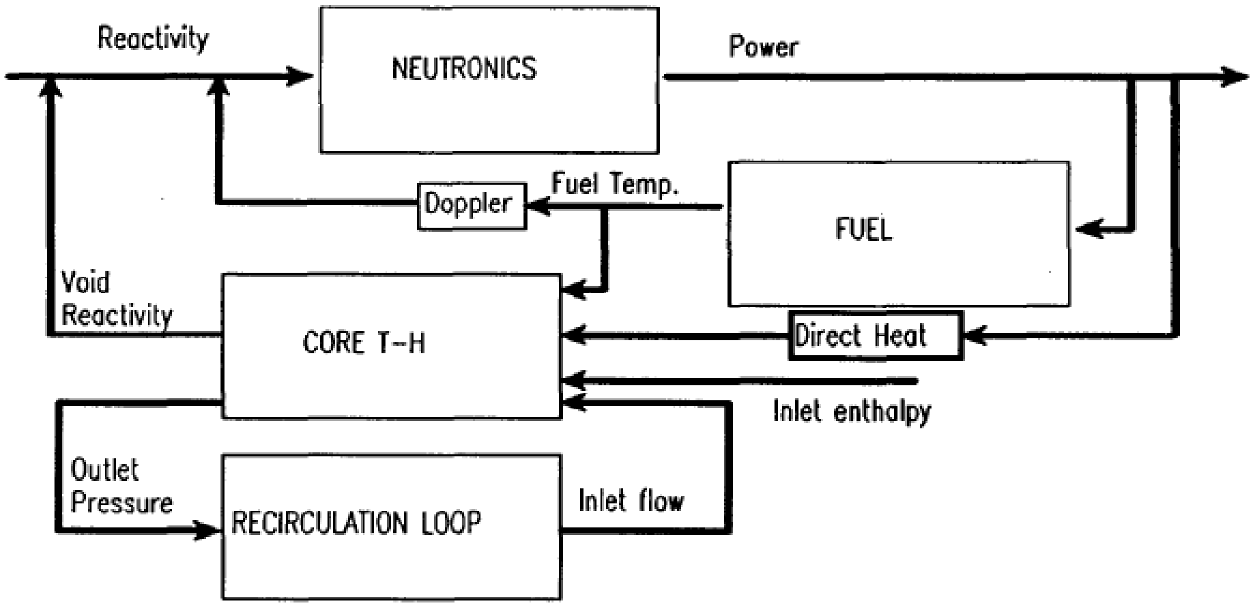


MELLLA+ Benefits

- The flow control window (FCW) allows
  - Global reactivity changes without control blade motion
  - Spectral shift operation
  - Reduces incidence of Fuel-Clad Interaction (FCI) fuel failure
- Reduced control blade pattern swaps
  - Reduces incidence of pellet-clad interaction fuel failure
- Low-flow depletion (spectral shift)
  - Improves fuel cycle economics

Feedback and Instability

Higher thermal power following 2RPT greatly increases the chances that the reactor will undergo unstable power oscillations. ATWS leading to instability is ATWS-I



ATWS-I Results

- Representative Case:
  - Generic BWR/5 model
  - TTWBP with 100% bypass capacity
  - Initial core flow rate is 85% rated
  - Initial power is 120% of originally licensed thermal power (OLTP)
  - Core exposure is peak-hot-excess (PHE)
  - Operators attempt to control reactor water level to top of active fuel (TAF) starting 110 seconds into event
  - Operators initiate SLCS at 120 seconds into event

PHE ATWS-I Case – Sequence of Events

Time (s)	Event
0.0	• Null transient simulation starts.
10.0	• Null transient simulation ends. • Turbine trip is initiated by closing the TSV. • Recirculation pumps are tripped on the turbine trip. • Feedwater temperature starts decreasing.
10.1	• TSV closes completely and starts opening again to simulate 100% turbine bypass.
11.1	• TSV (bypass) completes opening.
~11.4	• Steam flow starts decreasing.
~12.3	• Feedwater flow starts decreasing.
~95	• Power oscillation (instability) starts.
120	• Water level reduction (WLR) is initiated by reducing the normal water level control system setpoint linearly to TAF over 180 s.
130	• Boron injection is initiated and linearly ramped to full flow at 190 s.
~144	• Bi-modal oscillation of the core power is initiated.
~160	• Boron starts accumulating in the core.
~163	• Downcomer water level begins decreasing. • Peak cladding temperature of ~1700 K occurs.
~240	• Power oscillation ends.
400	• Simulation ends.

