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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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FUELS, MATERIALS, AND STRUCTURES SUBCOMMITTEE

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OPEN SESSION

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THURSDAY

AUGUST 24, 2023

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The Subcommittee met via hybrid in-person and Video Teleconference, at 8:30 a.m. EDT, Ronald Ballinger, Chairman, presiding.

COMMITTEE MEMBERS:

RONALD G. BALLINGER, Chair

CHARLES H. BROWN, JR., Member

VICKI BIER, Member

VESNA DIMITRIJEVIC, Member

GREGORY HALNON, Member

WALT KIRCHNER, Member

JOSE MARCH-LEUBA, Member

DAVID PETTI, Member
JOY L. REMPE, Member
THOMAS ROBERTS, Member
MATTHEW SUNSERI, Member

ACRS CONSULTANT:
DENNIS BLEY
STEVE SCHULTZ

DESIGNATED FEDERAL OFFICIAL:
ZENA ABDULLAHI
WEIDONG WANG

ALSO PRESENT:
TIMOTHY CREDE, Westinghouse
LESLIE FIELDS, NRR
GEROND GEORGE, NRR
JOSEPH MESSINA, NRR
BRIAN MOUNT, Dominion Energy
PATRICK RAYNAUD, RES

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

8:31 a.m.

CHAIR BALLINGER: The meeting will now come to order, everybody. This is the meeting of the Fuels, Materials and Structures Subcommittee of the Advisory Committee on Reactor Safeguards. I'm Ron Ballinger, chairman of today's subcommittee meeting.

ACRS members present and in attendance are Tom Roberts, Jose March-Leuba, Matt Sunseri, Dave Petti, Joy Rempe. I don't know if Robert, Bob Martin is going to be here or not. Vicki Bier, Greg Halnon, and Charles Brown. And on line will be I'm sure Vesna Dimitrijevic, yes, and Walt -- yes, Walt Kirchner.

Our consultants, Stephen Schultz and Dennis Bley are also -- Steve is here in person and Dennis is online.

Weidong Wang is the Designated Federal Official present in person and Zena Abdullahi is present virtually, as opposed to virtually present, as DFO as well.

During today's meeting, the subcommittee will review the NRC's staff safety evaluation for approving PWROG's hydrogen-based transient cladding strain limit topic report. The subcommittee will hear presentations by and hold discussions with the NRC staff, PWROG, and their consultants.

Part of the presentations by the applicant and the NRC staff may be closed to discuss information as proprietary to the licensee and its contractors pursuant to 5 U.S.C. 552(b)(c)(4).

Attendance at the meeting that deals with such information will be limited to the NRC staff and its consultants, PWROG, and those individuals and organizations who have entered into an appropriate confidentiality agreement with them. Consequently, we will need to confirm that we have only eligible observers and participants in the closed part of the in-person meeting, as well as those attending virtually.

The ACRS Section of the U.S. NRC public website provides our charter, bylaws, agendas, letter reports, and full transcripts of all full and subcommittee meetings including slides presented here. The meeting notice and agenda for this meeting are posted and we have not received any requests for any written statements or requests to make oral statements from the public prior to this meeting.

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

A transcript of the meeting is being kept and the open portion will be made available. Today's meeting is being held in person and over Microsoft Teams for ACRS staff and members, NRC staff, and the applicant. There is also a telephone bridge line and a Microsoft Teams link allowing participation of the public to join the open session.

When addressing the subcommittee, the participants should first identify themselves and speak with sufficient clarity and volume so that they may be readily heard. When not speaking, we request that participants mute their computer microphones or by phone press *6.

We'll now proceed with the meeting and I'd like to start by calling on Gerond George. You're there, I saw you, to make the NRC opening remarks. Before you go, we will have to decide at the end of this whether we recommend a letter, but we have information indicating that they would like a letter, so keep that in your mind when you ask questions and that's part of the presentation, because we're going to have to come up with a letter.

MR. GEORGE: Thank you, Chairman Ballinger. Before I get to my opening remarks, I would say there was a request not to have a letter. We did not need to have a letter.

CHAIR BALLINGER: You're apparently not close enough to the microphone.

MR. GEORGE: Okay, can you hear me now? Hello.

CHAIR BALLINGER: Yes, that's an AT&T advertisement.

MR. GEORGE: Yes, Gerond George, Branch Chief, Licensing Projects Branch. Before I get to my opening remarks, I think there's a little confusion. I guess we had stated we did not need a letter for this review.

CHAIR BALLINGER: Oh, okay. I've been under the impression all along that you wanted a letter when you read the 635 page NRC NUREG on statistics.

MR. GEORGE: I'm not sure what you're talking about, but I'll get to my opening remarks and I guess we can handle the letter later.

CHAIR BALLINGER: Okay, sure. By the way, whether we have a letter or not is not up to me. It's actually not up to you. It's up to the subcommittee.

MR. GEORGE: Subcommittee. That's right, that's right. Understand. Thank you.

Thank you, Chairman Ballinger, thanks for having us today. The NRC staff will present the safety evaluation for the Pressurized Water Reactor Owners Group 21001, the hydrogen-based transient cladding strain limit.

The topical report proposes an alternative to the hydrogen-based cladding strain limit currently used in our regs, regulation. We would like to thank the PWR Owners Group for providing the information and committing the resources for this review. Because of these efforts, our tech reviewers were able to complete a comprehensive and efficient review in a very short amount of time. So thank you, guys, very much for that.

And that would be it for my opening remarks. Thank you for your time today.

CHAIR BALLINGER: Okay, now I'm in a bit of a quandary. Who's doing the presentation first? I mean it's the PWROG folks, but I don't see anybody.

MR. GEORGE: I believe they are behind you. They need to walk up to the front. We won't make you guys turn around.