Base Case Conclusions

- Point in cycle studies confirm that PHE is the most limiting state-point
  - Large amplitude regional power oscillations develop (modal coupling with frequency doubling).
  - High amplitude power oscillations (local) results in calculation of high PCT (~1700 K [2600 °F]).
- Operator action to reduce level
  - Effective in reducing FW flow, limiting increase in core inlet subcooling and eventually eliminating inlet subcooling.
- Operator action to inject boron through SLCS
  - Effective in suppressing power oscillations and reducing core power level.

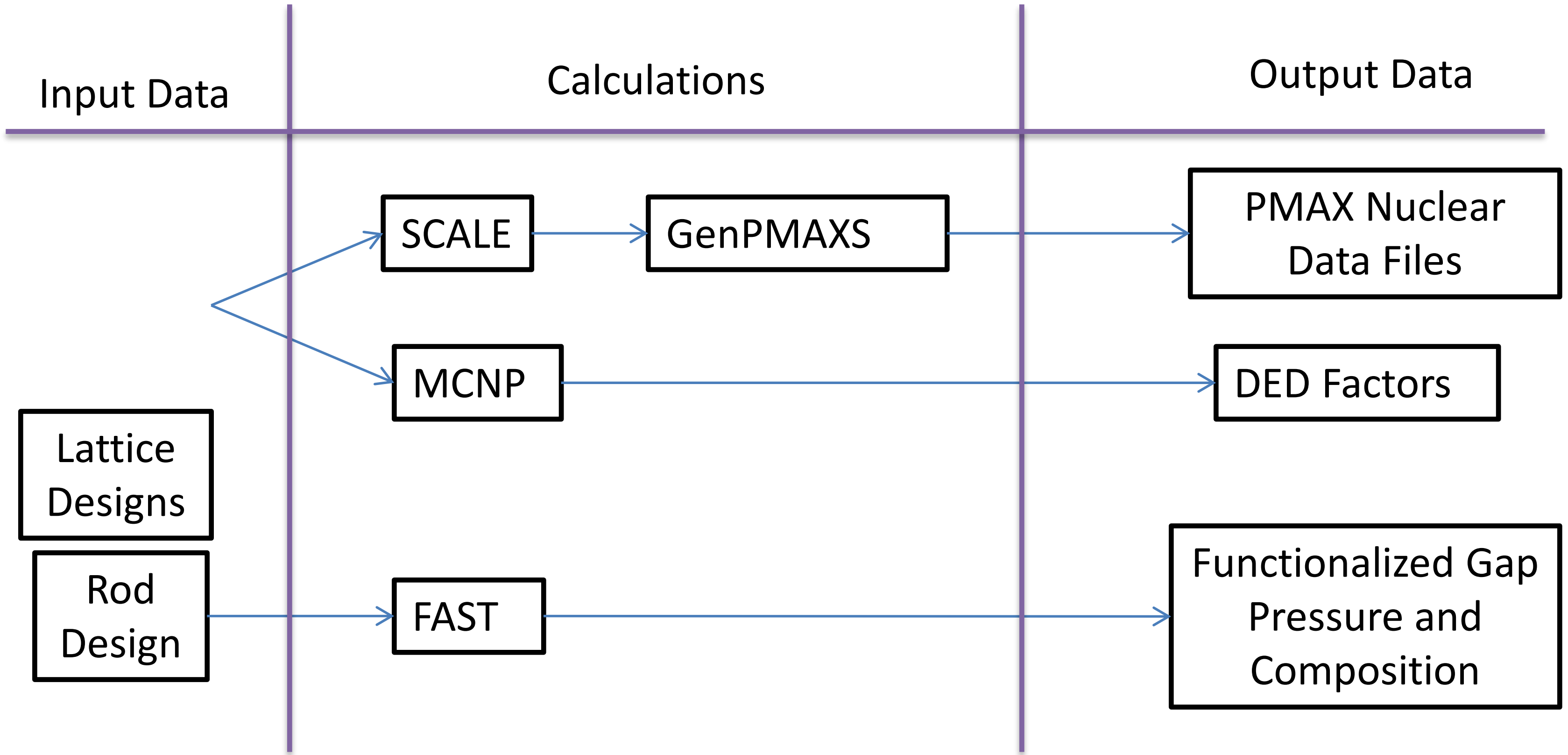
Methodology Overview: Codes

- TRACE
  - TRACE simulates the thermal-hydraulic response of the plant and core
- PARCS
  - PARCS simulates the neutron kinetics in three-dimensions
- SCALE/Polaris
  - The Polaris sequence calculates parameterized nuclear data
- MCNP
  - Coupled gamma/neutron transport calculations with MCNP establishes direct energy deposition factors
- FAST
  - FAST simulates fuel thermo-physical behavior over exposure and is used to calculate initial gas gap properties and other related thermal-mechanical conditions