MR. MOUNT: Is this close enough to the mic?

CHAIR BALLINGER: That sounds pretty good.

MR. MOUNT: Good morning. My name is Brian Mount. I'm the chairman for the Analysis Committee of the PWROG and I work for Dominion Energy. I'd like to thank the ACRS for taking an interest in our topical report and the NRC' SC on it.

Just to give you a brief little history of how we got here, as we've been looking at trying to improve our fuel economics, we keep pushing up against various limits and most recently that was the cladding strain limit that we've pushed into. Whenever we approach a limit, we always try to find ways to recover margin either through improvements and analytical inputs or if there's ways to improve the limit itself.

As part of this, we went off and started looking at what other activities were going on in the industry, within the NRC, and we saw that there are already hydrogen-based limits out there. We also came across the National Lab, the PNNL report, where they were looking at hydrogen-based credit -- or clad strain limit. With these ideas and these limits, we were thinking this was an excellent opportunity for us to improve our design limits and support even further fuel economic improvements or now what we are hearing is longer operating cycles, potential power uprates.

Ironically, every time we find a way to improve our margins, somebody is coming to look for it.

So as the NRC mentioned earlier, we are very appreciative of the NRC's review. This was a very well-run review. We are very appreciative of the preparedness that the staff came into. We had an audit with them. They were well prepared. They were very pointed in what they wanted and the information they needed to support filling the holes in the draft that Zena had prepared.

And with that, I'd like to turn it over to Mr. Tim Crede, who was our technical lead at Westinghouse for us. And although Tim is here, he was supported by a large number of other experts within Westinghouse to get to this report in such a good position for the NRC review. Thank you.

MR. CREDE: Thank you, Brian. Good morning, everybody. Can you hear me all right? Thank you.

Just a logistics questions first. Do you want me to share my screen around the slides or who's changing the slides?

CHAIR BALLINGER: I guess that's up to you.

MEMBER REMPE: I thought you were sharing

--

MR. CREDE: Okay. Do you want to try it? Okay.

MR. MOUNT: Leslie Fields.

MR. CREDE: All right, so my name is Tim Crede. I work for Westinghouse in the Fuel Rod and Thermal-Hydraulic Design Group. I was the technical lead on the project, although as Brian mentioned, I certainly had a very large and excellent support staff.

We can go to the next slide.

CHAIR BALLINGER: See if you've got a speaker on because we're getting feedback.

MR. CREDE: All right, so just the agenda for the open session, I wanted to go through a little bit of an introduction, talk about some background, give a high-level overview of the project, discuss the alternate strain limit that we proposed, a quick summary, and conclusions and then take any questions.

Next slide, please. So back in 2019, Westinghouse partnered with the PWR Owners Group to develop a new project. We were looking at an alternative way to evaluate transient cladding strain. Specifically, we were looking at a new limit. So the current limit that Westinghouse uses is taken straight out of NUREG-0800, the NRC Standard Review Plan. But we wanted a more data-driven and performance-based limit, something that was derived from test data specific to Westinghouse cladding outward. And the limit from the SRP is appropriate. It's conservative, but it is not based on our Westinghouse measured data.

So what we were looking for is to develop further, more accurate strain limit that would have the benefit of increasing margin, what is typically the limiting time and life for transient cladding strain analyses which would allow utilities to pursue some of the programs Brian mentioned, uprates, loaded pattern optimization, cycle end extensions, things like that because for many of these plants, their most limiting fuel performance criterion does tend to be transient cladding strain. So we were looking for ways to both make the limit more accurate and a little side bonus is to recover some of that margin.

Next slide, please. So just a little bit of a background. If you do look at NUREG-0800 and look at Section 4.2, you will see that this is where we take our strain limit from, the current limit. I won't read it verbatim, but effectively what it says is that during a Condition II overpower, a transient event, we have thermal swelling of the fuel pellet.

It stands out at a rate faster than cladding expands. And it applies a stress strain on the cladding. There's some pellet cladding, mechanical interaction there.

And the purpose of the limit is to prevent an over training of the cladding during these Condition II transient events. So specifically, the outer diameter cladding pre-transient can't increase by more than one percent during the transient events.

Next slide, please. So the current one percent limits remains valid and conservative design limits. We are certainly not asking that the SRP be updated or changed. What we wanted to look at, however, is an alternative to that one percent limit that are using a generic one percent limit. We wanted one specifically for Westinghouse fuel. And when I say Westinghouse fuel, that is restricted to ZIRLO and Optimized ZIRLO which were our licensed cladding alloys at the time.

And when we looked at the data, what we noticed is that there's a very strong correlation between the material strengths or yield strengths, alternate tensile strength of our alloys and the hydrogen content. And the hydrogen content of cladding changes over time. It's a function of the oxidation process. As the fuel rod oxidizes, it's creating a zirconium oxide, as well as some free hydrogen, some amount of which is then absorbed back into the cladding.

Next slide, please. And so what we saw is not unique to Westinghouse fuel. There is a very well-established correlation between hydrogen content and material strength. It's something that we also noticed in a lot of open source material. As Brian mentioned, we saw it in a similar strain limit that was developed by PNNL. A lot of other scientific papers that we were able to find also indicated that there's a strong correlation between the hydrogen absorbed in the cladding and its material strength.

And the reason -- the reason is as that hydrogen gets absorbed, it is soluble up to a point. Once it hits the terminal solid and solubility limit instead of being soluble what we would call the excess hydrogen, the hydrogen above the solubility limit starts to form zirconium hydride platelets in the cladding and these hydrides can act as cracked propagation pathways such that it makes it easier to fail when you have high PCMI such as you would expect to see during an Condition II transient.

Next slide, please. And so the alternate limit that we're proposing instead of a flat one percent is a function of uniform elongation. Uniform elongation is associated with the materials' ultimate tensile strength. It is effectively the amount of strain at which the deformation ceases to become stable and uniform. It is bend necking and things like that start to occur and you actually start to see a breakdown of the material. So the limit we're proposing is rather than a straight one percent flat limit, it's actually a function of the uniform elongation.

Next slide, please.

MEMBER MARCH-LEUBA: Pardon me, just for my education. When we look at all the top materials, you know (unintelligible) like Dr. Ballinger. When you said percent, I see that the units are -- it's percent units per meter? What is the one percent?

MR. CREDE: It's percent increase of the cladding diameter. So we take the ratio of the pre-transient and the post-transient cladding diameter.

MEMBER MARCH-LEUBA: And you go back to the previous slide. So in -- doesn't this .01 in the excess scale, there is one percent?

MR. CREDE: Yes.

MEMBER MARCH-LEUBA: Okay.

MR. CREDE: And this is just a generic figure. The numbers are just what I put into Excel to make it plot, just to show what it looks like. These are not specific to any actuals here. But yes, this would be the one percent strain.

MEMBER HALNON: Hey, Tim, the process of hydrogen getting into -- is that a consistent process without any variables that could affect it differently causing the calculation to be --

MR. CREDE: It is how we model. We assume a fractional hydrogen pickup, so it you have a certain amount of oxidation, we assume a certain fraction of the hydrogen that's been generated is absorbed into the cladding. And that is not something that we created or developed as part of this. We have a preexisting approved corrosion model where we have -- one we did a few years ago for -- ZIRLO and Optimized ZIRLO. And it established the hydrogen pickup fraction that we assumed. But yes, we assume a steady hydrogen accumulation throughout life.

MEMBER HALNON: Okay.

CHAIR BALLINGER: He's being a little bit more theoretical than he needs to be. These are empirical correlations.

MR. CREDE: Yes. Thank you.

CHAIR BALLINGER: For an oxidizing environment, it's usually seven percent of the hydrogen produced ends up in the cladding. For hydrogen over pressure environment which is PWR, it's like 25 percent usually, right?

MEMBER HALNON: Okay, so we're ballparking this.

CHAIR BALLINGER: To say the least. But it's been ballparked for 40 years.

MEMBER HALNON: Tim, you mentioned it's for ZIRLO and for Optimized ZIRLO Westinghouse cladding.

MR. CREDE: Correct.

MEMBER HALNON: Is it different for each or have you confined the data so that you're looking for one that would represent both of those cladding materials?

MR. CREDE: So we weren't sure how we were going to do it when we first started. When we looked at the data, we saw that the uniform elongations were both alloys, was very, very similar. And so the limit that we developed does apply to single limit for both.

If you look at other alloys, they would need slightly different ones. If you look at the PNNL model, their database is mostly zirc 2 and zirc 4. It behaviors similarly, but it is different. In our cases, they were close enough, we have one model for both. If we would do other alloys, it could be different.

MEMBER KIRCHNER: Tim, this is Walt Kirchner. I'm attending virtually. Could you just explain -- I know we're not in a closed session, but just for the public and the record, why ZIRLO and Optimized ZIRLO is different from the older circuloid clads and why this might be appropriate to apply to these newer alloys.

MR. CREDE: Yes. So I can give a more detailed answer at the closed session, but for the open session what I will say is that Westinghouse ZIRLO and Optimized ZIRLO alloys have components in them and additives that are added in addition to the zirconium that make the material strength a little bit higher than what you would typically see with zirc 4 or zirc 2. It is a material reason that we manufactured to have a little bit more material strength.

MEMBER KIRCHNER: And this is manifested in primarily by less hydrogen uptake?

MR. CREDE: No, no. The material strength itself is tied to the hydrogen uptake over time, but even when you would have very low hydrogen and it would be soluble, you would still expect a higher material strength for ZIRLO and Optimized ZIRLO because of the additives and the manufacturing process that it undergoes.

MEMBER KIRCHNER: Okay. Thank you.

MEMBER ROBERTS: This is Tom Roberts. Can you talk briefly about the limitation that is applicable to Condition II over power events?

MR. CREDE: Yes, yes, absolutely. So the reason we sort of limited to Condition II events is because those are the only times really where or how we evaluate it that you would see that high stress. Obviously, you would see high stress at high strains for Condition III and IV, major accidents, but we don't use this limit for those accidents. They have their own methods and procedures and everything to look at LOCA and drop rod, rod ejection, things like that.

When we do our fuel performance evaluations, we are focused on ensuring that the cladding will not fail during Condition I and Condition II and we don't look at it for Condition I operation because the strain never gets high enough to be a concern. With older methodologies at 4, we used to have a steady-state strain limit, but it was recognized when we submit it at 5 that it was overly conservative and they got rid of it. We focus on the Condition II strain limit because that is the most restrictive.

MEMBER ROBERTS: Okay, thank you, sir. The Condition III and IV, the more severe action scenarios, the existing limits are not being reached yet, is that the issue?

MR. CREDE: Right. We would not apply this to those accidents. So they have different criteria that they use to evaluate. Effectively, the cladding can't fail under those conditions. They use different sets of analyses to not ensure that it doesn't fail, but -- or that we don't under predict how many rods are actually failed. But this is not -- this does not change or affect the way we look at Condition III and IV accidents.

MEMBER ROBERTS: Okay, thank you, sir. Condition II are essentially AOOs where you're required to show that the plant can still be operated after the event?

MR. CREDE: Correct, yes.

MEMBER ROBERTS: Okay. Thank you.