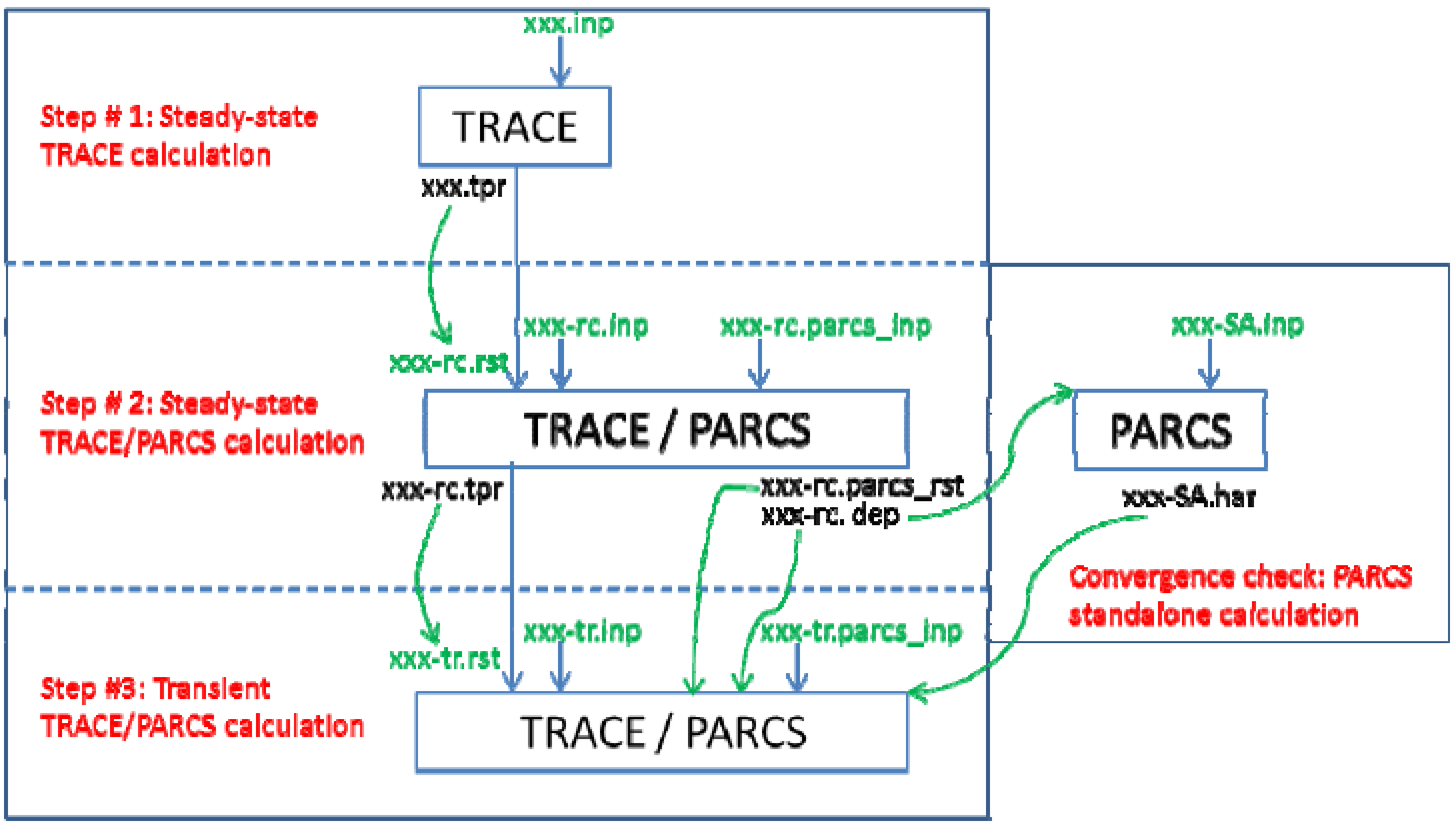
Methodology Overview: Tools

- Scripting Tools
  - Scripting tools are used for automatic generation of core inputs for TRACE
- SNAP
  - Visualization tool used for generating TRACE thermal-hydraulic, control system, and heat structure models
- GenPMAXS
  - Code that converts SCALE output into PMAX files for use in PARCS

Methods: Fuel Properties



Methods: Systems Analysis



Comparison of T_{min} to T_{FTR} Data

Correlation	Mean Bias (Measured-Predicted) [K]	Root-Mean-Square Difference [K]
Groeneveld-Stewart	-37	45
COBRA/TRAC	14	27
Lienhard 1976	32	39
Lienhard 1982	25	34
Peterson-Bajorek	-97	100
Shumway	-117	119

Cladding temperature measured at inside surface, so outside surface expected to be ~10K higher, so a bias on this order is expected. T_{HN}+CT models compare well.

KATHY Test Indices

Experiment	Corresponding files
w/o feedback	
STS-123.03-1	104.02, 104.03, 105.01, 105.02, 106.01, 107.01, 108.01, 109.01, 110.01
STS-123.03-2	203.01, 203.02, 204.01, 205.01, 206.01, 207.01, 207.02, 207.03
STS-123.03-3	310.01
STS-123.03-4a	401.01, 402.01, 403.01, 404.01, 405.01, 406.01
STS-123.03-4b	407.01
STS-123.03-5	101.02*
with feedback	
SIN-123.03-A01a	A01.01
SIN-123.03-A01b	A01.02*
SIN-123.03-E01	E01.01
SIN-123.03-C01	C01.01
SIN-123.03-D01	D01.01
SIN-123.03-B01	B01.01
SIN-123.03-F01	F01.01