MR. CREDE: Unless there are other

questions, I think, Leslie, you can go ahead. No, sorry, I'm too far.

So the alternate limit that we propose as part of this project that we used are the measure data that we had available to develop a uniform elongation strain limit. We made it a function of the total hydrogen content of both the soluble and the insoluble or excess hydrogen. To determine the solubility limit, we used the Kerns correlation. The Kerns correlation is a very common model for solubility. It was developed back in the late '60s. It's been used ever since. It's part of the more recent NRC Reg. Guide 1.236, the PNNL model that we looked as part of this, and also used the Kerns model. It's a very, very common and widely used method for calculating solubility. That's what we used here as well.

And so what the limit looks like is your uniform elongation unit is flat when the claddings has very little hydrogen because when the hydrogen is soluble, it doesn't affect the material strength so the limit itself is a flat line. Once you exceed the solubility, you begin to form those zirconium hydrides in the cladding. That's where you see the strain limit start to degrade and it continues to degrade as we absorb more and more hydrogen into the cladding.

When you see the form and the form will be in the closed session, I apologize, but it looks very, very similar to the same strain limit that was developed by PNNL. Obviously, the numbers are a little bit different because the materials are a little bit different, but the formula model is exactly the same and what you would expect. It's a flat, uniform elongation limit until you start to degrade the material strength and then the limit drops off the board.

Last slide, please.

So just to summarize, again, Westinghouse and the PWR Owners Group partnered to develop a new and alternative strain limit, a function of the hydrogen content. We are not trying to replace the current one for said limit. This is an alternative. The one percent limit continues to be a valid method for design. But this limit does represent more of a data-driven, material-based limit that is specific to Westinghouse cladding alloys. It meets the NRC's requirement so that we maintain clarity and integrity during the conditions of operation and that does include Condition I operation as well.

It has the benefit of recovering margin. The most limiting time in life is strain which in most cases tends to be right around the point of cladding gap closure because at that early burn up we don't have a whole lot of hydrogen accumulated in the cladding and it does explicitly count for the strength and that utility loss that we do see with accelerated hydrogen pick up.

MEMBER MARCH-LEUBA: So just for context, so I understand. You're saying you want to keep both metals available. Is this because the hydrogen base method is more expensive to put in? You have to do additional calculations? And if you don't need it, you don't have to do that expense because basically you're using either one percent or one and a half percent.

MR. CREDE: So yes -- please.

MEMBER MARCH-LEUBA: I mean unless you want to go to closed session.

MR. CREDE: No, no, no.

MR. MOUNT: So the one percent limit that's in the SRP as applicable for BWRs, PWRs, so it's a much more generic, widespread limit. The Owners Group project has been only focused on ZIRLO and Optimized ZIRLO cladding materials and only the select number of participants who have joined the project are able to take advantage of it, so we can't --

MEMBER MARCH-LEUBA: You can't force other people to use your method, but you plan to use your method?

MR. MOUNT: Correct.

MEMBER MARCH-LEUBA: It's not an issue of it's very difficult to implement and it will cost a lot of money. It's just other people didn't join your group and therefore, they may not want to --

MR. MOUNT: And mainly with -- like I said, the other cladding materials in the boiler, we don't want to leave them without a limit.

MEMBER MARCH-LEUBA: The most important part from ACRS's point of view is not a technical reason. It's an implementation; I'm just stating.

MEMBER KIRCHNER: Tim, just a general question and Brian, you mentioned earlier that this was an issue -- part of the initiation here was that others were doing this and you mentioned PNNL's work there. What was PNNL's objective? Were they trying to demonstrate that even with this new information that the one percent limit was conservative or to evaluate what level of conservatism was within that limit?

MR. CREDE: I'm not -- I believe they were commissioned by the NRC to develop that limit. I think they were looking more at long term storage concerns and things like that. They were interested because at cold conditions, at storage conditions, when the temperature drops, your solubility drops, so you have a lot more hydrides in the cladding and I think they were looking at the material strength more so for storage concerns.

CHAIR BALLINGER: What we're talking about here is at temperature. The solubility for hydrogen at room temperature is basically zero, so anything that's in solution at high temperature is going to come out of solution as soon as they shut the plant, shut the plant down.

MEMBER KIRCHNER: Good. Thank you. Appreciate that.

MR. CREDE: Absolutely. Are we all set? Unless there are other questions that was all I had.

CHAIR BALLINGER: Okay, so we need to transition to the staff and I'm not sure who the presenter is. Okay, thanks.

Thank you very much and we'll see you in a little bit again.

Who's controlling the slides for you? There you go. Thank you.

MR. MESSINA: Good morning. My name is

Joseph Messina. I am a reactor systems engineer in the Nuclear Methods and Fuel Analysis Branch of NRR. Also here today with me on the side of the room is a co-reviewer of the topical report, Patrick Raynaud, who is a senior materials engineer in the Office of Research, who is on rotation to NRR during the duration of this review. So he assisted with it.

Next slide, please. So in this presentation, I'll be discussing the applicable guidance and regulations for the review, followed by some background information on hydrogen criteria, hydrogen-based criteria before we get into the review focal points. I'll end the presentation with limitations and conditions, as well as conclusion.

Next slide, please. So first, I wanted to provide an overview of what's proposed in the topical report. The topical report, as PWR Owners Group said, proposes a change in cladding strain limit as a function of cladding hygiene content for Condition II transients which are AOOs. I provided a non-exhaustive list of some examples of Condition II transients on the slide here and I'm not going to read them out, but just for your reference and this limit is intended to be an alternative to the one percent transient clad strain recommended in SRP 42.

Next slide, please. So here I'll provide some of the applicable regulation and guidance. So for this review, GDC-10 applies. GDC-10 establishes our SAFDLs, Specified Acceptable Fuel Design Limits, to ensure that the cladding does not fail during steady state or the focus of this review the effects of AOOs.