SIN-123.03-G01	G01.01
SIN-123.03-A11	A11.01
SIN-123.03-E11	E11.01
SIN-123.03-C11	C11.01
SIN-123.03-D11	D11.01
SIN-123.03-B11	B11.01
SIN-123.03-F11a	F11.01
SIN-123.03-F11b	F11.03
SIN-123.03-G11	G11.01
SIN-123.03-T01	T01.01, T01.02

Uncertainty Ranges

Para	dist	para	reference
1001	$\mathscr{U}$	±24%	Hou et al. (2017)
1002	$\mathscr{U}$	±24%	Hou et al. (2017)
1008	$\mathscr{U}$	±24%	Hou et al. (2017)
1009	$\mathscr{U}$	±24%	Hou et al. (2017)
1010	$\mathscr{U}$	±12%	[1]
1011	$\mathscr{U}$	±24%	Hou et al. (2017)
1012	$\mathscr{U}$	±24%	(Hou et al., 2017)
1013	$\mathscr{U}$	±24%	(Hou et al., 2017)
1014	$\mathscr{U}$	±16.66%	[2]
1015	$\mathscr{U}$	±24%	Hou et al. (2017)
1022	$\mathscr{U}$	±26.66%	(Porter et al., 2018)
1028	$\mathscr{U}$	±32%	(Porter et al., 2015)
1029	$\mathscr{U}$	±32%	(Porter et al., 2015)
1030	$\mathscr{U}$	±32%	(Porter et al., 2015)
1031	$\mathscr{U}$	±32%	(Porter et al., 2015)
1036	$\mathscr{U}$	±24%	Hou et al. (2017)
1037	$\mathscr{U}$	±24%	Hou et al. (2017)
1041	$\mathscr{U}$	±36%	Driscoll and Landrum (2004)
1042	$\mathscr{U}$	±25%	Saha and Zuber (1974)
kfac	$\mathscr{U}$	±5%	Borowiec et al. (2020)

Film Boiling Heat Transfer Coefficient

- Average from Experiment: ~2.0 kW/m^2-K
- Average from TRACE: ~1.3 kW/m^2-K
- TRACE in good agreement, slightly conservative

Average heat transfer coefficients after FTR.