Also, SRP-42, as mentioned, talks about a one percent transient clad strain limit. They say that there's no criterion for failure by PCMI or PCI, but two related criteria should be applied. And that's the one percent transient clad strain limit and avoiding fuel melting.

And the PWR Owners Group is obviously requesting an alternative to this recommended one -- this one percent.

Next slide, please. Before I get into the details of the review, I wanted to provide some background and context on hydrogen-based limits. This is not something brand new. The NRC has accepted cladding hydrogen as a surrogate for burn up effects in comparable regulatory applications. For example, in Reg. Guide 1.236 on control rod drop and control rod ejection accidents, it establishes PCMI curves, as shown in the bottom left, which is peak entropy rise as a function of excess cladding hydrogen and there are different curves for different temperatures, so like hot zero power, cold zero power, as well as for the different cladding types, SRA, so stress relief annealed cladding, as well as RXA, recrystallizing annealed cladding.

Additionally, draft rule though it's still with the Commission, 50.46 Charlie establishes alloy-specific hydrogen-based oxidation limits, as shown in the curve on the right, which is your ECR, so equivalent cladding reacted, as a function of hydrogen content. And as you see, hydrogen has a negative effect on the ductility of your cladding in reactor. So realistically, it's better that they provide a transient clad strain limit based on actual data rather than just a steady one percent for the entire lifetime of the rod.

Next slide, please. Since there are no specific guidance or review for an alternative to the one percent transient strain clad limit in the SRP, it's important to look at some of the primary focal areas of our review. And these can be broken down into four categories. I'll go into detail in each of these categories in the closed session.

In the open session, I'll just briefly

touch on each of them. So the first bullet, validation of the limit, this was the bulk of the review. There were a lot of questions on this, such as is there enough data? Is this data appropriate to model PCMI? Are the figures of merit appropriate? How bounding is the limit? And are there any trends and experimental data that might not be captured? So by that I mean should there be an additional variable that's not considered or should there be a separate limit, for example, Optimized ZIRLO versus ZIRLO cladding. So we looked into all of those as part of our quote unquote validation of the model.

Next, this second sub-bullet, the impact of AOO on post-transient fuel performance. So if the cladding undergoes an AOO, it will likely at least the limiting rods will likely exceed the yield strength. And the uniform elongation which is the strain corresponding to the ultimate tensile strain would be above -- if you get close to that, you're above the yield strength. And once you would exceed the yield strength, you put some plasticity on the cladding and there's some strain hardening. And also, if you have enough strain of the cladding, you might get reopening of the pellet cladding gap which is obviously detrimental to the transfer, but also would likely due to a rise in a fission gas release.

CHAIR BALLINGER: I have a question about that. There's the no lift off criteria during operation.

MR. MESSINA: Yes.

CHAIR BALLINGER: But after an AOO, if you've opened the gap, do they have to redo a calculation or is it basically all over, you have to take the fuel out?

MR. MESSINA: So as long as the transient cladding strain limit is not exceed, they can put that fuel back into the reactor and I do discuss some of how the Owners Group would discuss that and the impacts of that in the closed session.

The second to last bullet, integration with other methods, this was primarily just a check to make sure that they're using approved models for inputs and how they calculate, how they use the model exactly. And lastly, since the SOP does state that the one percent is for both PCMI and PCI or PCISCC, pellet cladding interaction stress corrosion cracking to be specific, we have to look at well, is there going to be any impact on PCI? Are we going to see more PCI failures? So we looked into that as well.

Next slide, please. So this slide just

contains our five limitations and conditions of the topical. They're not very interesting and they're relatively straight forward, nothing controversial in them. So first of all, they should be used for PWRs with Optimized ZIRLO or ZIRLO cladding. It's to note that Westinghouse's most recent cladding axiom which is the evolution of the ZIRLO cladding types, it's not applicable to that cladding. So if they wanted to either -- if they wanted to do something other than one percent transient clad strain before that, they would have to come in to the NRC for approval.

CHAIR BALLINGER: Is this a limited issue?

MR. MESSINA: I believe so and I believe it has to do with the axiom cladding -- the timing. So the axiom cladding topical report was -- it went to ACRS last October and this topical came in last summer. So I envision they may want to come in in the future with data to support an alternate strain limit for that.

The third bullet, it's not applicable to cladding with radial hydrides, oxides following, or hydride boostering. The cladding primarily had circumstantial hydrides in the testing, so those -- the limit goes out the door once you introduce some of these things.

CHAIR BALLINGER: Basically, with some kind of constraint on the quality control for the cladding itself, so that you don't end up with the texture that results in radial hydrides, so there's an indirect effect, right?

MR. MESSINA: Yes, and primarily we wanted them to be aware that if they notice anything like that, they should not be continuing to use this limit because it would not be applicable.

MEMBER KIRCHNER: Ron, this is Walt. Yes, the radial hydrides, that goes back to fabrication technique, doesn't it in QA?

MR. MESSINA: Yes.

MEMBER KIRCHNER: So by the trademark ZIRLO and Optimized ZIRLO, you would not expect to see radial hydrides. I mean, isn't this, Joseph, just a different way of putting a limit on the applicability of the actual cladding that this UE can be -- a limit can be applied to?

CHAIR BALLINGER: That's what I was inferring.

MEMBER KIRCHNER: That's what I'm thinking, Ron.

MR. MESSINA: So lastly, the two last ones, it should be used with PAD5, a few performance codes, so we looked at the models in PAD5 that were used to generate inputs for the cladding strain limit. And then lastly, the Condition II transients as I had discussed previously.

CHAIR BALLINGER: Not to put you on the spot, but I will, is there any reason for staff to believe that other types of cladding, modern ones, would not be able to use the same, if they were able to develop the data, use the same limits?

MR. MESSINA: I envision M5 --

CHAIR BALLINGER: Like M5 for example.

MR. MESSINA: I envision M5 would be able to do something similar, but as for the exact number it probably would differ because fabrication has such a great impact on the behavior.

CHAIR BALLINGER: But the hydrogen absorption is so much lower.

MR. MESSINA: Yes.

CHAIR BALLINGER: On these modern claddings, so --

MR. MESSINA: Okay, next slide.

MEMBER KIRCHNER: Before you go on, Joseph, this is Walt again, I find it a little strange that you limit it to the PAD5 code. Now that's the -- if I'm correct, that's the Westinghouse fuel performance code.

MR. MESSINA: Correct.

MEMBER KIRCHNER: For example, I want to use the FAST code that NRC developed with PNNL. Why would this model not work in the FAST code?

MR. MESSINA: Well, primarily what we're getting at with that condition and limitation is they need to use an NRC-approved code.

MEMBER KIRCHNER: Okay, yes.

MR. MESSINA: Your example of FAST, they could not use FAST because FAST has technically not been NRC reviewed, despite being an NRC code.

MEMBER KIRCHNER: Right, okay, all right. Fair enough. Thank you.

PARTICIPANT: And Joseph, on that point, as you said, what you've done -- a detailed review of the PADS code and how this has been input to it. So you basically have done the code review associated with this element.

MR. MESSINA: Part of it, yes. Next slide, please.

MEMBER MARCH-LEUBA: Basically, you use PAD5 to list how much hydrogen is in the cladding for the experiments. Just kind of embedded into the correlation. If you used a different code, you might have come up with a different hydrogen content?

MR. MESSINA: Possibly, yes. I believe so.

MEMBER MARCH-LEUBA: Because you used PAD5 to develop your correlation data. It's more accurate to continue to use PAD5, so if you want to use something different, you have to use the 5 or reanalyze the raw data.

MR. MESSINA: Thank you.

CHAIR BALLINGER: Again, it's not the issue, it's the way PAD5 does the calculation. That's independent of the amount of hydrogen that's actually absorbed.

MR. MESSINA: True.

CHAIR BALLINGER: During certain operations.

MR. MESSINA: And actually the test -- the data for hydrogen was mostly measured data, not a calculated, I believe.

So the conclusions, we find -- the NRC staff finds the proposed limit to be acceptable because the data is adequately representative of PCMI. The limit is reasonably bounding of the data to sufficient confidence that arrives that means the limit should not fail during a Condition II event by

PCMI. The limit integrates acceptably with existing fuel performance methodologies to capture the relevant phenomena associated with transient cladding strain and fuel behavior before and after AOOs as well as during AOOs because PAD5 has their method for how they approach these Condition II events.

And lastly, it's not expected to impact the number of PCI SEC failures.

That's it for me. Any questions?

CHAIR BALLINGER: Questions from the members?

Okay, this is going to be the end of the open session, so we now need to go out and ask for public comment. So if there are members of the public that wish to make a comment, please state your name and your organization and then make your comment.

Hearing none so far, so thank you again. So now we need to make a transition to the closed session and so I would suggest that we make a break until 9:30. Again, everything is squared away on who's going to be here or not. So we'll take what now amounts to a ten-minute break. Thank you.

(Whereupon, the above-entitled matter went off the record at 9:20 p.m.)

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ACRS Fuels, Materials, and Structures Subcommittee – Open Session
PWROG-21001-P/NP, Hydrogen-Based Transient Cladding Strain Limit

Brian L. Mount (Dominion), Tim M. Crede (Westinghouse)

August 24, 2023

Agenda

- Introduction
- Background and Overview
- Proposed Alternate Cladding Strain Limit
- Summary and Conclusions

Introduction

- In 2019, the PWR Owners Group (PWROG) approved a project to develop a new design limit for the transient cladding strain fuel performance criterion
- The current strain limit for Westinghouse fuel is contained in Section 4.2, “Fuel System Design” of NUREG-800, the NRC Standard Review Plan (SRP)
- The project objective was to develop an alternative, data-driven and performance-based design limit derived from test data and specific to current cladding materials
  - The new strain limit is a more accurate reflection of measured strain data
  - It also increases margin at the limiting time in life, to support licensees who are limited by the cladding strain design criterion when they pursue increased fuel duty, optimized loading pattern development, extended cycle lengths, etc.

Background and Overview

- NUREG-0800, Section 4.2 Revision 3, SRP Acceptance Criteria B. “Fuel Rod Failure,” vi. states:

  “The first criterion limits uniform strain of the cladding to no more than 1 percent. In this context, uniform strain (elastic and inelastic) is defined as transient-induced deformation with gauge lengths corresponding to cladding dimensions.”