Run No.	HTC after FTR (kW/m^2.K)
101.02	3.2
110.01	3.3
207.03	2.6
310.01	3.6
406.01	1.6
407.01	1.6
A01.02	0.7
A11.01	1.2
B01.01	3.0
B11.01	1.4
C01.01	2.2
C11.01	0.9
D01.01	1.6
D11.01	2.0
E01.01	1.0
E11.01	0.9
F01.01	2.1
F11.01	1.0
F11.03	0.8
G01.01	1.5
G11.01	0.8

Test 11 – Regional Coupling Test

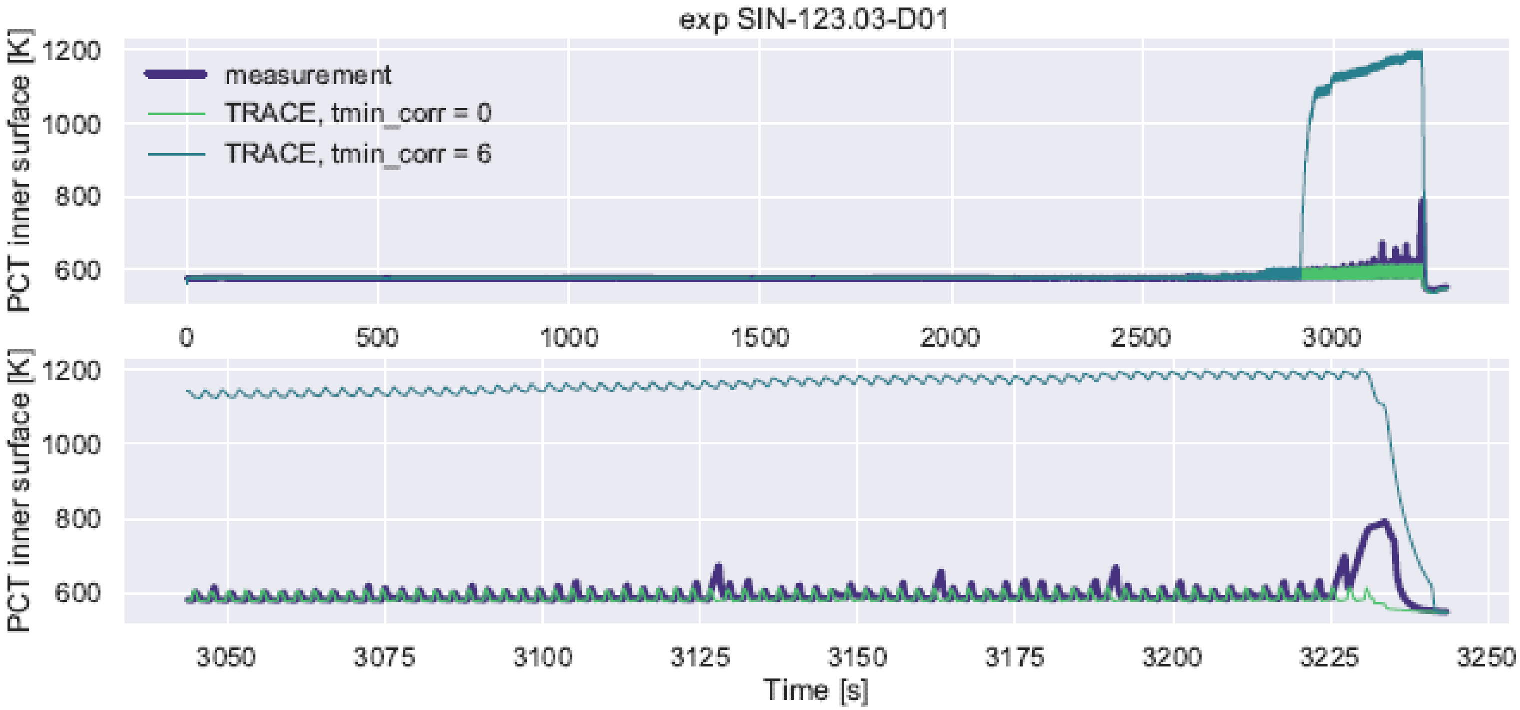


Figure 108: FOM: PCT inner surface [K] (fom_1), exp: SIN-123.03-D01

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