- The objective of the strain limit is to prevent fuel failures from over-straining the cladding due to thermal swelling of the fuel pellet during Condition II overpower transient events

Background and Overview

- The current 1% cladding strain limit is a valid and conservative design limit for zirconium-based cladding
- However, a review of measured strain data for Westinghouse fuel determined that a 1% cladding strain limit does not reflect the true behavior of current cladding alloys, **ZIRLO**® and **Optimized ZIRLO**™ High Performance Fuel Cladding Material
- Additionally, the material yield strength (YS) and ultimate tensile stress (UTS) are impacted by the hydrogen content of the cladding and change over time
  - Hydrogen is absorbed into the cladding material as a result of the oxidation process

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

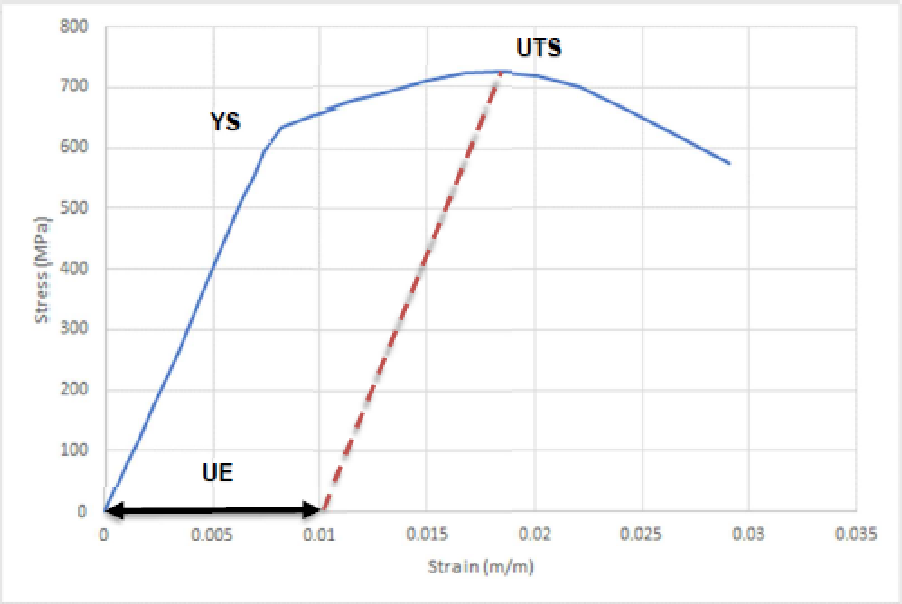
A fraction of the free hydrogen is absorbed into the cladding material

Proposed Alternate Cladding Strain Limit

- There is a well-established relationship between the hydrogen content and material strength
  - This is based on Westinghouse measured data, as well as other scientific organizations
- The material strength of the cladding is reduced as excess hydrogen begins to form zirconium hydride (ZrH) platelets
  - Hydrogen in the cladding is soluble until it reaches the terminal solid solubility (TSS) limit, which is a function of the cladding temperatures
  - Hydrogen above the TSS is “excess” hydrogen and leads to the formation of hydrides
- Hydrides act as crack propagation pathways through the cladding which make it more likely to result in cladding failure due to pellet-cladding mechanical interaction (PCMI)

Proposed Alternate Cladding Strain Limit

- Instead of a constant 1% strain limit, the new design limit is based on uniform elongation (UE)
  - o UE corresponds to the UTS of the cladding
  - o UE represents the strain at which deformation ceases to be uniform and stable



Proposed Alternate Cladding Strain Limit

- Westinghouse used available measured data to develop an alternative UE strain limit as a function of the total (soluble and excess) hydrogen content
  - The TSS is determined using the Kearns solubility correlation, which is a common model utilized by the NRC for PCMI cladding failure thresholds (see NRC Regulation Guide 1.236)
- The UE limit is a constant value at low hydrogen values (i.e., when the hydrogen is soluble) and degrades slowly once excess hydrogen begins to form ZrH platelets in the cladding
  - The UE limit is comparable to a strain limit developed by Pacific Northwest National Laboratory (PNNL) for zirconium-based cladding

Summary and Conclusions

- The PWROG approved a project to develop a hydrogen-based design limit for transient cladding strain
  - This is an alternative to the 1% strain limit contained in Section 4.2 of the SRP
- It represents a data-drive, performance-based design limit based on measured strain test data for Westinghouse cladding alloys
- The hydrogen-based strain limit:
  - Meets the NRC requirement for maintaining cladding integrity during Condition II overpower transient events,
  - Recovers margin at the historically limiting time in life (near the point of gap closure), and
  - Explicitly accounts for the cladding strength and ductility loss with hydrogen pickup

Questions?

NRC Review of PWROG-21001, Hydrogen-Based Transient Cladding Strain Limit

ACRS Fuels, Materials, and Structures SC
Open Session
August 24, 2023

Joseph Messina, Patrick Raynaud
Nuclear Methods and Fuel Analysis
Office of Nuclear Reactor Regulation

Outline

- Applicable guidance and regulations
- Historical background
- Review focal points
- Limitations and conditions
- Conclusion

Overview

- In PWROG-21001, the PWROG proposed a transient cladding strain (TCS) limit that is a function of cladding hydrogen content for condition II transients
  - Condition II transients include:
    - Feedwater (FW) malfunctions causing a decrease in FW temperature
    - FW malfunction causing an increase in FW flow
    - Excessive increase in secondary FW flow
    - Loss of normal FW
    - Inadvertent opening of a steam generator safety or relief valve
    - Uncontrolled rod cluster control assembly bank withdrawal at power
    - Uncontrolled boron dilution
    - Inadvertent ECCS actuation at power
- H-based TCS limit intended to be an alternative to the 1% TCS limit currently utilized

PRESSURIZED WATER REACTOR OWNERS GROUP

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PWROG-21001-NP
Revision 0

WESTINGHOUSE NON-PROPRIETARY CLASS 3

Hydrogen-Based Transient Cladding Strain Limit

Analysis Committee

PA-ASC-1671-A R1

July 2022

Westinghouse

Applicable Regulations and Guidance

- **GDC-10**: Establishes specified acceptable fuel design limits to ensure that the fuel is “not damaged” during normal operation, including the effects of anticipated operational occurrences (AOOs)
  - “Not damaged” means that fuel rods do not fail, fuel system dimensions remain within operational tolerances, and functional capabilities are not reduced below those assumed in the safety analyses during normal operation and AOOs

- **SRP 4.2 paragraph II.1.B.vi**: States that no criterion exists for fuel failure resulting from pellet-cladding interaction (PCI) or pellet-cladding mechanical interaction (PCMI), but that two related criteria should be applied:
  1) the strain of the cladding during a transient should not exceed 1%; and
  2) fuel melting should be avoided

Hydrogen-Based Limits – Historical Perspective

- The NRC has accepted cladding hydrogen content as a reasonable surrogate to BU effects in other comparable regulatory applications
- Historically, there is precedent for the use of hydrogen-based limits:
  - **RG 1.236** establishes hydrogen-based enthalpy failure criteria for PCMI during PWR control rod ejection and BWR control rod drop accidents
  - **Draft final rule 50.46c** establishes alloy-specific hydrogen-based oxidation limits

Fig. 5 of RG 1.236

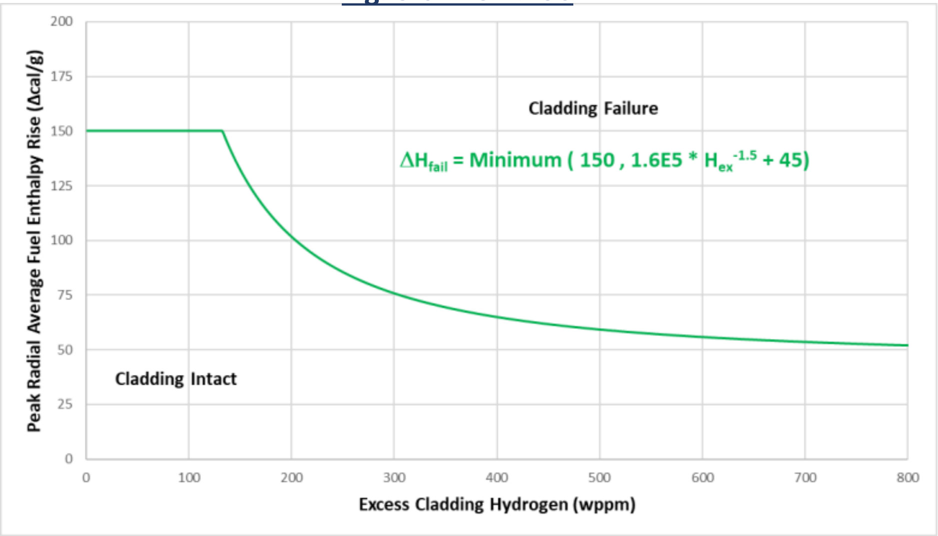
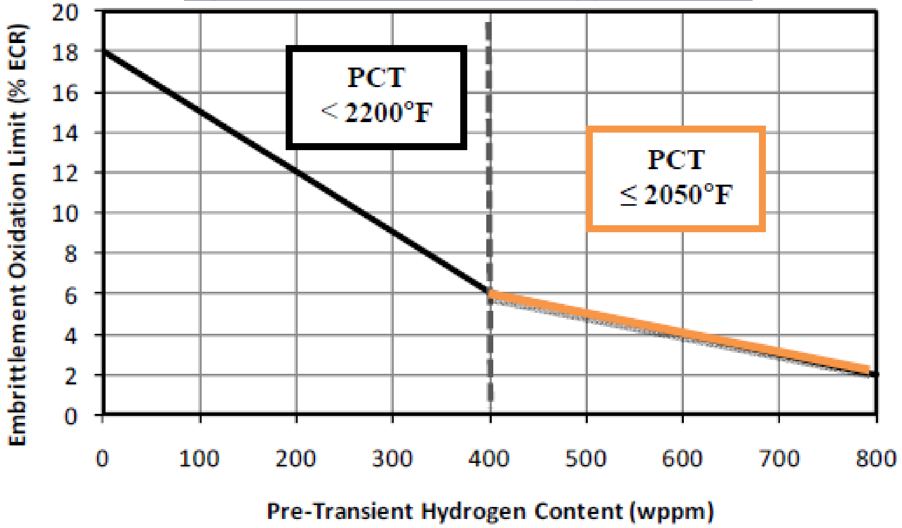


Figure 5. PCMI Cladding Failure Threshold—SRA Cladding below 500 Degrees F

Fig. 2 of Draft RG 1.224 (to support 50.46c)



Review Focal Points

- The NRC review focused on several areas:
  - Validation of limit
    - Quantity and quality of experimental data?
      - Is the experimental data representative of PCMI?
    - Are the figures of merit appropriate to accurately model PCMI?
    - Does the limit sufficiently bound the data?
      - Are there any potentially non-conservative regions?
    - Are there any trends in the experimental data that may not be captured by the limit?
  - Impact of AOO on post-transient fuel performance
  - Integration with other methods
  - Impact on PCI-SCC

Limitations and Conditions

The PWROG hydrogen-based TCS is limited to:

1. Use in Westinghouse or Combustion Engineering PWRs
2. Use with ZIRLO or Optimized ZIRLO cladding
3. Not applicable to cladding with radial hydrides, oxide spalling, or hydride blistering
4. Use with PAD5 fuel performance code
5. Condition II transients

Conclusion

The NRC staff find the hydrogen-based TCS limit in PWROG-21001 to be acceptable because:

1. the data presented is adequately representative of the PCMI phenomenon;
2. the proposed hydrogen-based TCS limit is reasonably bounding of the data so that there is a high degree of confidence that fuel rods that meet the limit will not fail due to PCMI during a Condition II event;
3. the proposed hydrogen-based TCS limit integrates acceptably with existing fuel performance methodologies to capture the relevant phenomena associated with TCS and fuel behavior before and after AOOs; and
4. the proposed hydrogen-based TCS limit is not expected to impact the number of PCI-SCC failures

Questions?